HYDROLOGIC EFFECTS OF ARTIFICIAL-RECHARGE EXPERIMENTS WITH RECLAIMED WATER AT EAST MEADOW, LONG ISLAND, NEW YORK

by Brian J. Schneider, Henry F. H. Ku, and Edward T. Oaksford

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations
Report 85-4323

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

Prepared in cooperation with the

NASSAU COUNTY DEPARTMENT OF PUBLIC WORKS

Syosset, New York

1987

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

U.S. Geological Survey
5 Aerial Way
Syosset, New York 11791
(516) 938-8830

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply inch-pound units	by	To obtain SI (metric) units
inch (in)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09294	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
foot per day (ft/d)	0.3048	meter per day (m/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
degree Fahrenheit (°F)	°C = 5/9 (°F-32)	degree Celsius (°C)
foot per day (ft/d)	0.3048	meter per day (m/d)

Equivalent concentration terms

microgram per liter (µg/L) = parts per billion (ppb)
milligram per liter (mg/L) = parts per million (ppm)

Other abbreviations

µS/cm = microsiemen per centimeter at 25 °Celsius
MPN = most probable number per milliliter
NTU = nephelometric turbidity units

Hydrologic Effects of Artificial-Recharge Experiments with Reclaimed Water at East Meadow, Long Island, New York

by Brian J. Schneider, Henry F. H. Ku, and Edward T. Oaksford

ABSTRACT

Artificial-recharge experiments were conducted at East Meadow from October 1982 through January 1984 to evaluate the degree of ground-water mounding and the chemical effects of artificially replenishing the ground-water system with tertiary-treated wastewater. More than 800 million gallons of treated effluent was returned to the upper glacial aquifer through recharge basins and injection wells in the 15-month period.

Reclaimed water was provided by the Cedar Creek advanced wastewater-treatment facility in Wantagh, 6 miles away. The chlorinated effluent was pumped to the recharge facility, where it was fed to basins by gravity flow and to injection wells by pumps. An observation-well network was installed at the recharge facility to monitor both physical and chemical effects of reclaimed water on the ground-water system.

Observations during the recharge tests indicate that the two most significant factors in limiting the rate of infiltration through the basin floor were the recharge-test duration and quality of reclaimed water. Head buildup in the aquifer beneath the basins ranged from 4.3 to 6.7 feet, depending on the quantity and duration of water application. Head buildup near the injection wells within the aquifer ranged from 0.3 to 1.2 feet. The head buildup in the injection wells is attributed to biological, physical, and chemical actions, which can operate separately or together. Recharge basins provided a more effective means of moving large quantities of reclaimed water into the aquifer than injection wells.

Two basins equipped with central observation manholes permit the acquisition of data on the physical and chemical processes that occur within the unsaturated zone during recharge. Results of 3-day and 176-day ponding tests in basins 3 and 2, respectively, indicate that reclaimed water is relatively unchanged chemically by percolation through the unsaturated zone because (1) the sand and gravel of the upper glacial aquifer is unreactive, (2) the water moves to the water table rapidly, and (3) the water is highly treated before recharge.

The quality of water in the aquifer zones affected by recharge improved, on the whole. Ground-water concentrations of nitrate nitrogen and several low-molecular-weight hydrocarbons, although significantly above drinking-water standards before recharge, decreased to well within drinking-water standards as a direct result of recharge. Sodium and chloride concentrations increased above background levels as a result of recharge but remained well within drinking-water standards and the New York State effluent standards established for this ground-water-recharge study.

INTRODUCTION

Several of man's activities on Long Island have interfered with the ground-water system. Excessive ground-water pumping has resulted in zones of aquifer depletion, loss of streamflow, and intrusion of saltwater into nearshore aquifer systems. Waste-disposal systems have caused widespread contamination of the shallow ground-water system, and the advent of sewering in Nassau County has led to an increase in consumptive loss. All of these effects could be partly mitigated through artificial recharge.

The need for artificial recharge on Long Island has been recognized since the 1930's, when stormwater was first routed from developed areas to stormwater basins that were designed to replenish the ground-water supplies. Since that time, several methods of artificial recharge have been tested on Long Island to dispose of cooling water and reclaimed wastewater, to augment streamflow, and to offset saltwater intrusion. As yet, such procedures have not become a necessity but may provide a means of partly alleviating future water shortages.

The most recent artificial-recharge studies on Long Island have been completed at a site at East Meadow, in central Nassau County (fig. 1), at which tertiary-treated wastewater (herein referred to as reclaimed water) from a sewage-treatment plant 6 mi to the south is piped into a group of shallow basins and injection wells to replenish the surficial aquifer. This investigation, which began in 1975, was conducted in cooperation with the Nassau County Department of Public Works and was designed to (1) evaluate the hydrologic and chemical effects of artificially replenishing the ground-water system with reclaimed water, and (2) determine whether the recharge procedure is practicable for future replenishment of the upper glacial aquifer.

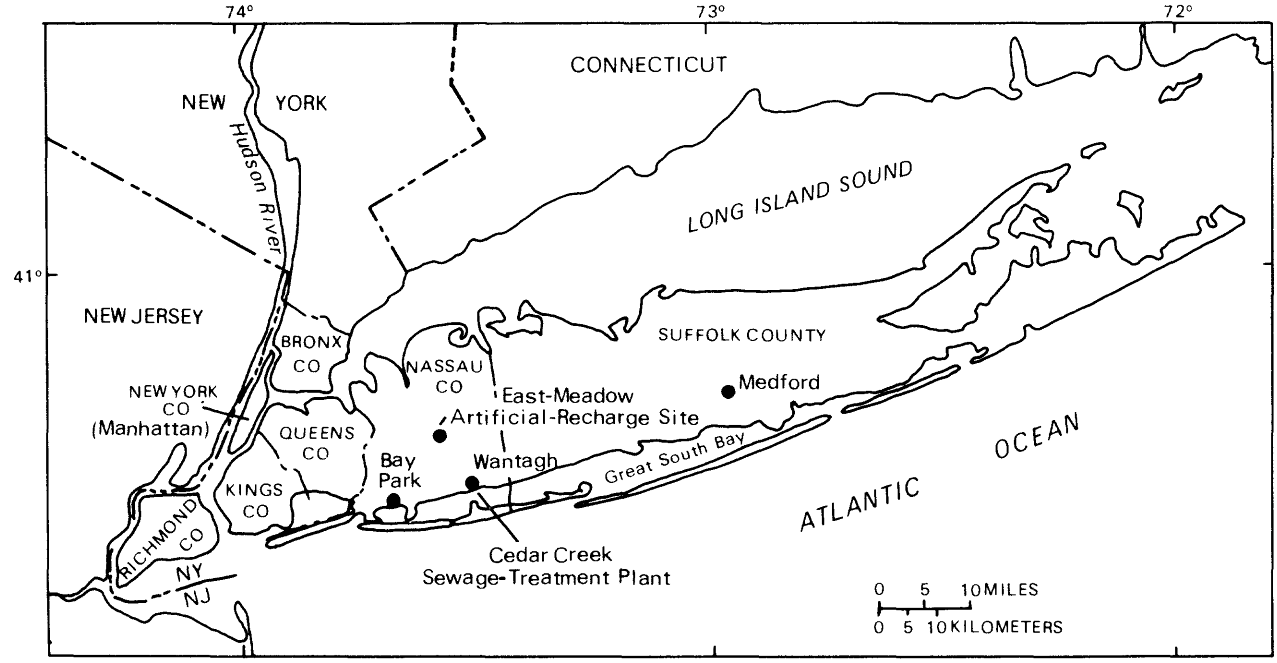

Figure 1.--Location of East Meadow artificial-recharge site and Cedar Creek sewage-treatment plant, Nassau County, N.Y. (Modified from Schneider and others, 1986.)

Purpose and Scope

This report documents the operating history of the East Meadow artificial-recharge facility and summarizes significant findings from a 15-month test period from October 1982 through January 1984. It evaluates the performance of the recharge basins and injection wells in terms of application rate and head buildup and summarizes the physical and chemical effects of infiltration through the unsaturated zone. The increases in water levels and changes in water quality within the ground-water system are depicted in graphs, maps, and tables.

Previous Studies

The history of artificial-recharge technology and considerations for its application on Long Island are described in reports prepared for Nassau County's Department of Public Works by Greely and Hansen (1963) and Holzmacher, McLendon, and Murrell (1980). The first experiments with artificial recharge were conducted with stormwater at recharge basins.

Other artificial-recharge experiments with reclaimed water were conducted at a deep-injection site at Bay Park (fig. 1) to recharge the Magothy aquifer directly to control saltwater intrusion. Several reports on the design, construction, operation, and effects of the study have been written by Cohen and Durfor (1966); Koch and others (1973); Ragone (1977); and Vecchioli and others (1980).

Recharge through a small test basin in Medford (fig. 1) to study the role of the unsaturated zone during artificial recharge was described by Prill and others (1979). The native geochemical conditions near the East Meadow recharge facility are described by Katz and Mallard (1980). The geohydrology of the East Meadow artificial-recharge facility is described in Aronson and others (1982), and a general nontechnical description of the East Meadow recharge facility is given by Aronson (1980). Schneider and Oaksford (1986) describe the design and monitoring capability of the recharge site and discuss preliminary effects of recharge. Schneider and others (1984) discuss the movement and chemical quality of reclaimed water in the unsaturated zone at the recharge facility.

Acknowledgments

Many people have been involved in the design, construction, and operational phases of the water-treatment and recharge facilities. Special thanks are extended to the Nassau County Department of Public Works, especially John F. Caruso, Deputy Commissioner, Francis J. Flood, Director of Environmental Engineering, James Oliva, Chief Sanitary Engineer at the Cedar Creek Wastewater Treatment Facility, and William Lahey, Supervisor of Wastewater Treatment Plant Maintenance.

Particular recognition is given to William R. Kaerhle of the U.S. Geological Survey for his assistance in modifying the flow-monitoring system at the recharge facility to allow collection of reliable flow data. Thanks are also extended to James Adamsky and his staff at the Nassau County Department of Health for analyzing water samples and providing some of the water-quality data used in this report.

Hydrogeology

Long Island is underlain by a sequence of southward dipping unconsolidated deposits of Late Cretaceous, Pleistocene, and Holocene age that overlie crystalline bedrock of Precambrian(?) age (fig. 2). The hydrogeologic units within the unconsolidated deposits have medium to high hydraulic conductivity and good to excellent water-transmitting properties. The major aquifers and confining units of Long Island, and a basic synopsis of ground-water flow, are presented by Smolensky (1984).

Directly overlying the bedrock is the Raritan Formation of Late Cretaceous age, which consists of the Lloyd Sand Member (Lloyd aquifer) and an overlying unnamed clay member (Raritan confining unit). The Lloyd aquifer is the deepest confined aquifer on Long Island and supplies a small percentage of the ground water used on Long Island.

Overlying the Raritan Formation is the Magothy Formation-Matawan Group, undifferentiated (Magothy aquifer), also of Late Cretaceous age. These deposits consist of clayey and silty fine to medium sand, some gravel, and clay layers. The Magothy aquifer is the island's largest source of fresh water for public supply and is as much as 1,000 ft thick. Overlying the eroded Magothy Formation-Matawan Group surface is the Monmouth Group (Monmouth greensand), which is a glauconitic sand and clay unit up to 200 ft thick and found primarily in southern Suffolk County and southeastern Nassau County.

Several Pleistocene deposits overlie the Magothy aquifer and Monmouth greensand. The oldest is the Jameco Gravel, found only in Kings, southern Queens, and southwestern Nassau Counties. The Gardiners Clay overlies most of the Jameco. In southern Nassau and southwestern Suffolk Counties, where the Jameco Gravel is absent, this greenish-gray clay was deposited on the eroded Magothy-Matawan surface. Two other Pleistocene clay layers on Long Island are

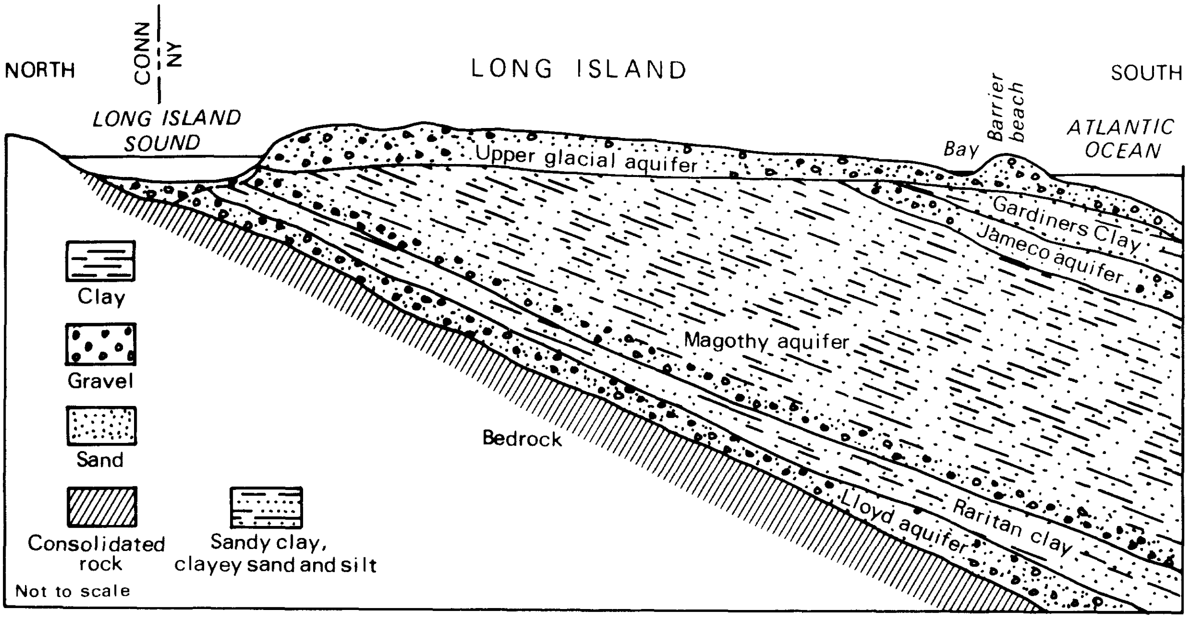

Figure 2.--Generalized geologic section showing relative positions of major aquifers, Long Island, N.Y. (Modified from Franke and McClymonds, 1972.)

the Smithtown clay confining unit and the "20-foot" clay unit. Most of Long Island's present topography is the result of Wisconsin deposition near the end of the Pleistocene Epoch. Meltwater from deglaciation flowed southward from the terminal moraines along the center of the island and deposited a sequence of coarse to fine sand and gravel that forms the outwash plain. This outwash forms what has been termed the upper glacial aquifer, which was once a major source of public supply. As a result of long-term contamination from surface sources, however, it is no longer used for public supply in Nassau County. The geohydrology of the outwash plain in the vicinity of the East Meadow artificial-recharge facility has been described by Aronson and others (1983).

The sole source of natural freshwater recharge to the ground-water system is precipitation, which averages 44 inches per year. Seasonal fluctuations in the water-table altitude are a reflection of the amount of precipitation, amount of percolation through the unsaturated zone, evapotranspiration losses, and rate of seaward discharge from the system.

A generalized north-south vertical section of Long Island (fig. 3) shows the directions of ground-water movement under natural (predevelopment) conditions. Near the ground-water divide, which runs east-west along the northern part of the island, ground water flows vertically downward and then horizontally. Ground water north of the divide eventually discharges into Long Island Sound, and ground water south of the divide discharges into Great South Bay and the Atlantic Ocean.

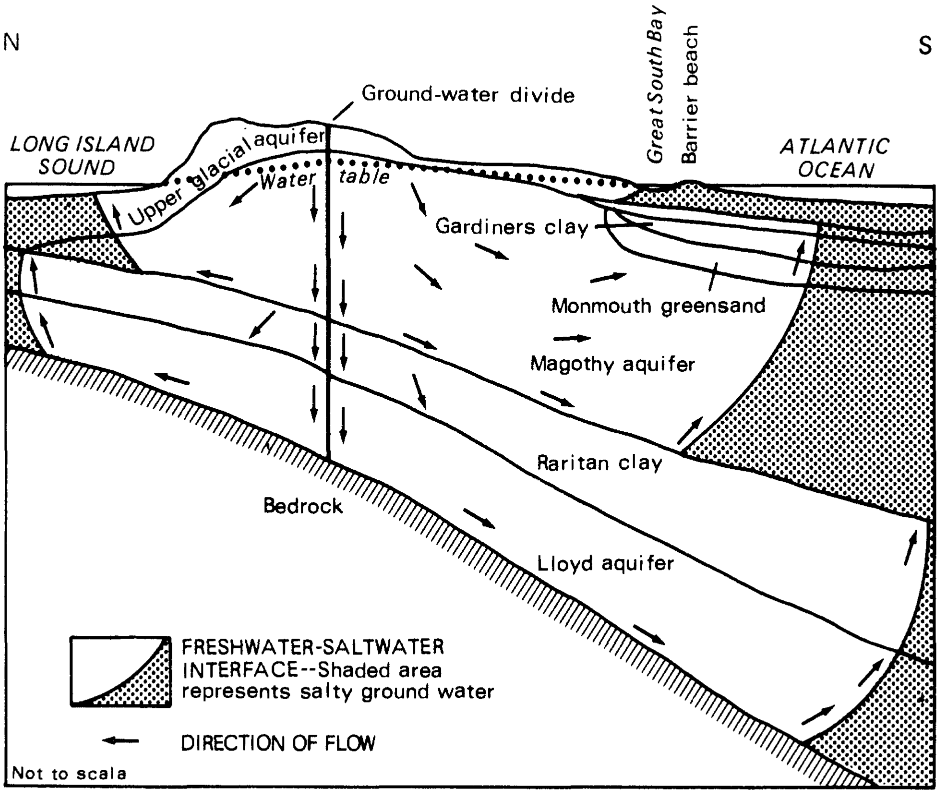

Figure 3.--Generalized hydrogeologic section showing ground-water flow paths under natural (predevelopment) conditions. (Modified from Smolensky, 1984.)

Ambient-Water Quality

More than 200 analyses for selected organic and inorganic constituents from 48 observation wells screened in the upper glacial and Magothy aquifers were used to characterize background water quality beneath the recharge facility prior to recharge operations. Previously collected data, published in a report by Katz and Mallard (1980), indicate that ground water beneath the site contained elevated concentrations of nitrate, chloride, sulfate, and ammonium ions; however, the concentration of those ions generally decreased with depth into the aquifer. Results of more recent sampling, listed in table 1, confirm the presence of nitrogen in elevated concentrations in both the upper glacial and Magothy aquifers.

Ragone and others (1980) describe probable sources of nitrogen to the ground-water reservoir, including domestic sewage, fertilizer for domestic purposes, exfiltration from sewers, surface contaminants washed by rainfall and overland runoff to recharge basins, agricultural fertilizers, animal wastes, landfills, and sewage-treatment plants. Most of these probable sources are found in and adjacent to the study area. Until 1980, the East Meadow community discharged domestic wastes to cesspools, and until 1979, the Meadowbrook Hospital and Nassau County Corrections Facility discharged their wastes to a secondary sewage-treatment plant (fig. 4). Also, the recharge facility is adjacent to a farm that uses a significant amount of agricultural fertilizers. The discharges from these major sources have caused concentrations of nitrogen in ground water near the site to exceed 10 mg/L, the New York State drinking-water standard.

ADVANCED WASTEWATER-TREATMENT FACILITY AND QUALITY OF RECLAIMED WATER

Reclaimed water was supplied by the advanced wastewater-treatment facility at the Cedar Creek sewage-treatment plant in Wantagh (fig. 1), a conventional activated-sludge facility designed to treat 45 to 50 Mgal/d of domestic sewage. A list of constituents and their concentrations in raw sewage entering the sewage-treatment plant is given in table 2 (p. 10). Approximately 5 Mgal/d of influent sewage is diverted after screening and grit removal to the advanced wastewater-treatment plant; the remaining 40 to 45 Mgal/d undergoes secondary treatment and then is discharged to the ocean. The advanced wastewater-treatment process consists of four steps (fig. 5):

1. chemically aided primary treatment to improve the removal of phosphorus, biochemical oxygen demand (BOD), suspended solids, and heavy metals;

2. a two-stage biological treatment system consisting of a nitrification-denitrification process to promote biological nitrogen removal in combination with oxidation of remaining carbonaceous material and secondary clarification;

3. rapid sand filtration and activated carbon treatment to reduce both suspended and dissolved organic compounds in the effluent to a few parts per billion; and

4. chlorination and storage to disinfect and store this effluent to allow for continuous delivery of 4 Mgal/d to the recharge facility.

Figure 4A.--Aerial photograph of the East Meadow artificial-recharge site. View is to northwest. (From Aronson, 1980.)

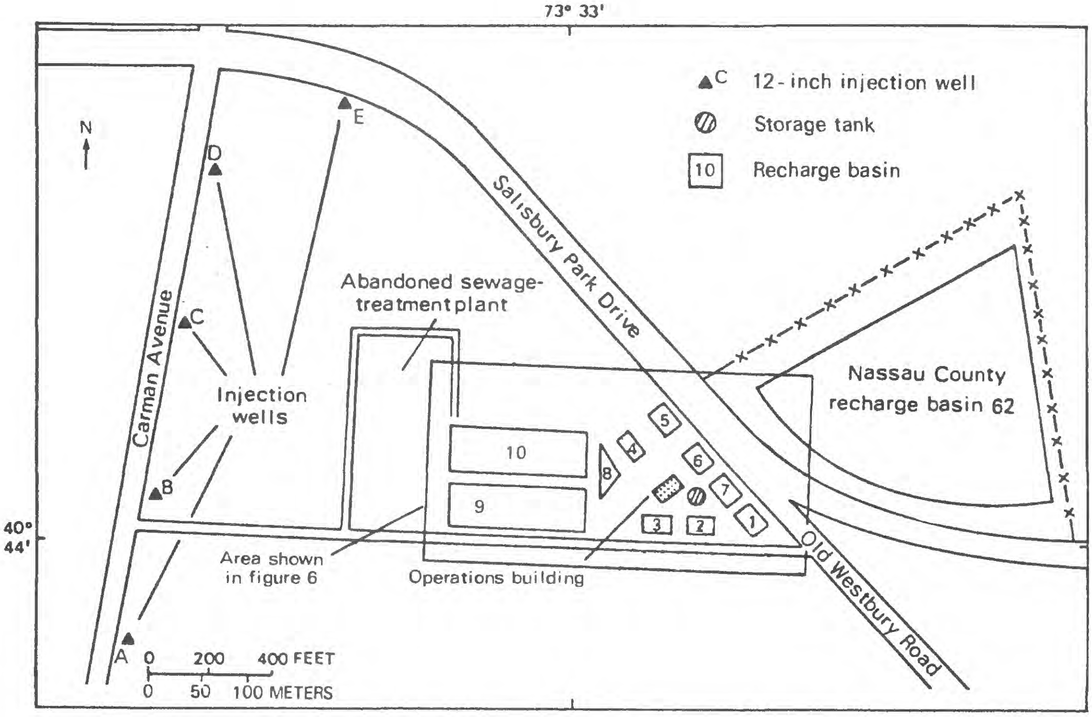

Figure 4B.--Position of injection wells and recharge basins. (Modified from Consoer, Townsend and Associates, 1978.)

Table 1.--Summary of ambient water quality in upper glacial and Magothy aquifers in study area, 1977-82

Constituent	Median	Minimum	Maximum	Number of samples
Temperature (°C)	14.0	12.0	18.5	181
Turbidity (NTU)	1.00	1.00	140	62
Specific conductance (µS/cm)	300	26.5	545	174
Oxygen, dissolved (mg/L)	3.80	.80	40.0	179
Nitrogen, total (mg/L as N)	.00	.00	20.0	162
Nitrogen, dissolved (mg/L as N)	9.10	.35	22.0	65
Nitrogen, organic total (mg/L as N)	.00	.00	1.00	142
Nitrogen, organic dissolved (mg/L as N)	.00	.00	1.00	50
Nitrogen, ammonia dissolved (mg/L as N)	.02	.01	2.40	100
Nitrogen, ammonia total (mg/L as N)	.01	.00	2.40	202
Nitrogen, NO2 + NO3 total (mg/L as N)	9.00	.03	25.0	205
Nitrogen, NO_2 + NO_3 dissolved (mg/L as N)	9.20	.08	25.0	204
Phosphorus, total (mg/L as P)	.01	.00	.75	204
Carbon, organic total (mg/L as C)	.80	.20	12.0	74
Calcium, dissolved (mg/L as Ca)	18.0	.80	55.0	205
Magnesium, dissolved (mg/L as Mg)	3.40	.30	9.30	205
Sodium, dissolved (mg/L as Na)	24.0	3.00	71.0	205
Potassium, dissolved (mg/L as K)	3.70	.20	10.0	203
Chloride, dissolved (mg/L as Cl)	28.0	1.80	100	207
Chromium, total recoverable (µg/L as Cr)	10.0	1.00	100	199
Iron, total recoverable (µg/L as Fe)	50.0	.00	18,100	207
Lead, total recoverable (µg/L as Pb)	.00	.00	450	203
Nickel, total recoverable (µg/L as Ni)	.00	.00	30.0	105
Zinc, total recoverable (µg/L as Zn)	30.0	10.0	860	172
Dichlorobromomethane total (µg/L)	.20	.00	1.00	84
Carbontetrachloride total (µg/L)	.20	.00	1.00	84
1,2-Dichloroethane total (µg/L)	.20	.00	130	53
Bromoform, total (µg/L)	.70	.00	8.00	84
Chloroform total (µg/L)	1.00	.00	33.0	84
Toluene, total (µg/L)	1.00	.00	3.00	80
Benzene, total (µg/L)	1.00	.00	30.0	80
N-butyl benzyl phthalate total (µg/L)	1.00	1.00	1.00	31
Tetrachloroethylene, total (µg/L)	5.10	.00	1,320	84
1,1-Dichloroethane, total (µg/L)	6.00	.00	300	84
1,1,1-Trichloroethane, total (µg/L)	7.95	.00	217	84
Chloroethylene, total (µg/L)	4.00	.00	500	84
2,4-Dimethylphenol, total (µg/L)	1.00	1.00	1.00	31
Di-n-butyl phthalate, total (µg/L)	1.00	1.00	5.00	31
Trichloroethylene, total (µg/L)	7.65	.00	260	84
Aldrin, total (µg/L	.00	.00	.01	175
Lindane, total (µg/L)	.00	.00	.01	175
Chlordane, total (µg/L)	.00	.00	1.00	175
DDD, total (µg/L)	.00	.00	.01	175
DDE, total (µg/L)	.00	.00	.01	174
DDT, total (µg/L)	.00	.00	.01	175
Dieldrin, total (µg/L)	.01	.00	1.40	175
Endosulfan, total (µg/L)	.00	.00	.01	173
Endrin, total (µg/L)	.00	.00	.02	175
Heptachlor, total (µg/L)	.00	.00	.01	175
Heptachlor epoxide, total (µg/L)	.00	.00	.06	175
PCB, total (µg/L)	.00	.00	.60	175
Mirex, total (µg/L)	.00	.00	.01	170
Silvex, total (µg/L)	.00	.00	.21	143
Solids, residue at 180°C dissolved (mg/L)	187	19.0	343	31
Solids, sum of constituents, dissolved (mg/L)	.00	.00	117	200
Mercury, total recoverable (µg/L as Hg)	.30	.00	.50	62

The quality of reclaimed water received at the recharge site met the requirements of the "State Pollutant Discharge Elimination Systems" permit set by the New York State Department of Environmental Conservation for discharge of reclaimed wastewater into the upper glacial aquifer. A list of constituents and allowed maximum concentrations is given in table 3. These limits were monitored daily by sewage-treatment-plant personnel. Whenever a constituent reached the concentration limit, recharge was halted until the concentration was lowered. The right-hand column of table 3 lists the median concentrations of all constituents analyzed for in reclaimed water.

The quality of injected reclaimed water is given in greater detail in table 4, which lists the quality of reclaimed water used during both basin and injection-well phases of operation.

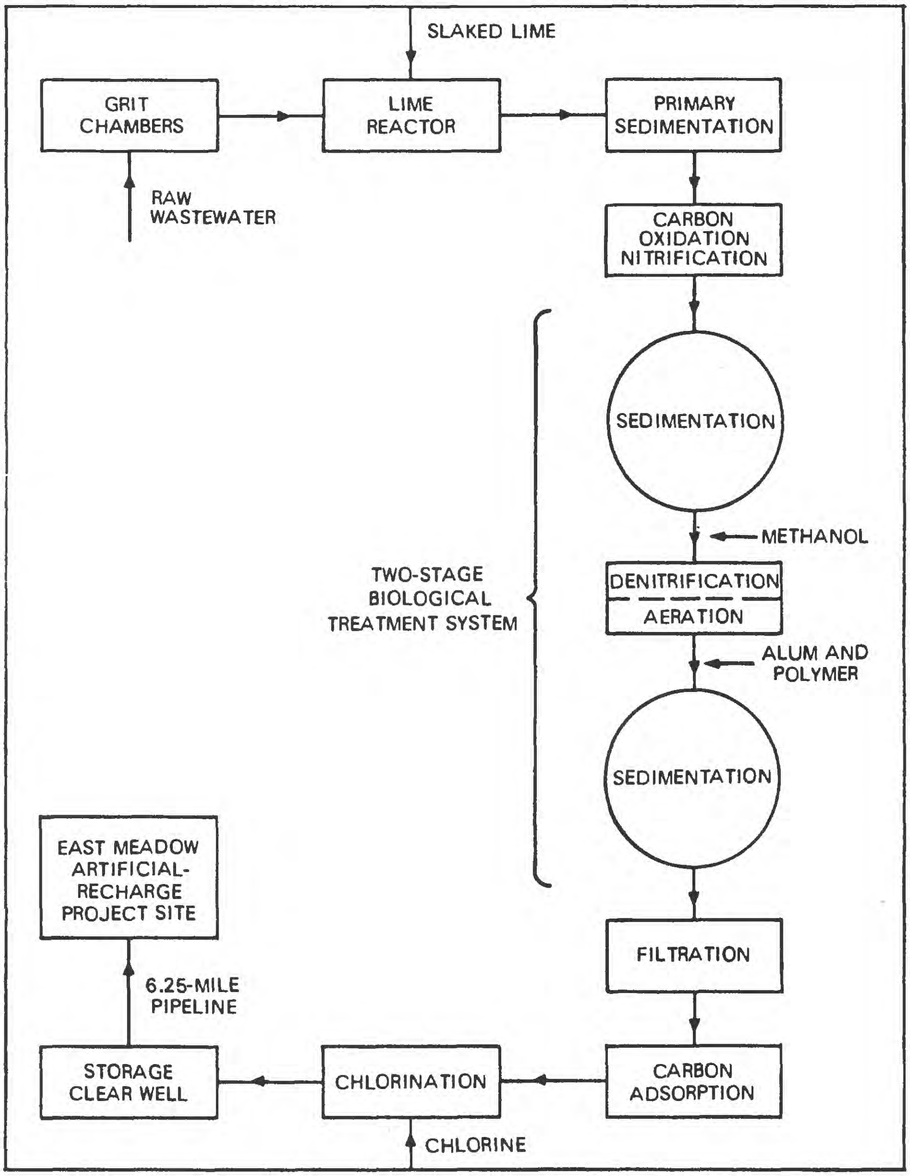

Figure 5.--Schematic diagram of the wastewater-reclamation process.

Table 2.--Concentration of selected constituents of untreated influent from Cedar Creek sewage-treatment facility

[All values in mg/L unless stated otherwise]

Constituent	Concentration	Constituent	Concentration
Alkalinity	190.	Silver	0.01
Aluminum	0.7	Sulfate	70.
Ammonia	22.0	Total organic carbon	155.
Arsenic	0.1	Zinc	0.7
Barium	0.2	Coliforms	5.0×10^7 MPN/100 mL
Biochemical oxygen demand	200.	Aldrin	0.0
Boron	0.3	Chlordane	0.0
Cadmium	0.01	DDT	0.0
Chemical oxygen demand	350.	Dieldrin	0.0
Chloride	165.	Endrin	0.0
Chromium	0.9	Heptachlor	0.0
Copper	0.2	Heptachlor epoxide	0.0
Cyanide	0.04	Methoxychlor	0.0
Hardness, as $CaCO_3$	102.	Polychlorinated biphenyls	0.2
Iron and manganese	2.0	Toxaphene	0.0
Lead	0.2	Silvex	0.0
Mercury	0.001	Total dissolved solids	500.
Nitrogen, total	35.	Turbidity	250.
Phenols	0.15	Suspended solids	200.
Phosphorus	16.	Volatile suspended solids	160.
Selenium	0.02	pH	7.4

Table 3.--Maximum concentrations allowed by New York State Department of Environmental Conservation State Pollutant Discharge Elimination System, and median concentrations in reclaimed water before recharge

Constituent	Reclaimed water Allowable maximum concentration	 Observed median concentration
	A. METALS (mg/L)	
Antimony	0.05	<0.01
Arsenic	0.025	<.005
Barium	1.00	<.5
Beryllium	0.20	<.005
Cadmium	0.01	<.001
Chromium, total	0.05	<.01
Cobalt	1.00	<.1
Iron	0.30	.04
Lead	0.025	<.01
Manganese	0.30	.036
Mercury	0.002	<.0005
Nickel	2.0	<.05
Selenium	0.01	<.005
Silver	0.05	.001
Thallium	0.02	<.01
Zinc	0.30	.04
Copper	0.20	<.05

(continued)

Table 3.--Maximum concentrations allowed by New York State Department of Environmental Conservation State Pollutant Discharge Elimination System, and median concentrations in reclaimed water before recharge (continued)

Constituent	Reclaimed water Allowable maximum concentration	 Observed median concentration
B. VOLATILE ORGANIC COMPOUNDS (µg/L)		
Dichlorofluoromethane	50.0	*
Chloroethene	1.0	*
Dichloromethane	50.0	.9
1,2-Dichloroethene	1.0	*
1,1-Dichloroethane	50.0	*
Trichloromethane	10.0	.5
1,1,1-Trichloroethane	50.0	*
1,2-Dichloroethane	2.0	*
Tetrachloromethane	0.3	*
Benzene	**	*
Trichloroethene	5.0	*
Bromodichloromethane	50.0	1.2
Methylbenzene	50.0	*
Dibromochloromethane	50.0	5.7
Tetrachloroethene	10.0	*
Chlorobenzene	10.0	*
Ethylbenzene	50.0	*
Tribromomethane	50.0	*
C. BASE/NEUTRAL-/OR ACID-EXTRACTABLE COMPOUNDS (µg/L)		
bis (chloroethyl) ether	0.09	<.5
1,4-Dichlorobenzene	10.0	<10
1,2-Dichlorobenzene	10.0	<10
Nitrobenzene	30.0	<10
bis (2-chloroethoxy) methane	2.0	<2
Naphthalene	30.0	<10
2-Chloronaphthalene	10.0	<10
Acenaphthylene	10.0	<10
Dimethyl phthalate	50.0	<10
2,6-Dinitrotoluene	50.0	<10
Fluorene	10.0	<10
Diethylphthalate	50.0	<10
Azobenzene	1.0	<1
Phenanthrene	10.0	<10
Anthracene	10.0	<10
Di-n-butyl phthalate	50.0	<10
Fluoranthene	0.2	<.5
Pyrene	0.2	<.5
Butyl benzyl phthalate	50.0	<10
bis (2-ethylhexyl) phthalate	75.0	<10
Di-n-octyl phthalate	50.0	<10
1,3-Dichlorobenzene	10.0	<10

-continued-

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* Below detection limit

** Not detectable by tests or analytical determinations referred to in New York State Department of Environmental Conservation, 1977, title 6, Official compilation of codes, rules and regulations, part 703.4.

Table 3.--Maximum concentrations allowed by New York State Department of Environmental Conservation State Pollutant Discharge Elimination System, and median concentrations in reclaimed water before recharge (continued)

	Reclaimed water	
Constituent	Allowable maximum concentration	Observed median concentration
C. BASE/NEUTRAL- OR ACID-EXTRACTABLE COMPOUNDS (μg/L) (continued)		
N-Nitrosodiphenylamine	14.0	<10
Phenol	1.0	<2
2,4-Dimethylphenol	1.0	<1
4-chloro,3-methylphenol	1.0	--
2,4,6-Trichlorophenol	2.0	<2
2-Nitrophenol	1.0	<1
2,4-Dichlorophenol	1.0	--
Acenaphthene	10.0	<10
D. CHLORINATED COMPOUNDS (μg/L)		
Alpha-BHC	0.2	*
Beta/gamma BHC	0.2	*
Delta BHC	0.2	*
Heptachlor	**	*
Aldrin	**	*
Dieldrin	**	*
Heptachlorepoxide	**	*
p,p-DDE	0.1	*
Endrin	**	*
Beta-endosulfan	5.0	*
p,p-DDE	0.1	*
Endrin aldehyde	**	*
Endosulfan sulfate	5.0	*
p,p-DDT	**	*
Mirex	0.1	*
Alpha chlorodane	0.03	*
E. MISCELLANEOUS CHEMICALS (in mg/L)		
Ammonia	2.0	0.7
Chloride	250.0	157
Fluoride	1.5	2.0
Nitrite plus nitrate	10.0	.73
Cyanide	0.2	.01
Chlorine residual (free)	5.0	0.4
Sodium	170.0	115
Oil and grease	15.0	<1

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* Below detection limit

** Not detectable by tests or analytical determinations referred to in New York State Department of Environmental Conservation, 1977, title 6, Official compilation of codes, rules and regulations, part 703.4.

Table 4.--Concentration of selected constituents in reclaimed water during recharge tests at basins and injection wells

Constituent	Basins[1] (median monthly values)	Recharge well[2] (median daily values)
5-day biochemical oxygen demand (mg/L)	<1	<1
Suspended solids (mg/L)	2	1
Total solids (mg/L)	528	542
Total dissolved solids (mg/L)	527	541
Nitrogen, organic total (mg/L)	.2	.2
Nitrogen, NH_4 as N (mg/L)	.7	.6
Nitrogen, NO_3 as N (mg/L)	.74	.18
Nitrogen, NO_2 as N (mg/L)	.02	<.01
Nitrogen, total (mg/L)	1.5	.8
Phosphorus, ortho as P (mg/L as P)	.3	.3
Phosphorus, total as P (mg/L as P)	.3	.4
Turbidity (NTU)	.6	.4
Cyanide (mg/L as CN)	<.01	<.01
Fluoride (mg/L as F)	.24	.23
Oil and grease (total, mg/L)	<1	<1
Chloride (mg/L as Cl)	156	146
Chemical oxygen demand (mg/L)	10	10
Hardness (mg/L)	177	180
Chlorine residual (free) (mg/L)	.4	.2
Total coliform (MPN/100 mL)	3.	<2
Fecal coliform (MPN/100 mL)	3.	<2
pH	7.5	7.4
Antimony, µg/L as Sb	<5.0	10.0
Arsenic, µg/L as As	<5.	<5.0
Barium, µg/L as Ba	<15.0	<50.0
Beryllium, µg/L as Be	<5.0	<5.0
Cadmium, µg/L as Cd	<1.0	<1.0
Chromium, µg/L as Cr	<10.0	<10.0
Cobalt, µg/L as Co	2.0	<100.0
Copper, µg/L as Cu	14.0	<50.0
Lead, µg/L as Pb	<10.0	<10.0
Mercury, µg/L as Hg	<.5	<.5
Nickel, µg/L as Ni	<50.0	<50.
Selenium, µg/L as Se	<.5	<.5
Silver, µg/L as As	<.50	<.50
Sodium, µg/L as Na	110	100
Thallium, µg/L as Tl	<10.0	<10.0
Zinc, µg/L as Zn	50.0	50.0
Iron, total µg/L as Fe	50.0	40.0
Manganese, µg/L as Mn	<50.	<50.

[1] October 1982 through December 1983 (excluding February 1983)

[2] October 11, 1983 through December 25, 1983

ARTIFICIAL-RECHARGE FACILITY

The East Meadow artificial-recharge site is in a 35-acre triangular area southeast of the intersection of Carman Avenue and Salisbury Park Drive in the Town of Hempstead (fig. 4). The site contains an operations building and 11 recharge basins. Eight of the basins were built specifically for artificial-recharge experiments; the other three were built earlier. Five injection wells were constructed for injection of reclaimed water directly into the aquifer. The site also contains the old Meadowbrook sewage-treatment plant, which was shut down in 1979.

A ground-water-monitoring network consisting of 96 observation wells was established within a 1-mi^2 area encompassing the recharge site. Each well site contains either one, two, or three wells of 2-, 3-, 4-, or 6-inch diameter screened at different depths. Table 5 gives statistics on each well; figures 9-11 in the next section show well locations.

Table 5.--Statistics on 6-inch, 4-inch, and 2-inch observation wells
[Locations are shown in figs. 9-11]

Well number State/Local	Total depth below land surface (ft)	Screened interval (ft below land surface)	Closest artificial-recharge point: Distance from source (ft)	Closest artificial-recharge point: Name
		A. 6-INCH-DIAMETER WELLS		
N9234 (1A)	205	200 - 205	1,650	Injection well E
N9235 (1B)	105	100 - 105	1,650	Injection well E
N9236 (1C)	50	45 - 50	1,650	Injection well E
N9217 (2)	50	45 - 50	2,250	Recharge basin 5
N9360 (3A)	205	200 - 205	100	Injection well D
N9361 (3B)	98	93 - 98	100	Injection well D
N9362 (3C)	45	40 - 45	100	Injection well D
N9363 (4A)	105	100 - 105	30	Injection well D
N9364 (4B)	45	40 - 45	30	Injection well D
N9449 (5A)	198	193 - 198	1,100	Center of site
N9450 (5B)	104	99 - 104	1,100	Center of site
N9451 (5C)	41	36 - 41	1,100	Center of site
N9218 (6)	44	39 - 44	1,500	Center of site
N9239 (7A)	205	200 - 205	1,500	Injection wells C and D
N9240 (7B)	105	100 - 105	1,500	Injection wells C and D
N9241 (7C)	45	40 - 45	1,500	Injection wells C and D
N9199 (8A)	105	100 - 105	125	Injection well C
N9200 (8B)	45	40 - 45	125	Injection well C
N9182 (9A)	196	191 - 196	25	Injection well C
N9183 (9B)	106	101 - 106	25	Injection well C
N9184 (9C)	45	40 - 45	25	Injection well C
N9193 (10A)	195	190 - 195	750	Center of site
N9194 (10B)	95	90 - 95	750	Center of site
N9195 (10C)	46	41 - 46	750	Center of site
N9196 (11A)	206	201 - 206	60	Basins 4, 5, and 6
N9197 (11B)	95	90 - 95	60	Basins 4, 5, and 6
N9198 (11C)	46	41 - 46	60	Basins 4, 5, and 6
N9367 (12A)	105	100 - 105	65	Basin 1
N9368 (12B)	45	40 - 45	65	Basin 1
N9219 (14A)	95	90 - 95	500	Injection well A
N9220 (14B)	45	40 - 45	500	Injection well A
N9247 (15A)	95	90 - 95	2,000	Center of site
N9248 (15B)	45	40 - 45	2,000	Center of site
N9221 (16A)	95	90 - 95	1,000	Injection well A
N9222 (16B)	45	40 - 45	1,000	Injection well A

- continued -

Table 5.--Statistics on 6-inch, 4-inch, and 2-inch observation wells (continued)

[Locations are shown in figs. 9-11]

Well number State/Local	Total depth below land surface (ft)	Screened interval (ft below land surface)	Closest artificial-recharge point: Distance from source (ft)	Closest artificial-recharge point: Name
	A. 6-INCH DIAMETER WELLS (continued)			
N9223 (17A)	108	103 - 108	1,250	Injection well A
N9224 (17B)	45	40 - 45	1,250	Injection well A
N9201 (18)	45	40 - 45	4,500	Injection well A
N9365 (19A)	95	90 - 95	600	Injection well A
N9366 (19B)	45	40 - 45	600	Injection well A
N9225 (20)	44	39 - 44	2,600	Injection well A
N9252 (21A)	195	190 - 195	3,500	Center of site
N9253 (21B)	95	90 - 95	3,500	Center of site
N9254 (21C)	46	41 - 46	3,500	Center of site
N9226 (22)	45	40 - 45	4,000	Center of site
N9689 (Basin 2)	45	20 - 45	15	Basin 2
N9690 (Basin 3)	45	20 - 45	15	Basin 3
N9692 (D6)	85	80 - 85	10	Injection well D
[1]N9821	36.6	25.5 - 33.9	0	Basin 2
[1]N9822	37.8	25.3 - 35.3	0	Basin 2
[1]N9823	37.7	25.2 - 35.2	0	Basin 2
[2]N9824	37.8	25.3 - 35.3	0	Basin 3
[2]N9825	37.7	25.2 - 35.2	0	Basin 3
[2]N9826	37.7	25.4 - 35.4	0	Basin 3
	B. 4-INCH-DIAMETER WELLS			
N10151	40	30 - 40	1,200	Center of site
N10152	85	75 - 85	1,200	Center of site
N10153	120	110 - 120	1,200	Center of site
N10154	38	28 - 38	1,950	Center of site
N10155	85	75 - 85	1,950	Center of site
N10156	120	110 - 120	1,950	Center of site
N10157	43	33 - 43	700	Injection well B
N10158	85	75 - 85	700	Injection well B
N10159	120	110 - 120	700	Injection well B
N10162	38	28 - 38	600	Center of site
N10163	85	75 - 85	600	Center of site
N10164	120	110 - 120	600	Center of site
N10165	42	32 - 42	900	Center of site
N10166	74	64 - 74	900	Center of site
N10167	120	110 - 120	900	Center of site

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[1] Observation wells at bottom of manhole 2.
[2] Observation wells at bottom of manhole 3.

Table 5.--*Statistics on 6-inch, 4-inch, and 2-inch observation wells (continued)*

[Locations are shown in figs. 9-11]

New York State well number	Total depth below land surface (ft)	Screened interval (ft below land surface)	Closest artificial-recharge point: Distance from source (ft)	Closest artificial-recharge point: Name
	B. 4-INCH-DIAMETER WELLS (continued)			
N10171	120	110 - 120	1,800	Center of site
N10172	85	75 - 85	1,800	Center of site
N10173	43	33 - 43	1,800	Center of site
N9131	46.5	39.5 - 44.5	500	Center of site
	C. 2-INCH-DIAMETER WELLS			
N9603	54.0	20.30 - 54.05	0	Center of basin 1
N9600	59.1	16.9 - 59.16	0	West side of basin 2
N9601	64.1	15.9 - 64.10	0	Center of basin 2
N9602	60.0	20.1 - 60.05	0	East side of basin 2
N9599	61.4	16 - 61.40	25	Between basins 2 and 3
N9596	50.1	9.3 - 50.15	0	West side of basin 3
N9597	54.8	13.8 - 41.90	0	Center of basin 3
N9598	57.4	15.5 - 57.40	0	East side of basin 3
N9811	44.5	24.5 - 44.5	0	Center of basin 4
N9812	44.2	24.2 - 44.2	0	Center of basin 5
N9813	50.7	30.7 - 50.7	0	South side of basin 6
N9604	52.9	21.1 - 52.94	0	Center of basin 7
N10065	50.0	45 - 50	300	South rim of basin 8
N10066	50.0	45 - 50	400	North of site
N10067	50.0	45 - 50	400	East of site
N10068	50.0	45 - 50	800	Southeast of site
N10069	50.0	45 - 50	250	South of site
N10070	50.0	45 - 50	300	Southwest of site
N10071	50.0	45 - 50	1,000	Southwest of site
[3]N9084	143	139 - 143	15	South of well A
[3]N9085	94	90 - 94	15	West of well E
[3]N9691	45	40 - 45	10	Inside well vault D

[3] Three-inch-diameter observation well.

Recharge-Basin Design

Seven shallow recharge basins (nos. 1-7 in fig. 4B) were constructed on the site. They were used to evaluate (1) management practices to optimize recharge schemes; (2) causes of clogging of the basin floor during ponding of reclaimed water; and (3) the ability of the unsaturated zone (the sand and gravel deposits between the basin floor and the water table) to alter the quality of percolating reclaimed water. A schematic diagram of the recharge facility showing relative positions of basins, wells, and the distribution system is shown in figure 6.

Each basin has a 5,000-ft^2 floor area (50 ft x 100 ft) and is 5 ft deep. Encircling the basin floor is a 1-ft-high concrete retaining wall designed to confine infiltration to the basin-floor area. Five of the seven shallow basins (basins 1, 4, 5, 6, and 7) were constructed with sloping walls lined with impermeable liners (fig. 7). The sloping walls provide a greater storage area, and the lining also ensures that water will infiltrate only at the basin floor, which facilitates calculation of infiltration rates. Basins 2 and 3

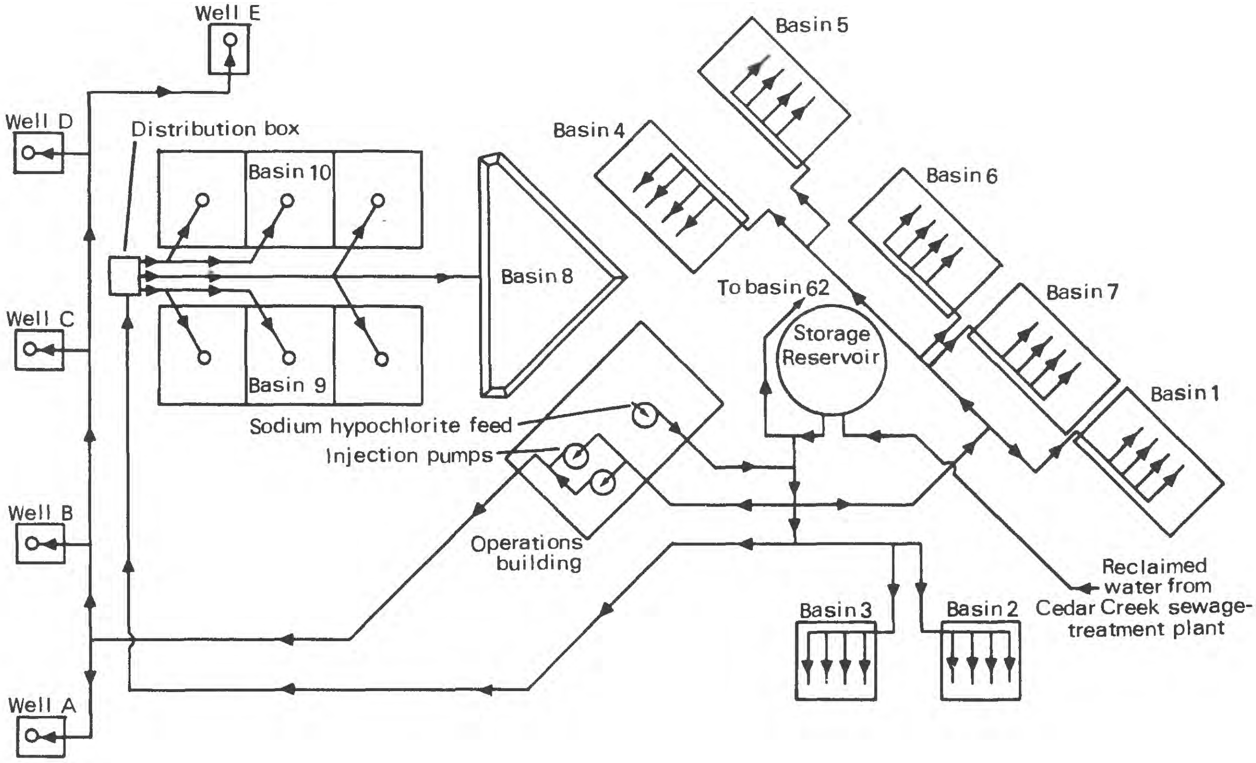


Figure 6.--Schematic diagram of East Meadow artificial-recharge site showing relative position of recharge basins, injection wells, and water-transmission mains. (Modified from Aronson and others, 1983.)

also have a 5,000-ft^2 infiltration area and are 5 ft deep, but each has vertical concrete walls that extend 4 ft below the basin floor and a circular observation manhole that can be used to monitor the unsaturated zone during recharge operations. The floor of basin 6 is covered with 6 inches of uniform pea-size gravel, which is expected to extend the clogging zone and help disperse clogging agents.

A distribution system consisting of four parallel 4-inch fiberglass pipes was installed within each basin (fig. 7). A series of 2-inch holes was drilled along the bottom of each pipe. In this way the reclaimed water, which was fed by gravity from the 40,000-gal storage reservoir (fig. 4B), was distributed evenly throughout the basin.

Four other basins were available for storage, should clogging limit the capacity of basins 1 through 7, and one basin (basin 8, fig. 4) was available for deep-ponding experiments. This basin has a depth of 15 ft, a floor area of 3,213 ft^2, and a total infiltration area of 17,322 ft^2.

Basins 9 and 10 (fig. 4) are shallow and were used for the ponding of sewage from a secondary-sewage-treatment plant that was shut down on June 22, 1979. These two basins can be used for containment of water in excess of that required for operation of basins 1 through 8.

The remaining basin, Nassau County stormwater recharge basin 62 (fig. 4), is connected to the recharge system and provides emergency storage should one or more basins need to be bypassed for maintenance.

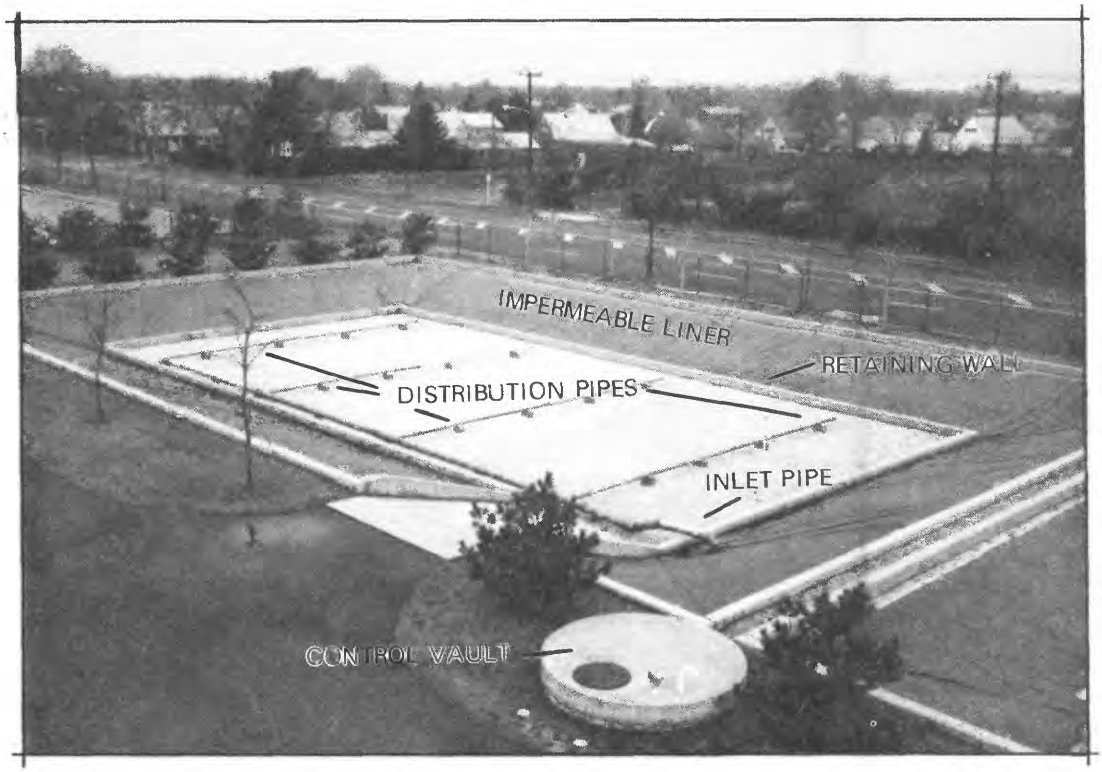
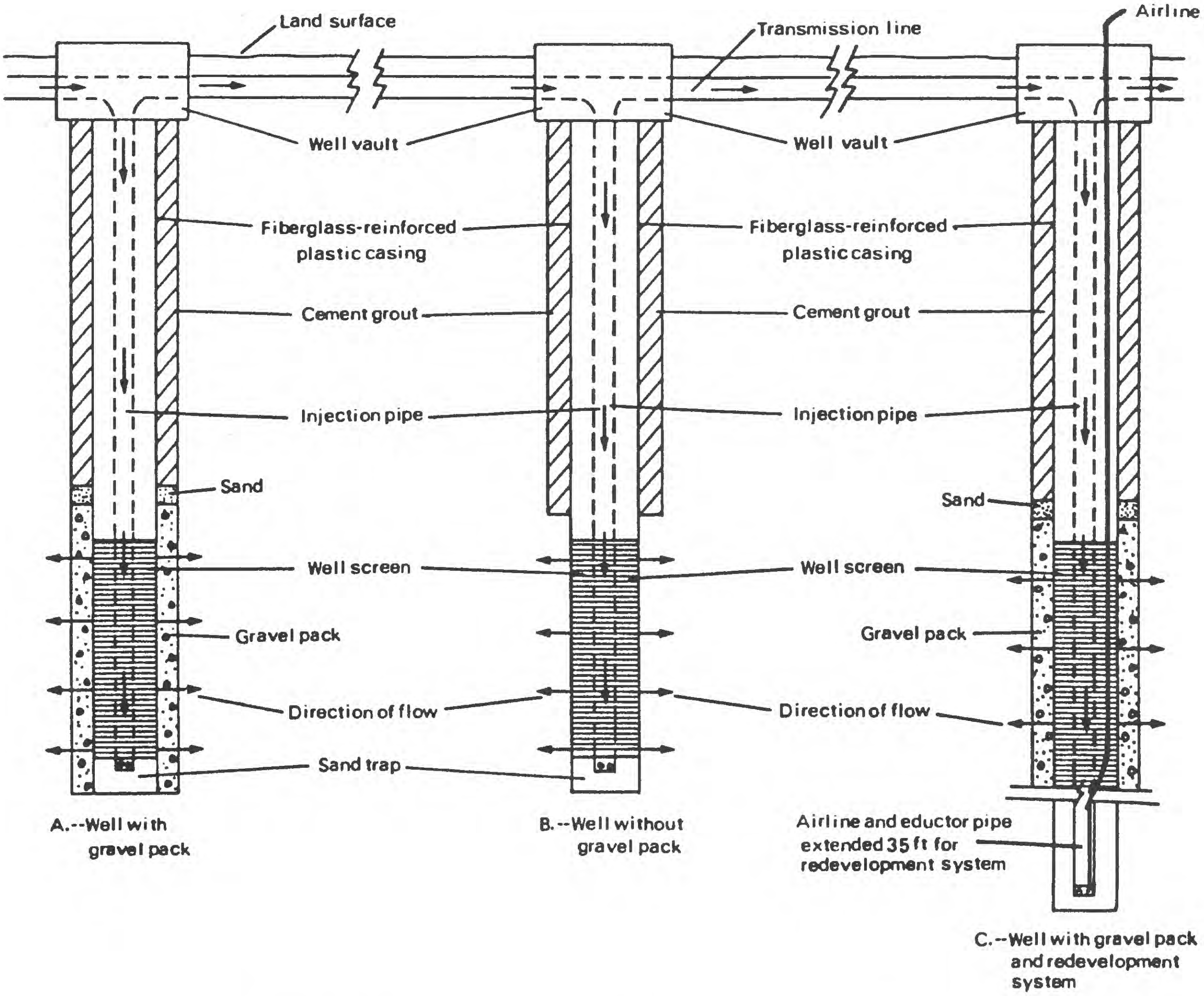


Figure 7.--Typical shallow recharge basin at recharge facility. (From Schneider and Oaksford, 1986.)

Recharge-Well Design

A second method of artificial recharge used at the facility entails the injection of reclaimed water through a system of five wells. The injection wells were drilled by the reverse rotary method, a method commonly used on Long Island for large-diameter wells. All five wells were constructed with fiberglass-reinforced epoxy casing 65 ft in length and 1 ft in diameter. A stainless-steel, 60-slot, wire-wrapped screen 30 ft long and 1 ft in diameter was attached to the casing and extends from 65 to 95 ft below land surface. A 5-ft length of fiberglass casing that was attached to the bottom of the screen was used in four of the wells to act as a sand trap.

The wells are of three types. The first type (A in fig. 8) has an artificial gravel pack surrounding the screen. (This type was installed at



A.--Well with gravel pack

B.--Well without gravel pack

C.--Well with gravel pack and redevelopment system

Figure 8.--Comparison of three types of injection wells. (Locations of wells are shown in fig. 4B.) (Modified from Schneider and Oaksford, 1986).

well sites B, C, and D, shown in fig. 4B). The second type (B in fig. 8) has the screen in contact with natural aquifer material and is installed at well site A. (See fig. 4B.) Comparison of the two types enables evaluation of the operating effectiveness of a natural-pack well in relation to that of an artificial-pack well. The coarse-grained texture of the upper glacial aquifer is appropriate for natural-pack wells. These wells are less costly to construct than those with artificial gravel packs but are more prone to clogging at the well screen and therefore can be expected to require more frequent redevelopment. A gravel pack provides a larger effective well diameter and a larger zone for distribution of clogging material, which could reduce the frequency of redevelopment.

The third type of well (C in fig. 8) is similar to type B except that it has a built-in redevelopment system that requires installation of an air line. Compressed air was pumped through the air line to provide air-lift pumping and surging for redevelopment. To obtain proper submergence of the air line, the well was deepened to about 135 ft by extending the length of the sand trap below the screen. The only well of this type at the recharge facility was well E (fig. 4B).

Two injection pumps (one used for injection, the other for reserve) transfer a part of the reclaimed water from the storage reservoir to the injection wells. The flow to each well was measured by a venturi flow meter inserted in the reclaimed-water line and was indicated on the injection-well flow controller on the recharge-meter panel in the operations building. The desired flow rate was set on this controller, which in turn regulated the position of the butterfly valve in the reclaimed water-supply line to maintain the desired flow rate.

Each injection well was equipped with a pressure transducer that functions as a head-measuring device. Operation according to design specifications called for reclaimed water to be injected until the head reached 25 ft above static level, or approximately 10 lb/in^2. At this time, the well is disconnected from the recharge system and redeveloped. Should this occur unexpectedly during recharge operations, the well is automatically shut down, and the reclaimed water is routed to the recharge basins, overriding the current mode of basin operation. Manual flow control was used during all phases of injection-well operation, however, to route as much water as possible to each well without modulation. This allowed the head inside the well to rise even higher than 25 ft. The total amount of water injected with four wells in operation is 2 Mgal/d. Each well injects 0.5 Mgal/d (350 gal/min).

Observation-Well Network

The East Meadow Recharge Facility contains an observation-well network designed to monitor both hydraulic and water-quality effects of adding reclaimed water to the ground-water reservoir. The network contains 96 wells, all of which are within 1 mi of the site. The network contains 6-inch- , 4-inch- , 3-inch- , and 2-inch-diameter wells. Data from these wells have aided in evaluating aquifer response to recharge in terms of aquifer-head fluctuations and water-quality changes.

Six-Inch-Diameter Observation Wells

The observation-well network contains 26 clusters of one, two, or three 6-inch-diameter wells screened at different depth intervals below land surface. Locations of the 6-inch-diameter observation wells are shown in figure 9.

Of the 54 observation wells, 46 consist of a 6-inch-diameter fiberglass casing and a 5-ft section of 6-inch, 10-slot type 316 stainless-steel screen. The water levels in all these wells were continuously recorded by battery-powered, float-activated digital water-level recorders. Water-level hydrographs were maintained for each well before, during, and after recharge tests. Two of the other eight wells contain multiple screen settings between 20 and 45 ft below land surface. The remaining 6 wells are at the bottom of manholes 2 and 3 within the test basins and are discussed on page 40. Data on the 6-inch observation wells, including screen depth and distance to closest points of artificial recharge, are given in table 5A (p. 14).

Water samples were obtained periodically from all wells by submersible pump. The samples were sent to the U.S. Geological Survey laboratory in Doraville, Ga., for chemical analysis including determination of inorganic constituents, volatile organic compounds, base/neutral-extractable and acid-extractable organic compounds, and chlorinated compounds. In addition, the Nassau County laboratory at the Cedar Creek wastewater-treatment plant analyzed samples taken daily from the reclaimed-water storage tank and periodically from several observation wells for volatile organic compounds.

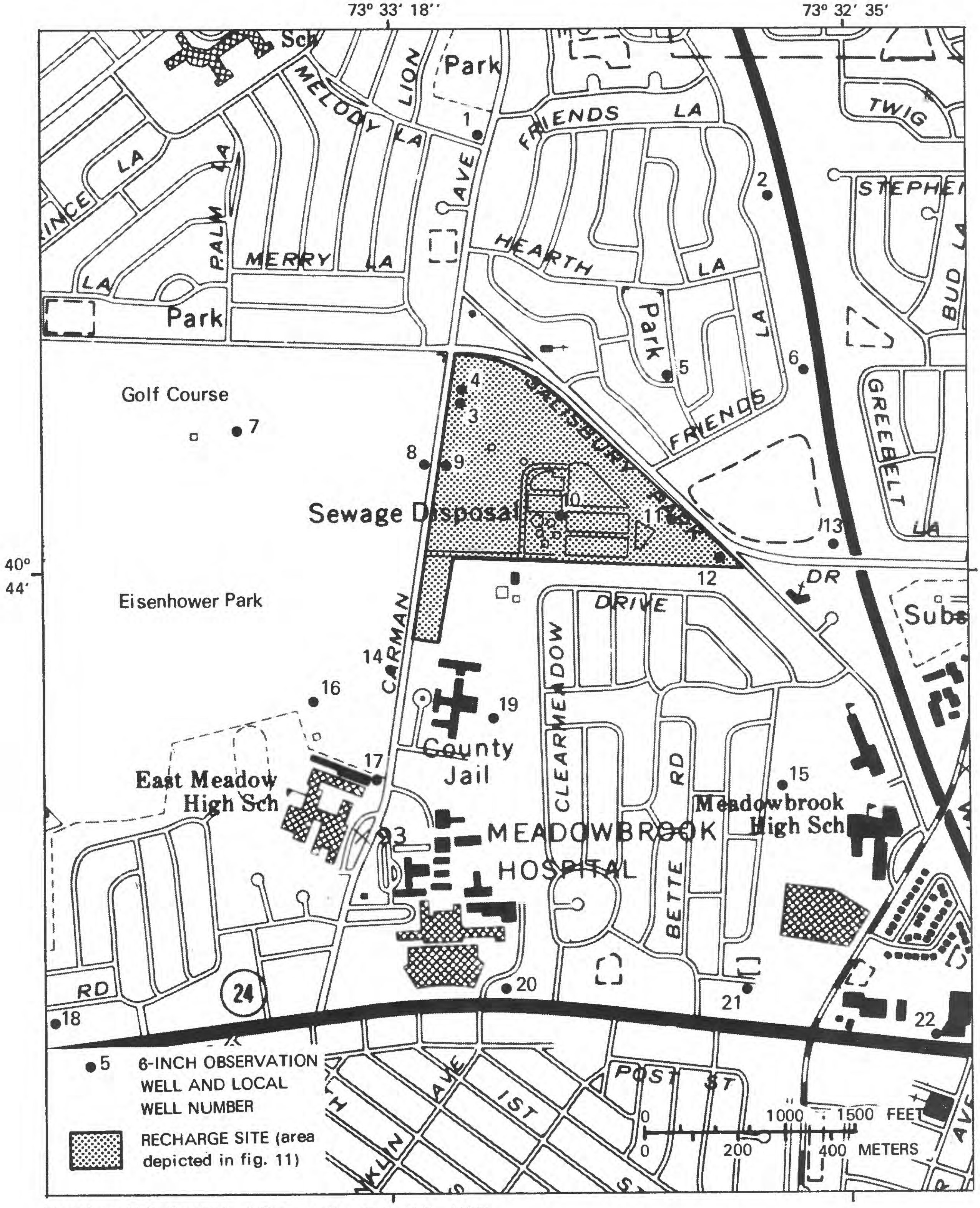
Four-Inch-Diameter Observation Wells

To help further delineate the plume of reclaimed water formed by artificial recharge, 18 four-inch observation wells (fig. 10) were installed in 1983 (well N9131 not included). The wells are grouped in six clusters with three wells per cluster. The three well depths in each cluster were 120, 85 (except one well at 74 ft), and approximately 40 ft. Each well was finished with 4-inch steel casing and a 10-ft section of stainless-steel screen. Each screen was gravel packed.

The total depths, screened intervals, and distance from closest recharge source for each of the 4-inch observation wells are listed in table 5B (p. 15).

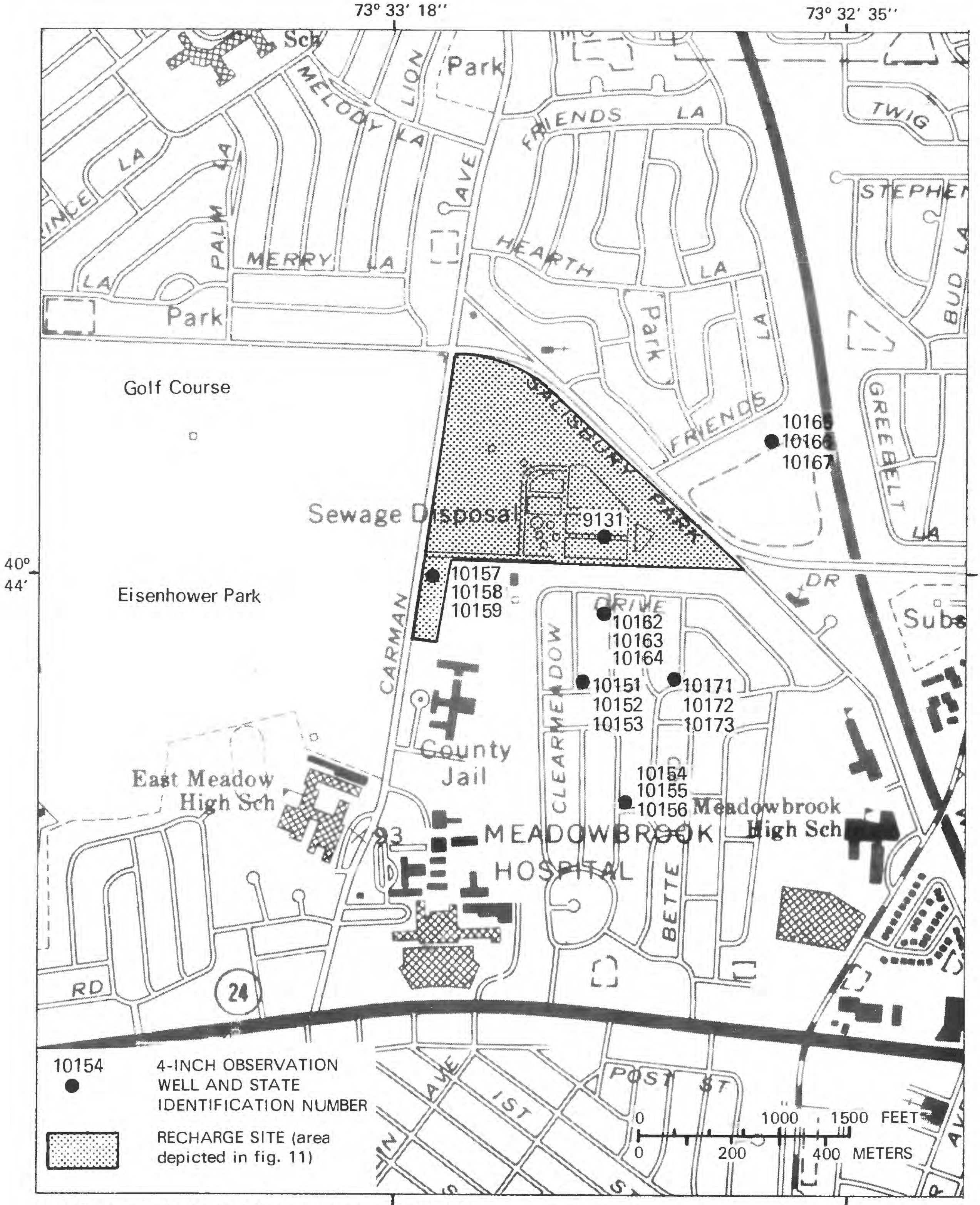
Two- and Three-Inch-Diameter Observation Wells

Two-inch polyvinyl-chloride observation wells were installed within the seven recharge basins and at several other locations (fig. 11) to monitor physical properties and chemical constituents of reclaimed water directly beneath and adjacent to recharge basins. These wells are useful in measuring ground-water mounding beneath the basins and were also the first to show the effects of recharge; thus, water samples obtained from these wells before and after recharge operations reveal changes sooner than samples from other wells. A small-diameter submersible pump and a compressed-air bladder pump were used to collect water samples.



Base from U.S. Geological Survey, Freeport, N.Y., 1979

Figure 9.--Location of 6-inch diameter observation wells. (From Aronson, 1980.)



Base from U.S. Geological Survey, Freeport, N.Y., 1979

Figure 10.--Location of 4-inch observation wells.

The 2-inch observation wells in and adjacent to the recharge area ranged in depth from about 44 to 64 ft. Some of the holes were drilled to 80 ft to obtain geologic information. Screened intervals in wells within the basins were between 20 and 50 ft long; screened intervals in wells outside the basins were 4 to 5 ft long. The total depth and screened intervals of all 2-inch observation wells in and adjacent to the recharge facility are listed in table 5C (p. 16); three 3-inch observation wells are included. Wells N9084 and N9085 are test holes installed for geologic information; well N9691 was installed near injection well vault D and was used to monitor water-level changes opposite the screened zone of the injection well.

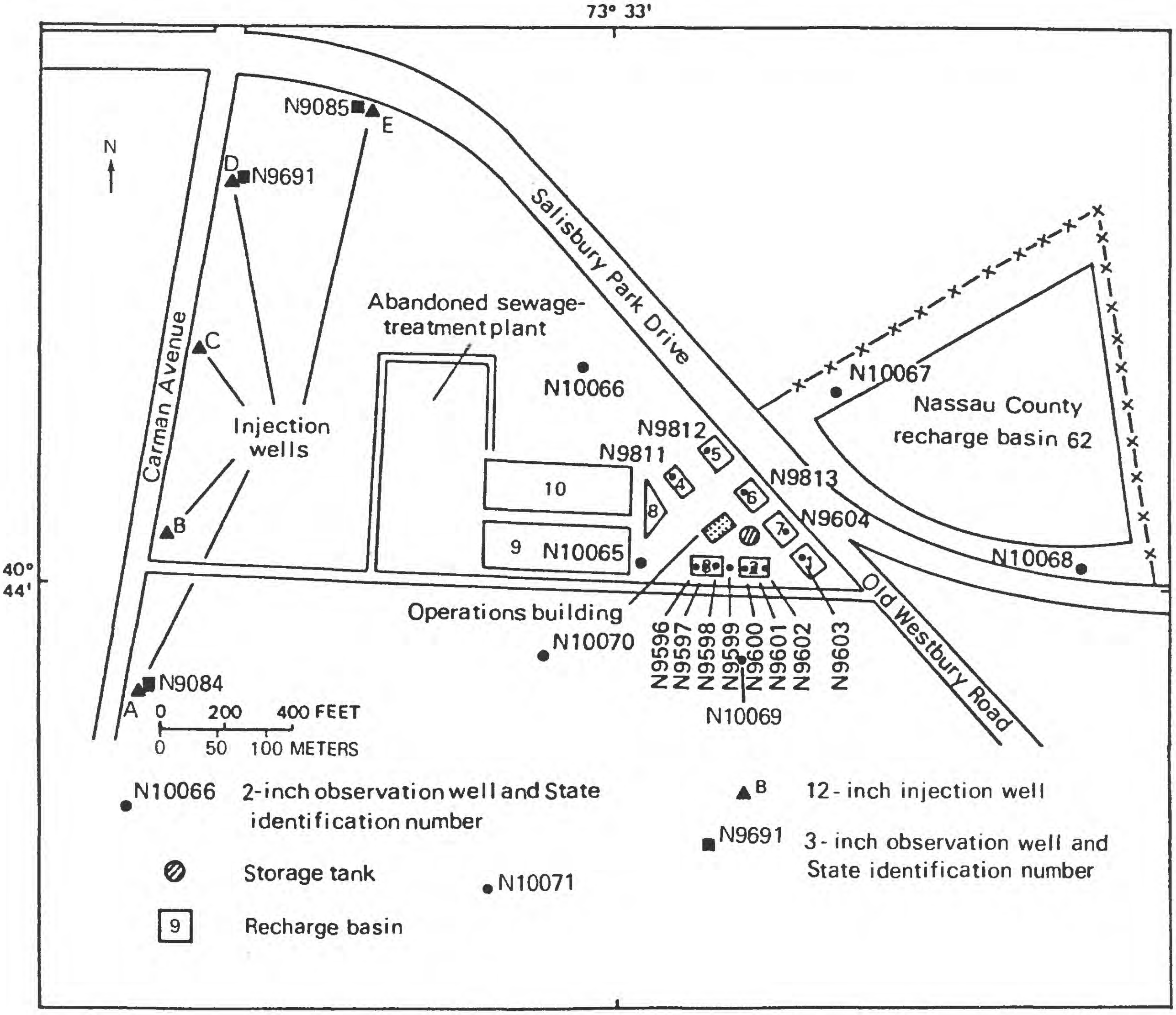


Figure 11.--Location of 2-inch and 3-inch observation wells. (Modified from Schneider and Oaksford, 1986.)

DESCRIPTION OF RECHARGE OPERATIONS AND OBSERVATIONS

The artificial-recharge facility became operational on October 6, 1982, and operations ceased on January 9, 1984. Within that period (460 days), more than 8.02×10^8 gallons of reclaimed water were returned to the ground-water system. More than 7.2×10^8 gal (89 percent) was applied to the recharge basins, and 8.7×10^7 gal (11 percent) was injected through wells. The dates, locations, and quantities of recharge are given in table 6. An average of 2.35×10^6 gal/d was applied in 338 days through basins and 50 days through injection wells.

From October 6, 1982 to January 29, 1983, five recharge basins were used in the automatic-flow-control mode. This method maintained a preset flow rate through use of automatic butterfly valves in the supply lines to each basin. A complete description of design and operations is given by Consoer and Townsend (1978) and Schneider and Oaksford (1986). In the 2.5-month hiatus between January 30 and April 18, 1983, the flow-monitoring system for each basin and injection well was modified to include manometers, which allowed exact measurement of the flow rate at any given time. From April 18, 1983 to October 5, 1983, the recharge basins were operated in the manual mode. The butterfly valve within the supply line was opened to allow desired flow, and the storage reservoir was filled to capacity. Because the altitude of reclaimed water within the storage reservoir dictates the flow rate, a constant head was maintained within the storage reservoir to maintain a constant flow rate to each basin.

From October 5, 1983 to January 9, 1984, recharge basins and injection wells were used together in the manual mode. Reclaimed water was routed to the injection well by injection pumps; therefore, head in the storage reservoir was not a factor. However, head in the storage reservoir was maintained constant because the recharge basins were in operation at the same time.

Flow rate, flow total, basin or injection-well water level, and basin-water temperature were measured hourly by hand during all operating periods. These measurements permitted calculation of daily flow rates, basin-stage fluctuations, and a temperature-adjusted infiltration rate. Of the 11 basins and five injection wells available for recharge, seven basins and all five wells were used.

Testing at basins 1, 4, 5, 6, and 7 consisted of releasing reclaimed water at desired flow rates into each basin and (1) monitoring the onset of clogging and noting its possible causes; (2) calculating infiltration rates in relation to test duration; (3) monitoring local water-level fluctuations in response to recharge; (4) measuring and mapping the extent and height of ground-water mounding; and (5) collecting and analyzing water samples from beneath the facility to detect changes in local ground-water chemistry. Recharge tests were done at basins 2 and 3 in the summer and fall of 1983 to monitor the effect of percolating reclaimed water on the unsaturated zone; results of these tests are described on page 40.

All five injection wells were used in the fall and winter of 1983. A 1-day injection test at wells D and E was done in early October 1983 to evaluate the recharge and monitoring equipment. A 50-day test followed soon

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

[All values are in gallons]

Water-application dates	Duration, in days	A. Basins						
		1	2	3	4	5	6	7
10- 6-82 to 10- 8-82	2	1,100,800	--	--	--	--	--	--
10- 6-82 to 10-12-82	6	--	--	--	--	3,026,300	3,181,100	3,244,800
10-15-82 to 10-29-82	14	7,409,500	--	--	--	6,417,600	6,248,700	7,475,900
12-15-82 to 12-18-82	3	1,732,400	--	--	1,537,800	--	1,580,500	1,608,200
12-22-82 to 12-24-82	2	1,076,200	--	--	989,800	--	974,800	1,005,200
12-30-82 to 1- 8-83	9	5,004,000	--	--	4,563,500	--	4,525,200	4,645,400
1-14-83 to 1-19-83	5	--	--	--	--	--	--	2,848,400
1-17-83 to 1-29-83	12	6,490,300	--	--	--	--	--	--
1-14-83 to 1-29-83	15	--	--	--	--	--	6,954,100	--
1-19-83 to 1-29-83	10	--	--	--	4,844,000	--	--	--
4-18-83 to 6-20-83	63	--	--	--	31,085,450	41,561,200	30,876,400	37,289,100
6-20-83 to 6-23-83	3	--	--	2,924,200	--	1,790,700	2,043,000	--
6-23-83 to 7-10-83	17	--	--	--	7,769,700	6,786,000	7,627,000	10,133,100
7-15-83 to 7-18-83	3	--	--	--	1,356,000	827,600	--	--
7-18-83 to 7-26-83	8	--	8,438,400	--	--	--	--	--
7-26-83 to 9- 6-83	42	--	41,171,100	--	--	36,001,400	37,203,500	40,666,500
9- 6-83 to 9-12-83	6	--	6,522,600	--	4,064,810	3,592,400	--	5,977,800

Water-application dates	Duration, in days	A. Basins (continued)						
		1	2	3	4	5	6	7
9-12-83 to 10- 3-83	21	--	19,669,560	--	--	--	--	17,968,800
10- 3-83 to 10-20-83	17	--	15,922,000	--	14,830,100	19,484,250	--	16,804,800
10-20-83 to 10-30-83	10	--	9,645,060	--	--	--	--	8,998,100
10-31-83 to 12- 5-83	35	--	33,696,000	--	--	--	--	31,726,080
12- 5-83 to 12-31-83	26	--	14,826,240	--	[a]2,395,200	20,007,360	14,774,400	[b]6,048,000
12-31-83 to 1- 9-84	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

B. Injection wells

Water-application dates	Duration, in days	A	B	C	D	E
10- 5-83 to 10- 6-83	1	--	--	--	370,500	480,500
10-20-83 to 12- 5-83	45	22,724,640	22,366,080	18,691,200	17,028,360	--
12- 7-83 to 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 days.

after, with no more than four wells in operation at one time, to evaluate the operation of the injection wells and to monitor response of the aquifer system to long-term injection of reclaimed water.

The following section describes the operation and performance of each basin and injection well in terms of dates and duration of recharge, flow rates, total volume, infiltration rates, and stage or head buildup resulting from clogging due to turbidity, bacteria, or air entrapment.

Recharge Basins

Basin 1

During 42 days of total operation, 23 Mgal of reclaimed water was released into this basin. (See table 6 for dates and volumes.) Flow rates for all operating periods ranged from 365 to 400 gal/min. Recharge periods lasted from 2 to 14 days. During these periods, infiltration rates ranged from 0.55 to 0.60 ft/h. During initial water application at this and other basins, entrapped air was observed escaping through the water near the soil surface. In some tests, the basin floor ponded (became completely covered) immediately, indicating a lower infiltration rate. As the entrapped air escaped, normal infiltration resumed, and water stage declined. Further evidence of entrapped air was detected at all basins with impermeable liners on their sloped walls. As reclaimed water was initially added to the basins, the liners, which lie flat against the sloped walls, billowed up in response to air that was being pushed up from underneath. After several hours, the liners returned to their original position, indicating the escape of all entrapped air.

Ponding depth during the 12-day test beginning January 17, 1983, is plotted in figure 12. The increase in stage beginning January 23, 1983 during this test could be attributed to surface clogging due to increased turbidity of the reclaimed water. High turbidity values can occur during periods of

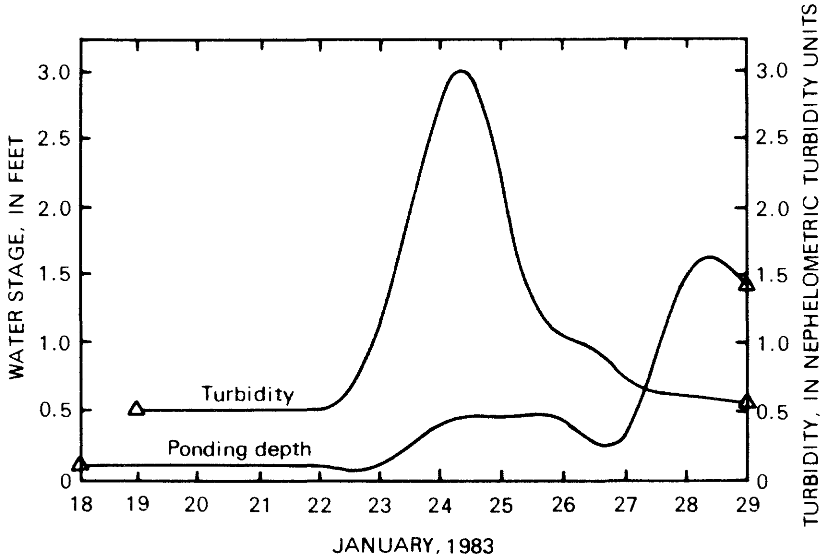


Figure 12.

Water stage and turbidity of reclaimed water during 14-day test in basin 1, January 1983.

electrical or mechanical failures or during high hydraulic loading at the treatment plant. Once the infiltrating surface becomes clogged, a decrease in turbidity will not reverse the stage buildup. The highest stage measured within basin 1 was 1.6 ft on January 28, 1983, which was the next-to-last day of that test. Basin 1 was not used after January 29, 1983 because several instrument parts were needed for repairs in other basins.

Basin 4

In 132 days of operation (see table 6 for dates and volumes), this basin received nearly 74 Mgal of reclaimed water. Inflow rates were between 300 and 800 gal/min. Recharge periods ranged from 2 to 63 days. The longest continuous test period at this basin was from April 18 through June 20, 1983. Infiltration rates during this test ranged from 0.52 to 0.60 ft/h. Although water stage reached 1.45 ft in this test, the basin was not totally ponded (that is, parts of the basin floor were exposed) for the first 22 days (fig. 13). Ponding in mid-May 1983 could be attributed to an accumulated increase in total coliform concentration in reclaimed water (fig. 14); this increase in bacteria could also be the cause of stage buildup in other basins. Figure 15 shows the total coliform concentration throughout the entire recharge period.

On August 10, 1983, the distribution piping system that routes reclaimed water across the basin floor was removed. The basin floor was tilled to the 1-ft depth, and water was released onto the sloped, lined basin-wall area outside the 1-ft-high retaining wall. After water had filled this area, it spilled over the retaining wall onto the basin floor. The combination of tilling and redistribution of reclaimed water allowed inflow rates to double without ponding. No ponding occurred from October 3 to October 20, 1983, even at flow rates exceeding 600 gal/min.

Basin 5

In 209 operating days, basin 5 received nearly 150 Mgal. This basin was operated with inflow rates ranging from 300 to 700 gal/min. When inflow rates were maintained at 350 gal/min, water stage never exceeded 0.8 ft (fig. 13), but when inflow was increased to 650 gal/min, as in August 1983 (fig. 13), stage increased to 2.30 ft. Infiltration rates during this period (July 26 through September 12, 1983) ranged between 0.84 and 1.04 ft/h.

Coliform concentration, as mentioned previously, could be correlated with an increase in water stage that began on May 21, 1983. Although coliform concentration in reclaimed water received at the recharge facility decreased thereafter, the water stage continued to increase.

Another phenomenon common to basin 5 and several others was the development of insect populations during the spring, summer, and fall of 1983. Observed in this basin were larval and adult stages of mosquitos and dragonflies and several species of water beetles. These populations thrived in ponded areas or in isolated pools during nonponding conditions. Extended ponding periods (several weeks in length) as well as favorable meteorologic conditions, such as high temperature and high humidity, could be the

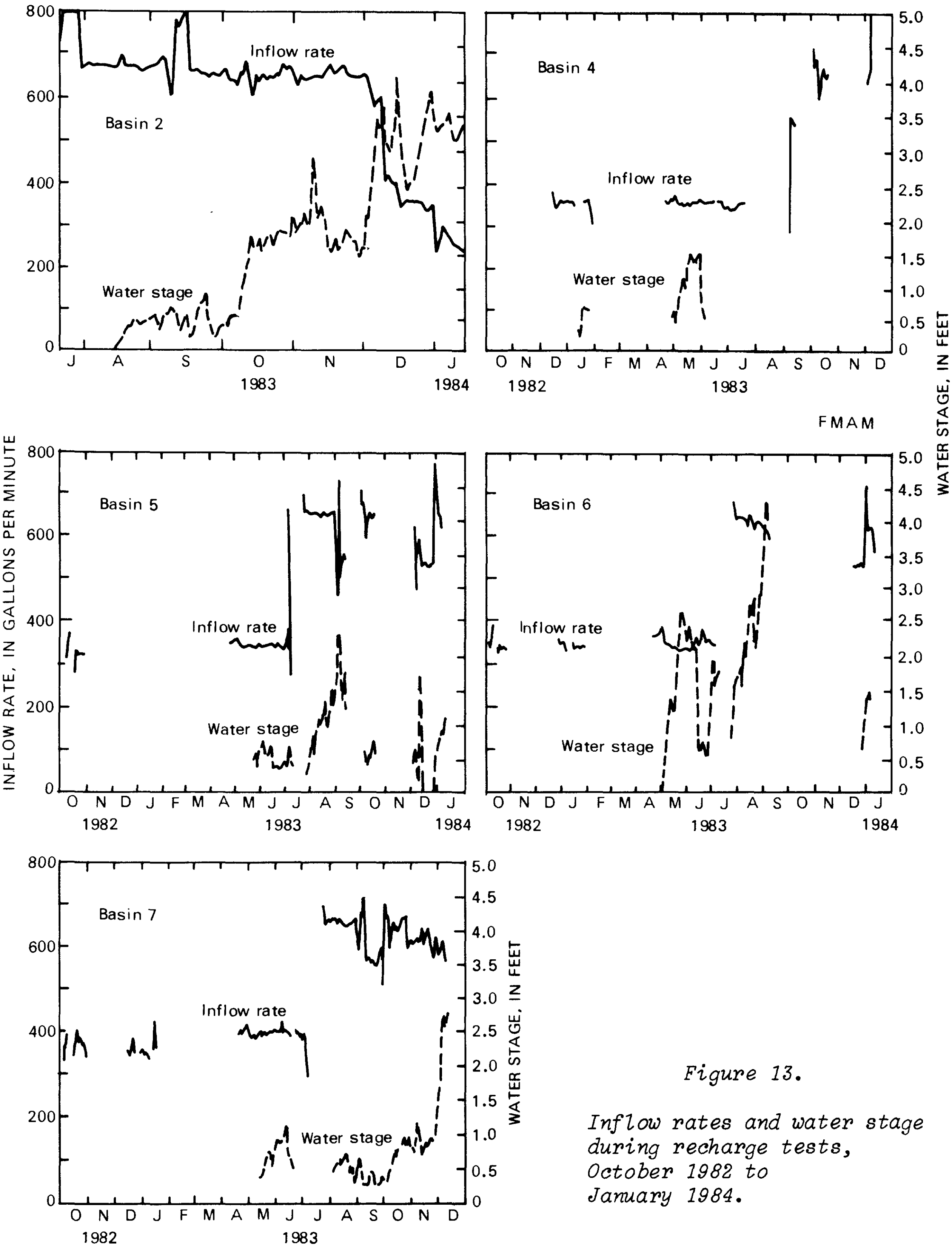


Figure 13.

Inflow rates and water stage during recharge tests, October 1982 to January 1984.

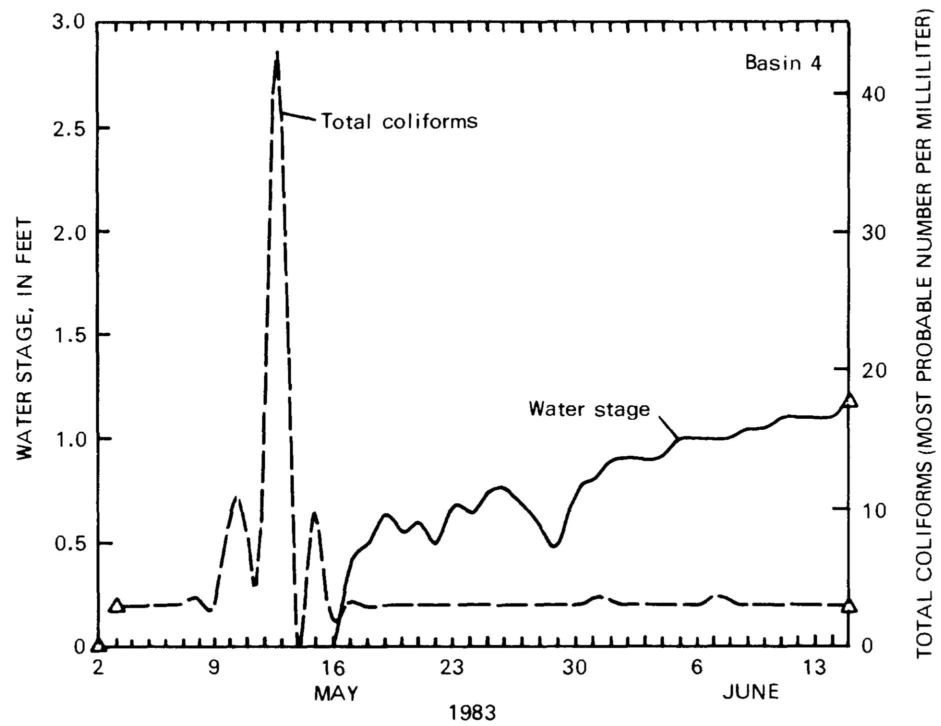


Figure 14.--Water stage in relation to total coliform concentration in basin 4, May 1 to June 15, 1983.

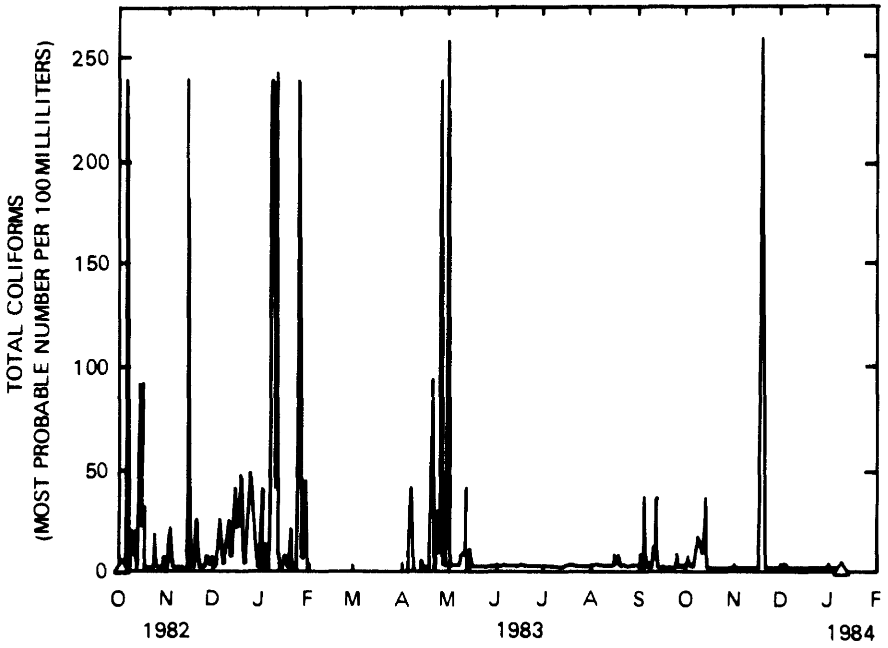


Figure 15.--Total coliform concentration in reclaimed water during recharge operations, October 1982 through January 1984.

conditions needed for development of these populations. Vegetative growth within the basin could also provide a protective substrate for insect eggs. Basins 2, 5, and 7 were allowed to grow natural vegetative cover to increase infiltration channels, and insects developed in these basins.

Basin 6

Throughout the recharge periods, which ranged from 2 to 84 days, basin 6 received more than 120 Mgal of reclaimed water (table 6). Inflow rates ranged from 325 to 700 gal/min during the 211 days of operation. Infiltration rates during the longest recharge test at this basin (April through July 1983) were calculated to range from 0.56 to 0.62 ft/h. The highest stage reached at this basin was 2.82 ft after 38 days (fig. 13). The reclaimed-water stage during a 41-day test in July and August 1983 exceeded 4 ft. Flow rates during this test ranged between 590 and 680 gal/min.

Insect populations developed at this basin during July and August 1983 despite the layer of pea-size gravel over the basin floor, which prevented the growth of vegetation. Insects were just as prevalent here as in other basins.

Basin 7

In 266 days of operation (see table 6 for dates and volumes), this basin received nearly 200 Mgal of reclaimed water. Inflow rates were between 350 and 690 gal/min. Recharge periods ranged from 2 to 137 days; during the longest period, 137 consecutive days from July 26 to December 11, 1983, the basin received nearly 1 Mgal/d. Infiltration rates during this test ranged from 0.97 to 1.1 ft/h.

Early in the test periods, ponding either did not occur or levels rose less than 1 ft (fig. 13). Toward the end of November and early December 1983, however, stage increased to a peak of 2.8 ft, at which time operations were stopped because of a malfunction at the treatment plant. This ponding coincides with an increase in total coliform on November 18, 1983 to over 250 MPN.

Summary of Recharge-Basin Operation

More than 715 Mgal of reclaimed water was returned to the upper glacial aquifer through the recharge basins. This has demonstrated that reclaimed water can be easily used for recharge at this site with only limited action to maintain high infiltration rates.

Infiltration rates throughout all periods of operation at all basins ranged from 0.52 to 1.5 ft/h. Measurement of infiltration rate when water was applied on a continuous basis was based on water stage and pumping-rate records. Reclaimed-water stage was manually recorded every hour by plant personnel with a staff gage installed within each basin. Pumping or delivery rate was computed from readings of a totalizer, an electronic counting device that measures total cumulative flow during automatic operations, and readings of manometers (during manual operation) connected to the supply lines. Infiltration rate was determined by the equation:

$$I = \frac{D_R}{A} \pm \Delta s \qquad (1)$$

where: I is infiltration rate, in ft/h;
D_R is delivery rate, in ft^3/h;
Δs is change in basin storage, in ft/h; and
A is basin area, in ft^2.

To reliably measure infiltration rate, the basin floor should be completely covered with water so that fluctuations in basin stage can be measured. For a majority of operating cycles, however, some basins had no ponding, or the floor became only partly ponded. During those conditions, infiltration rate was calculated from the delivery rate divided by percentage of basin floor that was ponded. Unless stated otherwise, infiltration rates given for each basin were measured during periods when the floor was fully ponded.

Observations and measurements made during basin operation have shown that higher-than-planned inflow rates of 350 gal/min can be maintained and that operating periods can be extended to several months if necessary. Recharge basins have accepted high rates for longer periods without major surficial modifications such as scarification, stripping, or alternating drying and ponding cycles. However, the surface of basin 4, as mentioned previously, was tilled after the distribution piping was removed before testing in August 1983 and was found to accept an even greater flow rate thereafter. The probable cause for this increased rate is correlated to both tilling and to alteration of the inflow-pipe system.

Basins 2 (discussed later), 5, and 7 were permitted to grow natural vegetation unimpeded throughout all testing periods. These basins sustained high infiltration and hence high inflow rates, possibly because the root systems created a network of flow channels.

During all tests, one of the characteristics that affected basin performance was the quality of reclaimed water. Any temporary change in physical or biological character such as turbidity or coliform count seemed to cause clogging to some extent. These materials can clog pore spaces at the basin surface and thereby reduce the rate at which water can infiltrate. For example, basins 4, 5, 6, and 7 began operating on April 18, 1983 at 350 gal/min (fig. 13) and continued without ponding until mid-May 1983. Several high coliform counts in the reclaimed water in late April and early May could have caused all four basins to become ponded.

In summary, recharge-basin performance was influenced by several individual factors and by a combination of factors. Generally, recharge basins were able to transmit reclaimed water through the basin floor to the surficial aquifer with little or no delay. The increase in water stage (decreased infiltration rate) at any time can be correlated with decreases in the quality of reclaimed water, higher inflow rates, and extended operating periods.

Injection-Well Operation

Before testing in October 1983, all five injection wells (locations shown in fig. 4B) were redeveloped because they had not been pumped in 4 years. After redevelopment, samples were obtained to document the chemical quality of water near the wells before recharge.

Preinjection Redevelopment and Sampling

Redevelopment of wells A, B, C, and D consisted of surging and pumping 7-ft sections of the screen isolated between inflatable packers. After one section of screen was redeveloped, the assembly was moved and the process repeated for the next screen section. Isolating and working short intervals of the screen gives maximum agitation per unit area. In well E, the whole 30-ft section of screen was redeveloped at one time by an air-line and eductor-pipe system that permitted the introduction of compressed air for surging. Each method had advantages and disadvantages. Developing short intervals of screen allows for more complete redevelopment but was more costly and time consuming. Redeveloping the entire 30-ft screened section at once was easier but did not allow maximum agitation per unit screened area.

The redevelopment was done during August and September 1983. The procedure consisted of surging the screen in 7-ft isolated sections with a submersible pump rated at 500 gal/min. Each section was surged five or six times with the pump on for 2 minutes and off for 1 minute. At the end of the surge cycle, each of the 7-ft sections was pumped for 10 minutes, and a turbidity sample was taken. In most samples, the turbidity value after surging and pumping was less than 20 NTU (Nephelometric turbidity units).

The well with the built-in air-lift redevelopment system (well E, no. N9206 in fig. 4B) was surged nine times, with 5 minutes on and 2 minutes off. The turbidity reading at the end of the surge cycle was 13 NTU.

Water samples were collected from each injection well at the completion of redevelopment cycles. Results (table 7) describe the chemical quality of formation water near the injection wells before the start of the injection test.

Injection Tests

Two separate series of injection tests were made between October 5, 1983 and the end of December 1983. The first was designed to test the injection pump and the flow meters and to ascertain the approximate rate of head buildup in the injection wells. The second test was designed to stress the wells with as much water as they could accept until the head inside the wells reached 35 ft above the static water level, which would be above land surface.

During the first test, injection wells D and E (N9205 and N9206 in fig. 4B) were used. The test began at 11:30 a.m. on October 5, 1983 and continued for 24 hours. The average injection rates were 264 and 350 gal/min for wells D and E, respectively. The head buildup at wells D and E and at two nearby observation wells--N9691 (upper glacial aquifer) and N9085 (Magothy aquifer)--8 ft and 44 ft away, respectively, is plotted in figure 16. The head buildup

Table 7.--Concentration of selected constituents in formation water near injection wells, September 9, 1983

[Well locations are shown in fig. 4B;
dashes indicate value below detection limit]

	Well number				
Constituent	N9202 A	N9203 B	N9204 C	N9205 D	N9206 E
pH	6.2	6.3	5.7	5.8	5.6
Specific conductance (μS/cm at 25 °C)	400	628	350	393	333
Calcium (mg/L)	29	59	[a]	23	23
Magnesium (mg/L)	5.7	16	[a]	7.1	4.0
Potassium (mg/L)	6.4	2.2	[a]	5.3	6.2
Sodium (mg/L)	25	80	[a]	33	27
Chloride (mg/L)	26	90	[a]	38	26
Fluoride (mg/L)	0.1	<0.1	[a]	<0.1	<0.1
Sulfate (mg/L)	45	85	[a]	39	42
Lead (μg/L)	5	12	[a]	7	3
Chromium (μg/L)	10	10	[a]	20	20
Iron (μg/L)	130	80	[a]	600	290
Nickel (μg/L)	5	4	[a]	2	3
Manganese (μg/L)	10	80	[a]	40	370
Zinc (μg/L)	10	20	[a]	10	10
Nitrogen, total as N (mg/L)	23	37	[a]	16	8.8
Nitrogen, total NH_4^+ as N (mg/L)	0.02	0.01	<0.01	<0.01	0.05
Nitrogen, total NO_2 + NO_3 as N (mg/L)	22	36	18	16	8.2
Nitrogen, total organic as N (mg/L)	0.98	--	--	--	0.55
Carbon, total organic (mg/L)	0.9	2.8	1.2	1.0	1.2
Phosphorus, total (mg/L)	0.01	0.03	0.02	0.03	<0.01
Dichlorobromethane (μg/L)	--	<1	<1	<1	<1
Tetrachloroethylene (μg/L)	--	27	<1	330	<1
1,1,1-Trichloroethane (μg/L)	26.0	25	<1	9	22
Bromoform (μg/L)	--	<1	<1	<1	<1
1,2-trans-Dichloroethylene (μg/L)	--	14	<1	170	<1

[a] Analysis not performed.

within wells D and E after 1 day of injection was 6.5 and 23.5 ft, respectively. Head buildups measured in observation wells during this test ranged from 0.3 to 1.8 ft in the Magothy aquifer and 0.2 to 1.3 ft in the upper glacial aquifer. The loss through the well screen of well E was significant; loss through the screen of well D is minimal in comparison.

This 24-hour test was performed to carry out several objectives, including evaluating the injection pumps and monitoring equipment during operation, measuring head buildups within the injection wells, and the rise in water-table elevation due to injection. The results showed that the injection pumps and flow-monitoring equipment worked without a flaw and that approximate head buildups as well as water-table increases can be measured accurately.

All five injection wells were used during the second injection test, which began on October 20, 1983 and ended December 11, 1983. Four wells (A, B, C, and D) were used primarily from October 20 to December 7, 1983; well E was operated for the 4 days before the test end. The maximum injection rates were 340 gal/min for well A, 330 gal/min for well B, 257 gal/min for well C, and 250 gal/min for well D. Head data were not available for any well after November 30, 1983. Each well was operated at the constant rate mentioned above until head buildup within the casing reached approximately 35 ft. The depth to static water level from the top of each well casing before the test was approximately 27 ft. Individual head buildups during the first 40 days of this injection test, plotted in figure 17, ranged from less than 10 ft in well D (N9205) to approximately 25 and 20 ft in wells A (N9202) and C (N9204), respectively. Head within wells A and C continued to build up until the water level within the casing was 35 ft above static, which was considered the clogging level. This level was an arbitrary point based on pressure head and

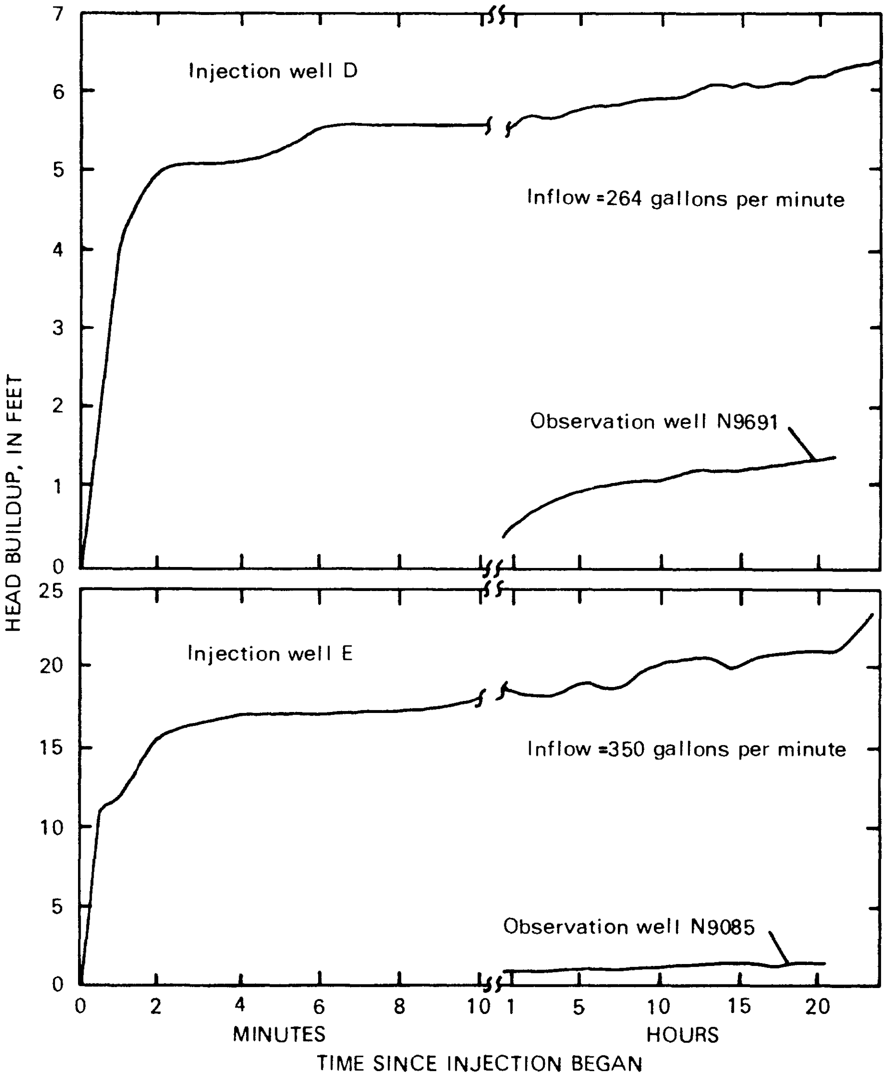


Figure 16.--Head buildup in injection wells D and E (N9205 and N9206) and in nearest observation wells (N9691 and N9085) during 1-day injection test, October 5-6, 1983.

well loss. At this time, all water was routed to recharge basins to facilitate redevelopment of all injection wells. This redevelopment was identical to the one done before recharge except that water-quality samples were obtained from the "first flush" of water removed from the casing.

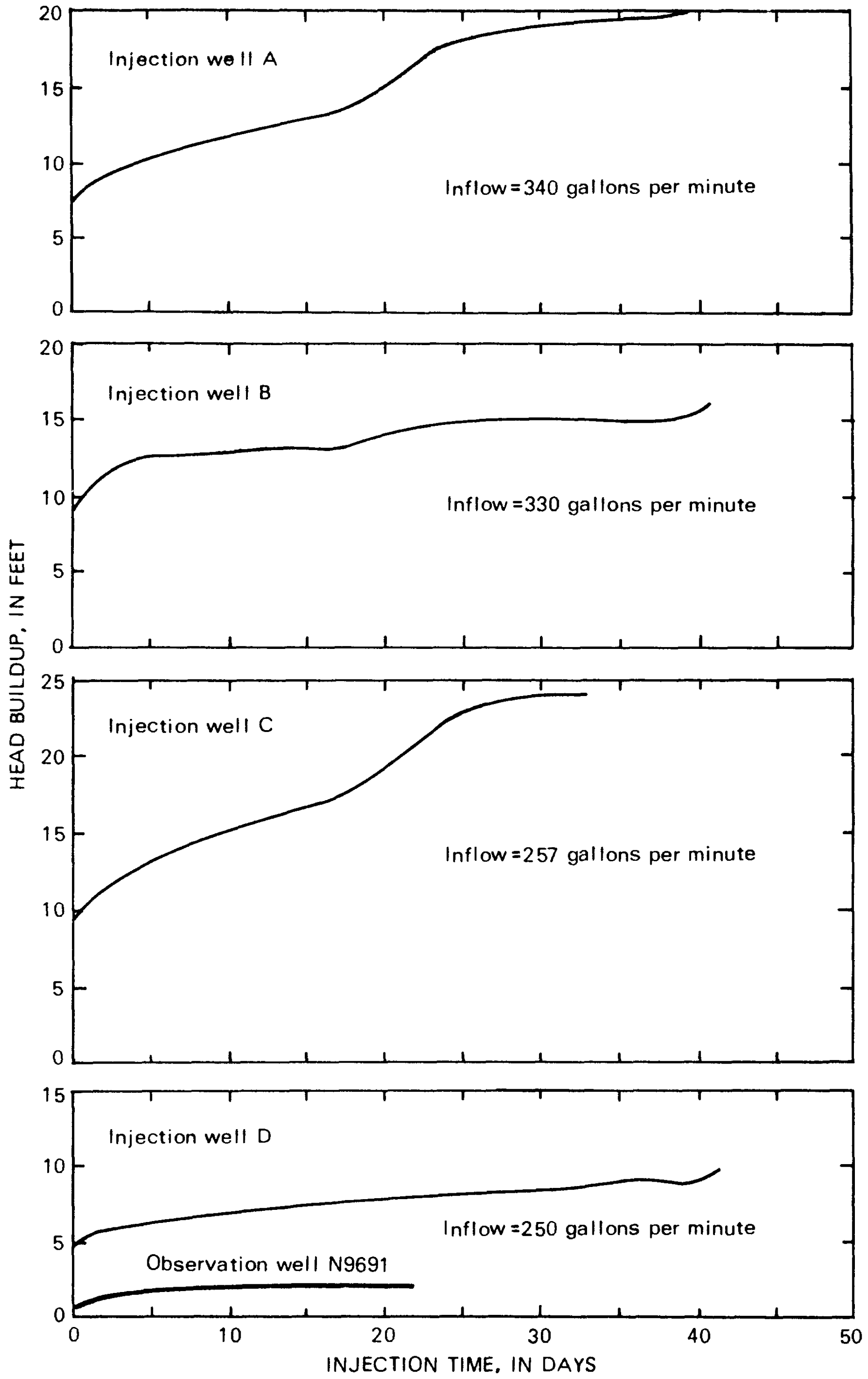


Figure 17.--Head buildup in injection wells A (N9202), B (N9203), C (N9204), and D (N9205) after 40 days during 50-day test beginning October 20, 1983. (Well locations are shown in fig. 4B).

Evaluation of Well Clogging

Head buildup or clogging in the injection wells can be attributed to biological, mechanical, and chemical action. These mechanisms can operate separately or together, as described below.

Biological activity.--This factor, due mainly to bacteria, caused significant well clogging during recharge experiments at Bay Park during 1968-73 (Ehrlich and others, 1979). Head buildup during an injection test with unchlorinated reclaimed water at Bay Park was higher than in all other tests. Also, the bacterial counts in the water first recovered from the filter pack after injection were much higher than in all other injection tests. The Bay Park study (Ehrlich and others, 1979) also indicated that when residual chlorine in the injected water was maintained at a level of about 2.5 mg/L, bacterial growth and attendant clogging was insignificant both in the gravel pack and at the formation face.

During the East Meadow injection tests, the chlorine residual was maintained between 0.2 and 1.5 mg/L at the treatment plant, and the bacteria count was less than 2 MPN/mL for total coliform and fecal coliform throughout the test, except on 2 days in November 1983, as shown in figure 15 (p. 31).

Mechanical clogging .--This results mainly from the filtration of suspended matter and(or) bubbles in the injection water onto the well screen, gravel pack, and aquifer face (Vecchioli and others, 1980). Turbidity was measured to document the suspended-solids concentration in the water; a plot of cumulative daily turbidity values is given in figure 18. The plot indicates that no abrupt change occurred during the 50-day test, and the turbidity values remained within a narrow range (0.2 to 0.5 NTU) except during the last 2 days, when it began to rise as a result of a treatment-plant malfunction.

Well clogging may also be caused by entrained or entrapped air resulting from turbulence or by bubbles arising from dissolved gases in the injected water, but this is not likely to occur at the injection wells because the

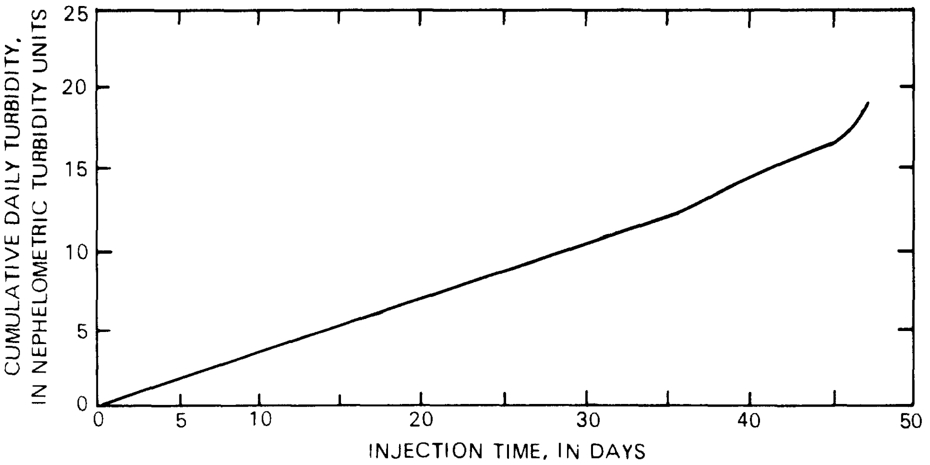


Figure 18.--Cumulative daily turbidity of injection water during 50-day injection test, October 20 through December 11, 1983.

water is injected under pressure below static water level. Also, the temperature of the reclaimed water was about equal to or warmer than aquifer water, which would tend to keep any gases in the injected water dissolved.

Chemical clogging.--Compounds of iron, aluminum, and phosphorus contributed to well clogging during the 1968-73 injection tests at Bay Park (Vecchioli and others, 1980), and redevelopment water at Bay Park contained high concentrations of iron (up to 44,000 µg/L).

The total recoverable iron concentration in reclaimed water during the injection test was low and relatively uniform (table 4); the highest value recorded was 70 µg/L, and the median value was 40 µg/L. Upon completion of the injection test on December 11, 1983, four of the five injection wells were redeveloped to determine the major cause of clogging. The median concentrations of selected constituents in the first flush of redeveloped water are given in table 8. The first slug of redevelopment water had total recoverable iron concentrations that ranged from 1,000 µg/L to 6,200 µg/L. Part of this accumulation probably resulted from the filtration of colloidal or larger particulates from the injected water, and part may have resulted from the chemical precipitation of the dissolved fraction of this constituent at or near the aquifer face.

In summary, clogging probably can be attributed to a combination of factors. The cause for the increase in head buildup 17 to 26 days after injection began (fig. 17) in wells A, B, and C is not easy to identify. Cumulative turbidity (fig. 16) did not vary, and total and fecal coliforms were below 2 MPN/100 mL for the duration of the test. Therefore, chemical and physical clogging apparently played a significant part, as evidenced by the high iron concentration in the redevelopment water.

Table 8.--Median concentration of selected constituents of water from redeveloped injection wells after December 11, 1983

Constituent or characteristic	Concentration
Specific conductance (µS/cm at 25 °C)	864
pH	7.5
Nitrogen, organic total (mg/L)	1.8
Nitrogen, NH_4 as N (mg/L)	.29
Nitrogen, NO_3 as N (mg/L)	.29
Nitrogen, NO_2 as N (mg/L)	.01
Nitrogen, total (mg/L)	2.3
Phosphorus (mg/L as P)	.69
Chloride (mg/L as Cl)	120.0
Fluoride (mg/L as F)	.4
Iron, total recoverable (µg/L as Fe)	1,650
Manganese (µg/L as Mn)	160
Potassium (mg/L as K)	13
Sodium (mg/L as Na)	97

Evaluation of Injection-Well Performance

Observations made throughout the injection tests indicate that injection wells did not operate to full efficiency. Head buildups within the well casings have indicated relatively rapid screen clogging, or clogging of the gravel pack or aquifer immediately around the well bore, and therefore reduced transmission to the formation. The type of packing around the well screen did not seem to play a role in well efficiency. Although well A (N9202), the only well without an artificially packed well screen, accepted higher recharge rates than all other wells, it was the first well to clog. Wells B and C (N9203 and N9204, respectively) clogged soon after or displayed heads indicative of clogging. It appears, therefore, that the type of packing surrounding the well screen did not greatly increase or decrease well performance. Given the same operating conditions, both types of wells would need frequent redevelopment.

EFFECTS OF ARTIFICIAL RECHARGE ON THE UNSATURATED ZONE

Two of the seven basins at the recharge facility are equipped with a circular observation manhole 12 ft in diameter that extends 16 ft below the basin floor and contains instruments for collecting data on the physical and chemical processes that take place within the unsaturated zone during recharge. Infiltration rates, pressure-head distribution, soil-moisture content, ground-water levels, and soil gases can be monitored, and inclined gravity lysimeters installed through the manhole wall allow the collection of soil-water samples for chemical analyses. Observation wells installed through the manhole floor into the upper glacial aquifer allow collection of water samples once reclaimed water intercepts the water table. The instrumentation is described more fully in Schneider and Oaksford (1986).

Two separate recharge experiments were conducted at these basins (basins 2 and 3 in fig. 4B) from June 20, 1983 through January 9, 1984. A 72-hour test was run at basin 3 from June 20-23, in which 3 Mgal of reclaimed water was returned to the ground-water system, and a 176-day test was run at basin 2 from July 18 through January 9, 1984, in which 153 Mgal of reclaimed water was applied.

72-Hour Test at Basin 3

On June 20, 1983, reclaimed water was released into basin 3 at a rate of 700 gal/min. Water ponded within the first 3 hours and reached its highest stage of 1.11 ft after 13 hours (fig. 19). This initial ponding was caused mainly by air entrapped within the soil. After 13 hours, the stage began to decline. Shortly thereafter, the supply pumps were shut down for 30 minutes during a treatment-plant malfunction, but inflow was maintained at 500 gal/min from the storage reservoir. This reduction in flow caused a rapid decrease in water stage. When the inflow was restored a half-hour later, water stage continued to decrease until parts of the basin floor were exposed. The infiltration rate at this time (fig. 19), 46 hours into the test, was therefore greater than 1.12 ft/h, the infiltration rate calculated for 700 gal/min inflow with no change in storage. Infiltration rate was estimated to range between 1.2 and 1.5 ft/h. This estimate is based on a recharge rate within a reduced infiltrating area. Because 75 percent of the 5,000 ft^2 basin was ponded, an estimated active recharge or infiltrating area was used in the infiltration-rate calculation.

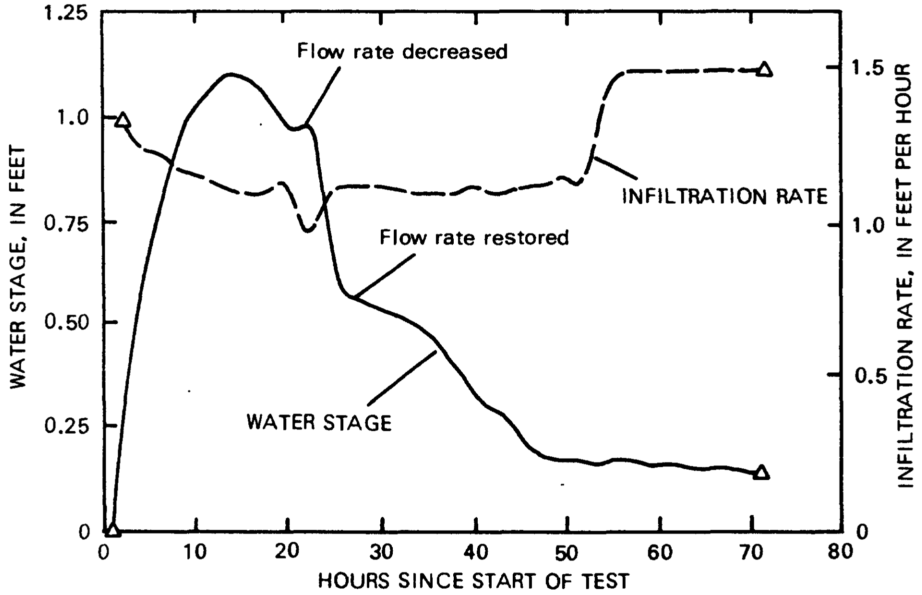


Figure 19.--Water stage and infiltration rate during 72-hour ponding test at basin 3, June 20-23, 1983. (Modified from Schneider and others, 1984.)

Depth and Effect of Controlling Zone

Pressure head in the unsaturated zone as measured by horizontal tensiometers during infiltration revealed the gradual formation of a clogging layer (fig. 20). No resultant reduction in infiltration rates was seen during this brief test.

Fourteen tensiometers had been installed through the walls of the manhole in all directions at depths ranging from 0.6 to 13.87 ft below the basin floor. Pressure-head measurements during the test indicated this layer to be between tensiometers 4 and 5 (approximately the 4- and 5-ft depths). Pressure heads before the test were negative (line 1, fig. 20) throughout the profile, ranging from -10.0 to -15.10 inches, but increased rapidly during the test to positive values, which indicates saturation within the upper 4 ft after 13 hours. Below 4 ft, pressure head was consistently 0 or negative, which indicates the persistence of unsaturated conditions. Measurements of soil tension, or negative pressure head, can indicate the presence and thickness of a controlling zone. Calculating vertical hydraulic conductivity of soil intervals through Darcy's law can indicate the degree of control that these zones exhibit. The basin's wall, which extends 4 ft below the basin floor, confines flow to the vertical direction. Hydraulic conductivity can thus be determined by the equation:

$$K = \frac{q}{\frac{dh}{dl} + 1} \cdot \frac{V_2}{V_1} \qquad (2)$$

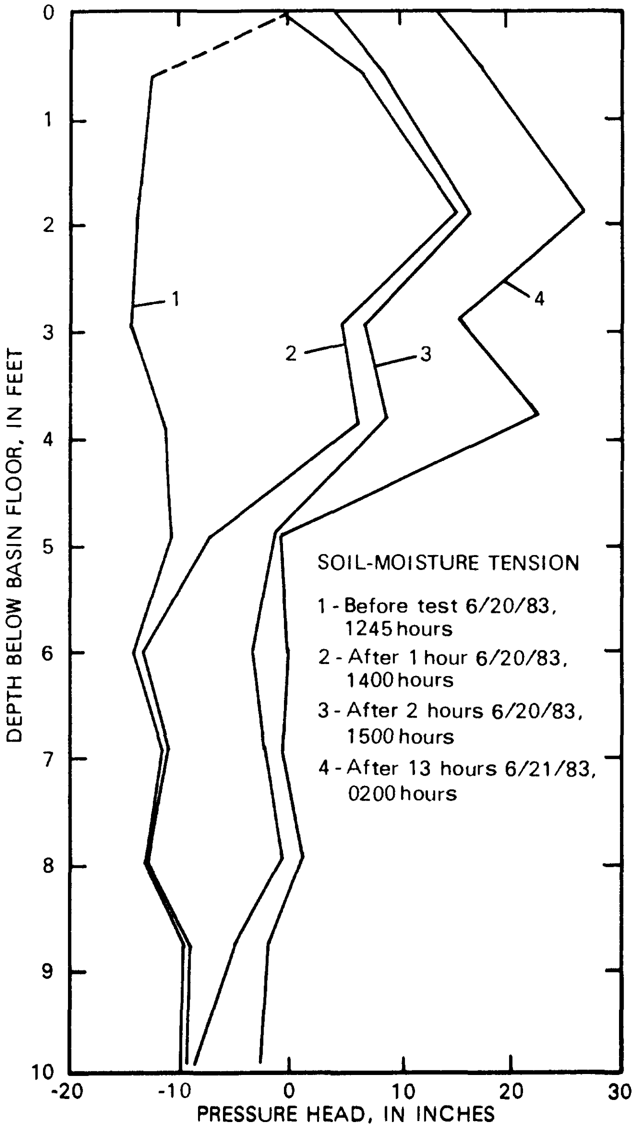


Figure 20.

Pressure head during infiltration of reclaimed water through the unsaturated zone beneath basin 3, June 20-21, 1983. (Modified from Schneider and others, 1984.)

where:
K = vertical hydraulic conductivity at 60° F, in ft/d;
q = infiltration rate, in ft/h;
dh = difference in pressure from the lower boundary to the upper boundary of a zone, in inches of water;
dl = thickness of the zone, in inches;
$\frac{dh}{dl} + 1$ = hydraulic gradient;
V_2 = kinematic viscosity of water in the basin, in centistokes;
V_1 = kinematic viscosity of water at 60° F.

Calculation of hydraulic conductivity from field data gathered on June 21, 1983 (line 4 on fig. 20) from the 0- to 5-ft depth interval is as follows: The infiltration rate, q, was 1.12 ft/h; V_1, the kinematic viscosity of water at 60° F, is 1.127 centistokes, and temperature of water in the basin was 66.6° F; therefore, V_2, the kinematic viscosity of water in the basin is

1.030 centistokes. Thickness of the interval is 58.92 inches, and pressure head at upper boundary is 13.44 inches and at the lower boundary is -1.15 inches.

Therefore, dh is 14.59 inches. From these values one can calculate K as follows:

$$K = \frac{q}{\frac{dh}{dl} + 1} \cdot \frac{V_2}{V_1} = \frac{1.12 \text{ ft/h}}{\frac{14.60}{58.9} + 1} \cdot \frac{1.03}{1.12} = 0.82 \text{ ft/h x } 24 \text{ h/d} = 19.7 \text{ ft/d}$$

Hydraulic-conductivity values for the 0- to 5-ft and 4- to 5-ft zones as calculated from test data in figure 20 are given in table 9. The computations indicate that the 4- to 5-ft interval contains material of lower permeability than that at other depths and that it limits the rate at which water can pass through that zone. The average hydraulic conductivity of this zone is 12.4 ft/d, almost half the value of 23.1 ft/d averaged over the entire profile. In most basins at this site, the greatest head loss occurs within the first foot beneath basin surface, but at this basin the controlling layer is at depth. Because this test was only 72 hours long, the effect of this layer on prolonged infiltration could not be seen. Most likely, ponding would have increased as water built up above the less permeable zone. This zone is probably not uniformly continuous beneath the basin because nearly 50 percent of the basin floor was exposed during the last 48 hours, which suggests that water moves with less resistance beneath other parts of the basin.

Table 9.--Hydraulic data on two depth intervals during ponding test at basin 3, June 20-23, 1983

Date	Time of day	Time since test began (hours)	Pressure head, (inches of water) Upper boundary	Lower boundary	Hydraulic gradient	Infiltration rate adjusted to 60 °F (ft/h)	Vertical hydraulic conductivity at 60 °F (ft/d)
		A. 0- to 5-ft interval (58.92-inch thickness)					
6-20-83	1345	0.45	0	-7.08	1.12	0.83	17.8
6-20-83	1445	1.45	4.8	-1.26	1.10	.93	20.2
6-20-83	1545	2.45	4.8	-1.19	1.10	1.03	22.5
6-22-83	0700	42	3.24	-2.20	1.09	1.12	24.6
6-23-83	0800	67	1.90	-2.20	1.07	1.37	30.7
		B. 4- to 5-ft interval (12.36-inch thickness)					
6-20-83	1445	1.45	8.65	-1.26	1.80	.93	12.4
6-20-83	1545	2.45	10.72	-1.19	1.96	1.03	12.6
6-21-83	1300	24	18.17	- .89	2.54	1.14	10.7
6-22-83	0700	42	13.80	-2.20	2.29	1.12	11.7
6-23-83	0800	67	13.00	-2.20	2.23	1.37	14.7

Movement of Wetting Front

Neutron geophysical logs were taken throughout the 3-day test period to monitor the movement of reclaimed water through the unsaturated zone. These soil-moisture logs were obtained from neutron-access tubes 1 through 6 (locations are shown in fig. 23) within and adjacent to basin 3 to show both the vertical and horizontal progression of the wetting front from the basin floor. In a series of neutron logs from access tube 5 within basin 3 (fig. 21A), the first "slug" of reclaimed water was shown to arrive at the water table after approximately 4 hours. The average vertical interstitial velocity calculated from the advance of the wetting front, if the water table is assumed to be at or near 24 ft below basin surface, is 6.0 ft/h. This value was verified by the water-table response at an observation well (N9826) within the manhole. The hydrograph from this well (fig. 21B) shows the increase in water level 3.5 to 4 hours after testing began. The mound reached its highest peak of 3.1 ft within 24 hours and remained nearly that high for the rest of the test. When recharge ceased, the mound subsided within 12 to 18 hours to its original level.

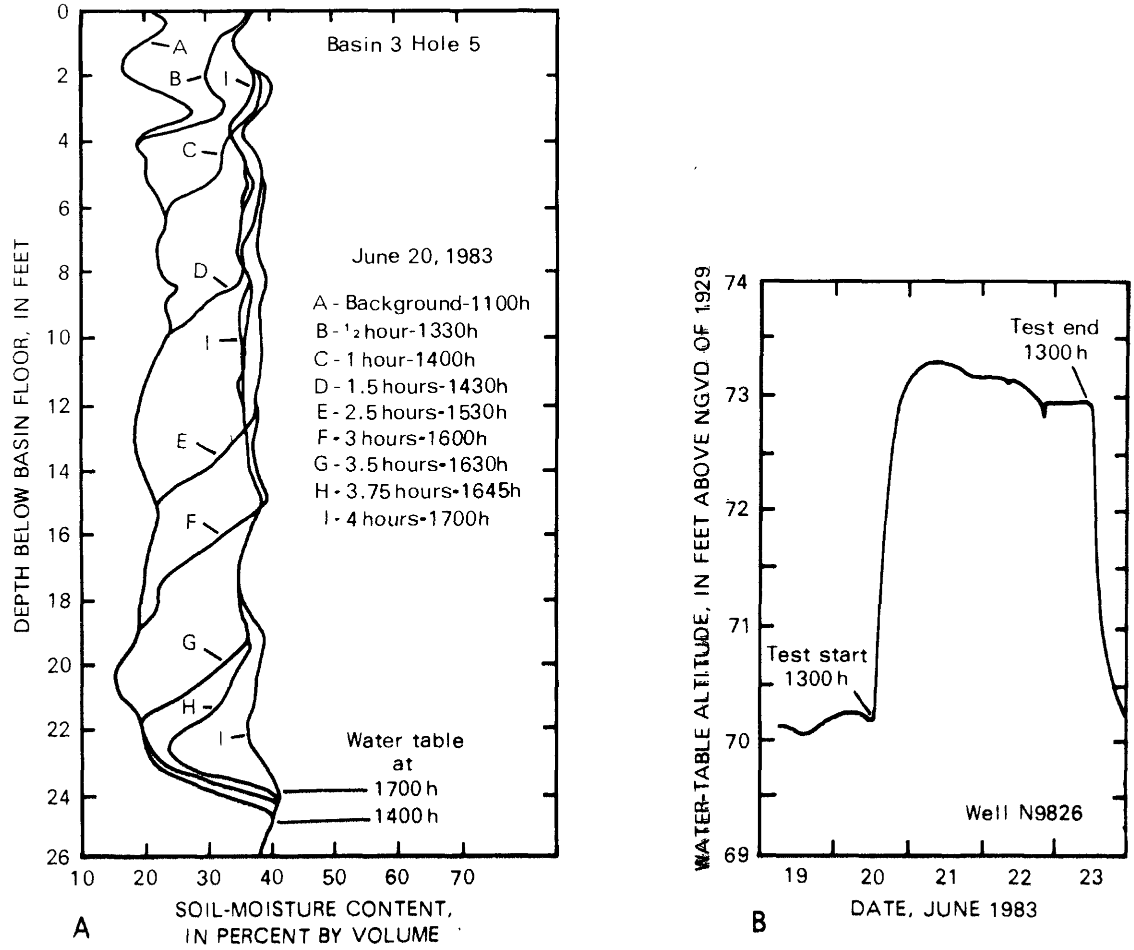


***Figure** 21.--Soil-moisture and ground-water levels beneath recharge basin 3 during 72-hour recharge test, June 20-23, 1983. A. Soil-moisture logs from first 4 hours of test. (Modified from Schneider and others, 1984.) B. Hydrograph of well N9826 (within basin) before and during test.*

Neutron logs obtained from access tubes 6, 12, and 18 ft west of basin 3 (fig. 22) indicate that lateral movement of water above the water table was negligible--moisture buildup ranged from 0 percent at a distance of 18 ft from the basin to 8 percent 6 ft away. This would indicate that movement beneath the area enclosed by the retaining walls is virtually vertical. The slight soil-moisture buildup just outside the retaining wall (fig. 23) indicates some degree of lateral movement, but this can be considered insignificant.

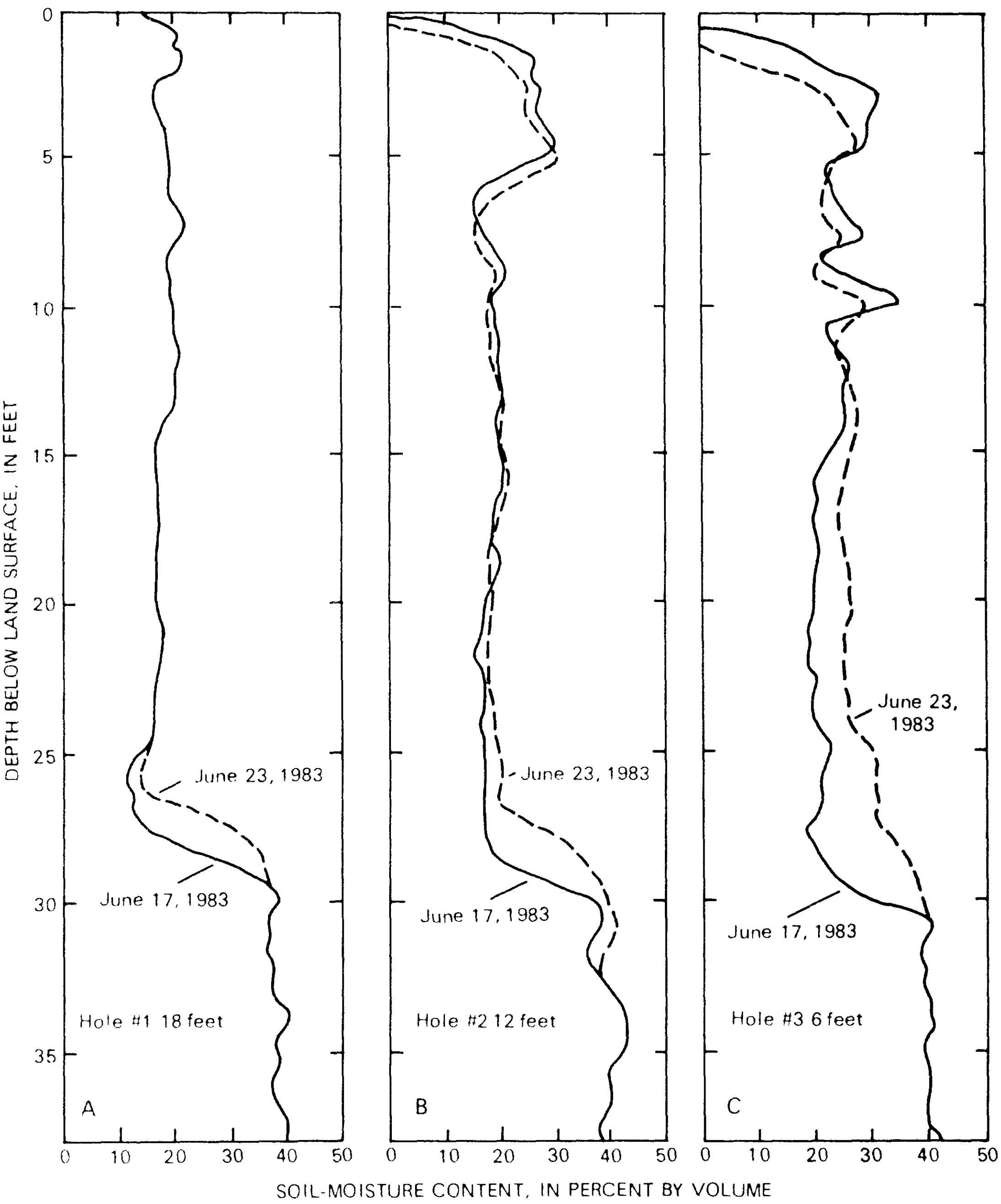


Figure 22.--Soil-moisture logs from neutron-access tubes 6 ft, 12 ft, and 18 ft west of basin 3 during 72-hour recharge test, June 20-23, 1983. (Locations are shown in fig. 23.)

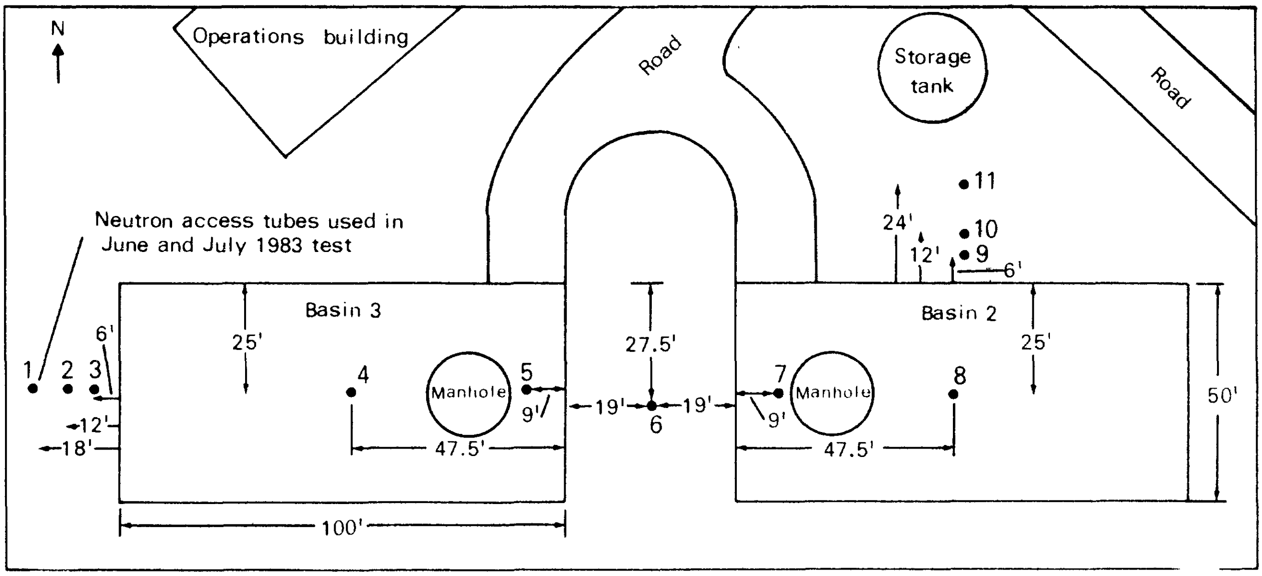


Figure 23.--Location of neutron-access tubes in and adjacent to basins 2 and 3. (Modified from Schneider and Oaksford, 1986.)

The disturbance on the soil-moisture log from the access tube 6 ft west of the basin between 9 ft and 11 ft below land surface (fig. 22) could be correlated with the layer of lower permeability 4 to 5 ft below the basin floor indicated by tensiometers. Again, this zone is probably discontinuous, as indicated by its absence in the two other soil-moisture logs.

Chemical Quality of Reclaimed Water Within the Unsaturated Zone

One purpose of these experiments was to observe the effect of the unsaturated zone on the chemical quality of reclaimed water as it percolates to the water table. The four gravity lysimeters in basin 3, installed through the manhole wall at depths of 2.5 ft, 5.3 ft, 8.2 ft, and 11 ft below the basin floor, permitted collection of water samples from the unsaturated zone during infiltration.

The gravity lysimeters (fig. 24) consist of (1) a 6-inch-diameter stainless steel tube that extends diagonally upward through the manhole wall into the soil; (2) an extended screened-plate assembly within the tube to retain the soil; (3) a purging system that can be used to redevelop the lysimeter should it become clogged; and (4) an airtight end cap that prevents exchange between the air in the manhole and soil atmosphere. The hydraulic design considerations for the installation of gravity lysimeters used at this facility are discussed by Oaksford (1983).

Lysimeters 1, 3, and 4 (at depths of 2.5 ft, 8.2 ft, and 11 ft, respectively) captured sufficient volumes of reclaimed water to permit daily sampling, but lysimeter 2, whose capture plane is 5.3 ft below the basin floor, did not, probably because it tapped the less conductive silt layer discussed previously or, possibly, because the process of installation compacted the material, making the soil at the lysimeter opening virtually

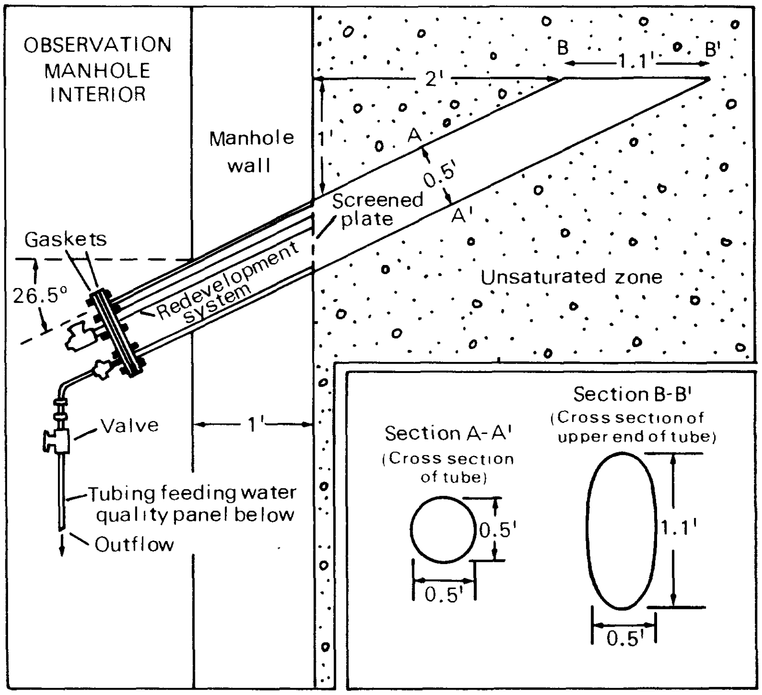


Figure 24.

Cross section through inclined gravity lysimeter. (From Schneider and others, 1984.)

impermeable, which would cause diversion of percolating water around and away from the plane of capture.

A total of 20 samples were taken during the 72-hour test, including four from reclaimed water ponded in the basin, four from each working lysimeter, and four from an observation well within the basin and screened at the water table. Samples were analyzed for selected inorganic constituents (table 10A), nitrogen, carbon, and phosphorus (table 10B), heavy metals (table 10C), and low-molecular-weight organic compounds (table 10D).

Soil-water sampling was timed to obtain water from the same slug as it passed the successive lysimeters. The data presented in table 10 are arranged in sequence from left to right, showing the chemical history of a given slug of water as it moved from the basin to the water table. The first day of recharge marked the first passage of reclaimed water through the system, and samples collected at respective depths represent the first arrival of reclaimed water and therefore reflect the effects of its mixing with soil water that was in the unsaturated zone before recharge. The data in table 10 indicate that most constituents move through the unsaturated zone with little or no change in concentration.

One of the few constituents that was affected during travel through the unsaturated zone was phosphorus (table 10B). The decrease on June 20, the first day of sampling, from 0.35 mg/L to 0.01 mg/L within the unsaturated zone is attributed largely to dilution by mixing with native pore water. Decreases in concentration throughout the profile in the subsequent daily samplings support the conclusion that phosphorus was being adsorbed by the earth material. The samples collected on June 22 and 23 show an increase in phosphorus concentration at the first lysimeter, indicating that the adsorptive capacity of the upper 2.5 ft of material was approaching its limit.

Table 10. Chemical analysis of reclaimed water from recharge basin 3, unsaturated zone, and water table beneath basin during recharge test of June 20-23, 1983

A. INORGANIC CATIONS AND ANIONS

		Source				
			Lysimeters[1]			Observation
Date	Constituent	Basin	1	3	4	well (N9825)
6-20-83	Calcium (mg/L)	49	30	42	30	32
	Magnesium (mg/L)	6.7	3.4	1.5	1.3	2.6
	Potassium (mg/L)	12	4.0	13	6.8	34
	Sodium (mg/L)	96	38	57	61	45
	Chloride (mg/L)	120	84	110	110	60
	Fluoride (mg/L)	0.3	0.1	--	0.1	0.1
	Sulfate (mg/L)	71	36	58	81	44
	pH	7.3	6.6	6.6	5.4	7.1
	Specific conductance (μS/cm)	822	445	607	603	527
6-21-83	Calcium (mg/L)	50	48	49	47	42
	Magnesium (mg/L)	7.7	7.4	7.6	7.4	6.0
	Potassium (mg/L)	12	11	12	12	28
	Sodium (mg/L)	94	95	96	95	92
	Chloride (mg/L)	120	120	120	120	120
	Fluoride (mg/L)	0.2	0.2	0.2	0.2	0.2
	Sulfate (mg/L)	63	63	62	63	65
	pH	7.3	7.3	7.4	7.4	7.5
	Specific conductance (μS/cm)	800	797	817	801	814
6-22-83	Calcium (mg/L)	50	50	51	49	47
	Magnesium (mg/L)	7.4	7.3	7.5	7.3	6.9
	Potassium (mg/L)	12	11	12	12	20
	Sodium (mg/L)	92	93	93	90	93
	Chloride (mg/L)	110	110	110	110	110
	Fluoride (mg/L)	0.2	0.2	0.2	0.2	0.3
	Sulfate (mg/L)	71	69	68	68	69
	pH	7.5	7.5	7.5	7.6	7.6
	Specific conductance (μS/cm)	814	797	810	805	804
6-23-83	Calcium (mg/L)	52	51	51	51	48
	Magnesium (mg/L)	7.7	7.6	7.8	7.6	7.3
	Potassium (mg/L)	12	12	12	12	17
	Sodium (mg/L)	91	91	93	91	95
	Chloride (mg/L)	120	120	120	120	120
	Fluoride (mg/L)	0.3	0.2	0.2	0.3	0.3
	Sulfate (mg/L)	82	81	82	81	80
	pH	7.3	7.2	7.2	7.3	7.2
	Specific conductance (μS/cm)	841	827	833	838	838

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[1] Lysimeters 1, 3, and 4 are 2.5, 8.2, and 11 ft below basin surface, respectively.

Table 10. Chemical analysis of reclaimed water from recharge basin 3, unsaturated zone, and water table beneath basin during recharge test of June 20-23, 1983 (continued)

		Source				
			Lysimeters[1]			Observation
Date	Constituent	Basin	1	3	4	well (N9825)
	B. NITROGEN, CARBON, AND PHOSPHORUS SPECIES (all values in mg/L)					
6-20-83	Nitrogen, total as N	0.7	0.60	0.9	0.7	1.3
	Nitrogen, total NH_4^+ as N	0.03	0.3	0.03	0.02	0.03
	Nitrogen, total NO_2 + NO_3 as N	0.39	0.3	0.5	0.5	0.97
	Nitrogen, total organic as N	0.27	0.27	0.37	0.18	0.27
	Carbon, organic total	2.10	3.0	4.6	1.6	2.7
	Phosphorus, total	0.35	0.01	0.01	0.01	0.03
6-21-83	Nitrogen, total as N	1.0	0.8	1.0	0.7	0.7
	Nitrogen, total NH_4^+ as N	0.04	0.02	0.03	0.02	0.03
	Nitrogen, total NO_2 + NO_3 as N	0.60	0.4	0.5	0.50	0.5
	Nitrogen, total organic as N	0.36	0.38	0.47	0.18	0.17
	Carbon, organic total	2.00	1.90	1.90	1.6	1.9
	Phosphorus, total	0.43	0.06	0.02	0.01	0.02
6-22-83	Nitrogen, total as N	0.70	0.8	0.8	0.90	0.8
	Nitrogen, total NH_4^+ as N	0.01	0.01	0.01	0.01	0.01
	Nitrogen, total NO_2 + NO_3 as N	0.50	0.50	0.50	0.60	0.60
	Nitrogen, total organic as N	0.30	0.3	0.3	0.30	0.20
	Carbon, organic total	2.10	2.3	2.1	1.9	2.3
	Phosphorus, total	0.36	0.13	0.02	0.02	0.03
6-23-83	Nitrogen, total as N	0.8	0.7	0.7	0.7	0.8
	Nitrogen, total NH_4^+ as N	0.03	0.05	0.01	0.02	0.01
	Nitrogen, total NO_2 + NO_3 as N	0.5	0.5	0.5	0.5	0.5
	Nitrogen, total organic as N	0.3	0.3	0.3	0.3	0.3
	Carbon, organic total	2.5	2.2	2.3	2.4	2.1
	Phosphorus, total	0.27	0.15	0.06	0.02	0.04
	C. HEAVY METALS (all values are in µg/L)					
6-20-83	Lead, total as Pb	3	9	10	20	3
	Chromium, total as Cr	10	20	20	20	20
	Iron, total as Fe	40	3,600	140	200	360
	Nickel, total as Ni	11	11	6	7	5
	Manganese, total as Mn	<10	70	30	20	10
	Zinc, total as Zn	270	130	90	80	100
6-21-83	Lead, total as Pb	7	12	19	12	9
	Chromium, total as Cr	10	10	10	10	20
	Iron, total as Fe	60	1,300	150	30	100
	Nickel, total as Ni	9	7	5	4	8
	Manganese, total as Mn	10	20	10	<10	<10
	Zinc, total as Zn	30	50	30	40	40
6-22-83	Lead, total as Pb	3	6	9	5	2
	Chromium, total as Cr	10	10	10	10	10
	Iron, total as Fe	70	590	860	130	60
	Nickel, total as Ni	15	10	8	9	4
	Manganese, total as Mn	<10	10	10	<10	10
	Zinc, total as Zn	30	50	100	30	30

Table 10. Chemical analysis of reclaimed water from recharge basin 3, unsaturated zone, and water table beneath basin during recharge test of June 20-23, 1983 (continued)

			Source			
			Lysimeters[1]			Observation
Date	Constituent	Basin	1	3	4	well (N9825)
	C. HEAVY METALS (continued)					
6-23-83	Lead, total as Pb	15	4	4	5	9
	Chromium, total as Cr	10	10	10	<10	10
	Iron, total as Fe	1,500	130	140	90	230
	Nickel, total as Ni	19	11	8	13	11
	Manganese, total as Mn	30	10	10	10	10
	Zinc, total as Zn	170	50	30	30	40
	D. LOW-MOLECULAR WEIGHT ORGANIC COMPOUNDS [All values are in µg/L; dashes indicate value below detection limit]					
6-20-83	Dichloromethane	0.70	0.31	2.31	0.51	0.15
	Trichloromethane	.28	.10	.41	.18	.11
	1,1,1-Trichloroethane	--	.03	--	--	.07
	Bromodichloromethane	.73	--	.16	.20	--
	Dibromochloromethane	3.51	2.93	5.21	5.71	1.54
	Tribromomethane	41.63	14.52	26.60	28.66	8.62
6-21-83	Dichloromethane	.83	.58	.63	.73	.71
	Trichloromethane	.25	.30	.39	.38	.26
	1,1,1-Trichloroethane	--	--	.17	--	--
	Bromodichloromethane	1.25	1.00	1.10	6.82	1.13
	Dibromochloromethane	11.02	3.41	8.67	10.18	10.28
	Tribromomethane	47.36	34.47	34.64	35.02	50.14
6-22-83	Dichloromethane	.72	1.5	.80	1.00	1.1
	Trichloromethane	.73	.60	1.00	.80	.60
	1,1,1-Trichloroethane	--	--	--	.30	--
	Bromodichloromethane	1.57	1.20	1.94	2.80	2.6
	Dibromochloromethane	3.26	10.80	3.40	12.00	12.3
	Tribromomethane	26.51	38.20	23.46	32.00	31.2
6-23-83	Dichloromethane	.20	1.5	1.40	2.50	6.0
	Trichloromethane	.30	.60	.60	.60	.5
	1,1,1-Trichloroethane	--	--	--	--	--
	Bromodichloromethane	.70	1.2	1.40	1.2	.8
	Dibromochloromethane	8.5	10.8	11.0	10.8	8.9
	Tribromomethane	40.0	38.2	36.0	45.0	36.0

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[1] Lysimeters 1, 3, and 4 are 2.5, 8.2, and 11 ft below basin surface, respectively.

All major inorganic anions and cations except potassium (table 10A) show relatively little change as they move through the unsaturated zone. Although the other major ions showed an initial decrease in concentration as a result of dilution by pore water, potassium showed a marked increase between the water table and lysimeter 4 during the first 2 days, which may reflect the stripping of potassium from the sand and gravel particles. This phenomenon subsided considerably after 3 days of testing. Ten pore-water samples collected from the unsaturated zone before recharge had an average sodium concentration of 15 mg/L and an average potassium concentration of 5 mg/L. This ratio (3:1) is much lower than the ratio in reclaimed water (8:1). The increase in sodium could force potassium to leach from exchange sites within the sand and gravel matrix until a new equilibrium is reached. The most pronounced change occurred on the first day of testing, when reclaimed water was initially released into the unsaturated zone, but as the system began to reach equilibrium over the next two 2 days, less potassium was leaching into percolating water, and potassium concentrations in ground water therefore decreased.

Results of heavy-metals analyses are shown in table 10C. Most notable is the initial increase in iron and manganese, which are presumably derived from iron and manganese hydroxide coatings commonly found on the sand and gravel of the unsaturated part of the upper glacial aquifer. Most of the other metals show either a net decrease or no change with passage through the unsaturated zone.

Concentrations of selected low-molecular-weight organic compounds known to be present in the reclaimed water (table 10D) remained virtually unchanged during passage through the unsaturated zone.

Five-Month Test at Basin 2

On July 18, 1983, basin 2 (fig. 4B) was put into operation for 176 consecutive days until January 9, 1984. The average inflow rate from July 18 to December 5 was 665 gal/min. After December 5, the inflow rate was decreased progressively (fig. 25) from 425 gal/min to 250 gal/min in response to increasing basin stage until the test ended on January 9. A total of 153 Mgal of reclaimed water was transmitted to the ground-water system through this basin. No ponding was evident for the first 28 days, and only 50 to 75 percent of the floor was covered with water during this time. During the next 14 weeks, however, ponding increased to approximately 2 ft. In the next 5 to 10 days, by December 6, 1983, when stage increased to 3.5 ft, the inflow rate was reduced from 650 to 425 gal/min. This procedure reduced the water stage for several days, but on December 15 it began to increase once again and peaked at 3.7 ft. The inflow rate was again reduced, this time to 250 gal/min, after which the stage remained relatively constant until January 9, 1984, when operations ceased. This test proved that high recharge rates can be preserved if necessary for many weeks with no substantial maintenance procedures.

The infiltration rates of this basin were moderate to high during the first month of this test, when only 50 to 75 percent of the basin was covered, and, as the inflow rate neared 800 gal/min, the infiltration rate equaled 2.6 ft/h. However, since most of the test was conducted at an inflow rate of 665 gal/min, the infiltration rates were closer to 1.1 ft/h.

The effect of recharge at 1 Mgal/d through a single basin was observed when basin 2 was operated by itself for several days. The hydrograph in figure 26 shows the increase in water levels in a well 10 ft north of the basin 2 retaining wall. During the 8 days that this basin was in operation alone (July 18-25, 1983), the water level rose nearly 3.0 ft. Directly beneath the manhole, mounding reached 4 ft above static level. The lateral extent of the mound after 8 days at an inflow rate of 700 gal/min is shown in figure 27. Ground-water mounds that developed during all recharge periods reached 80 percent of their total heights within 96 hours. The mounds subsided within 12 to 18 hours when recharge was discontinued.

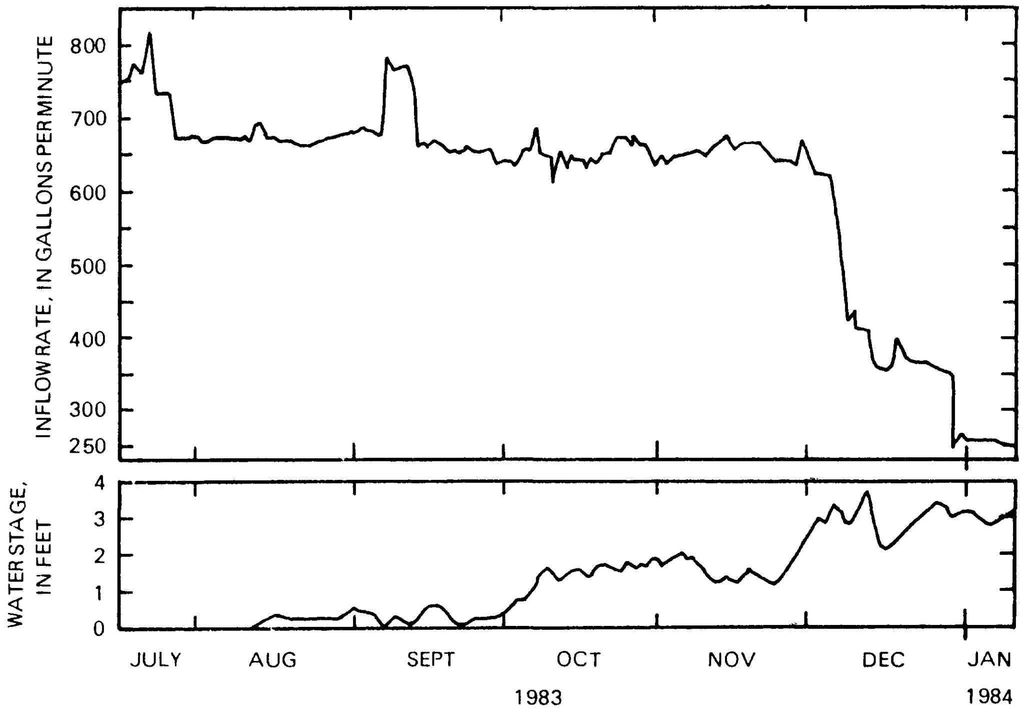


Figure 25.--Inflow rate and water stage in basin 2 during 5-month recharge test, July 18, 1983 to January 9, 1984.

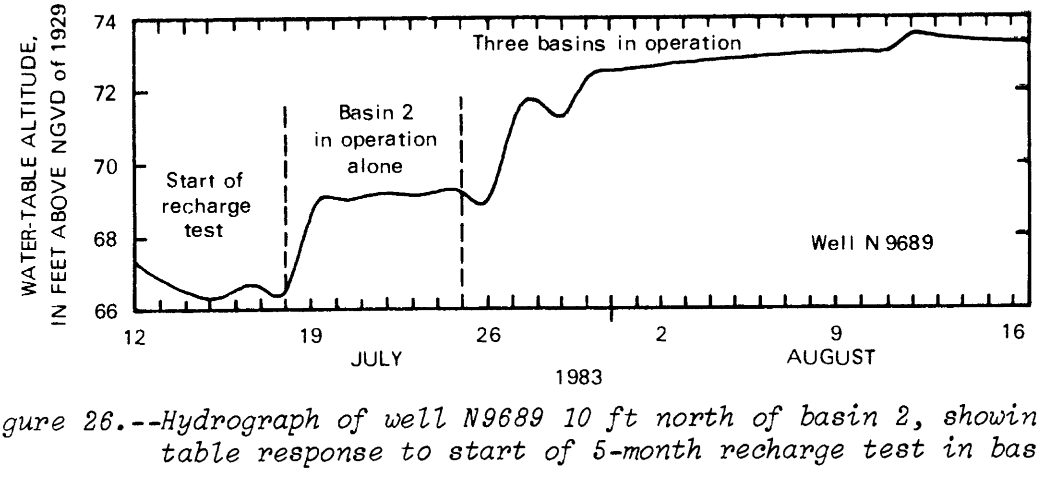


Figure 26.--Hydrograph of well N9689 10 ft north of basin 2, showing water-table response to start of 5-month recharge test in basin 2.

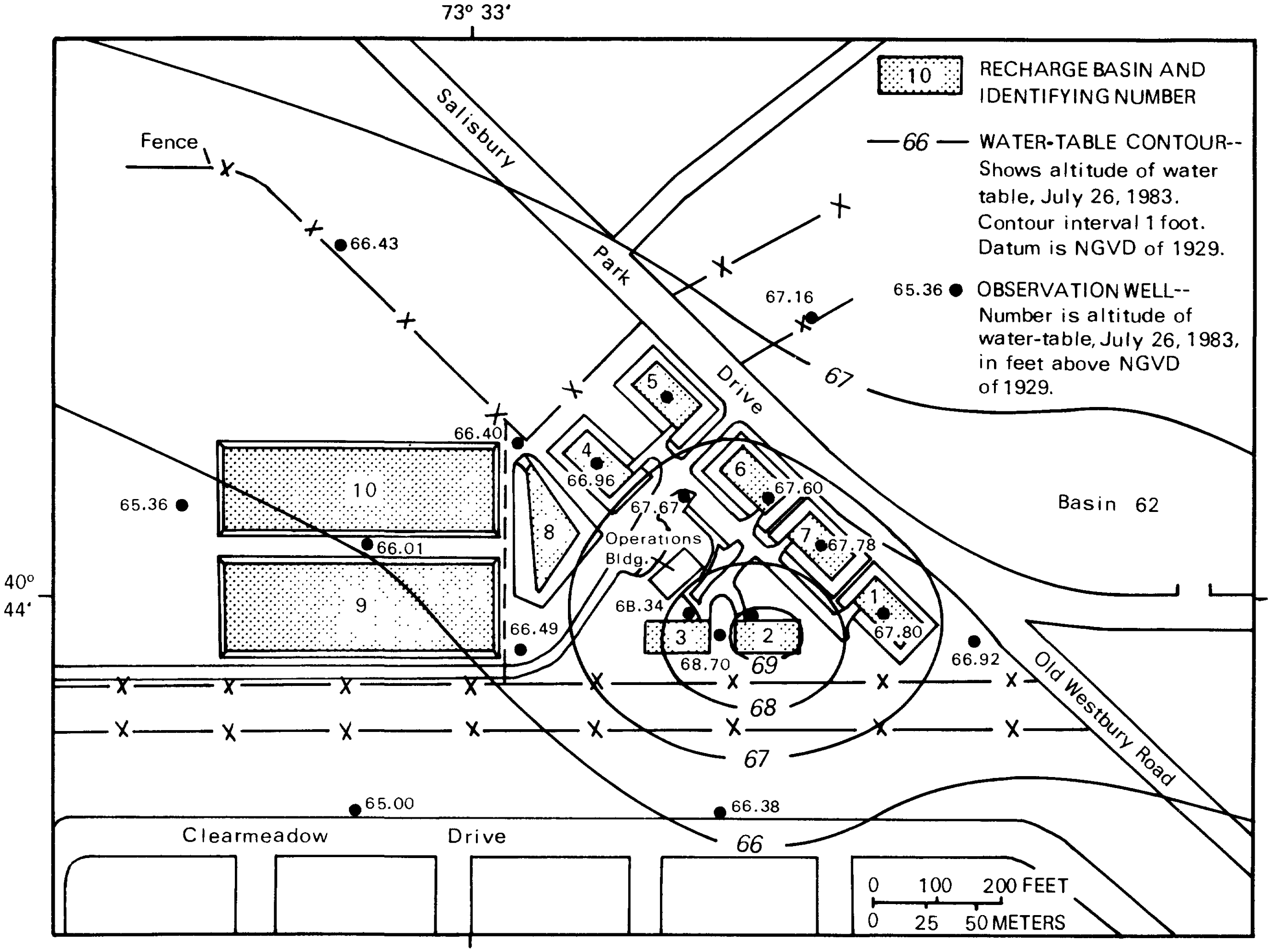


Figure 27.--Ground-water mound after first 8 days of 5-month recharge test at basin 2.

Development of Controlling Layer

Although basin 2 is less than 100 ft from basin 3, in which the 72-hour test was conducted, it showed different unsaturated-zone characteristics and dynamics. Also, the silty layer that begins 4 ft beneath basin 3 is absent beneath basin 2.

After about 7 days of recharge, a controlling layer began to form at basin surface, as indicated by the soil-moisture tension (fig. 28A). Soil-moisture tension during the first 7 days of operation (fig. 28A) shows a return toward an unsaturated condition beginning 1 day after the test began, and the unsaturated condition remained throughout the profile for the duration of the test, as shown in figure 28B. At the time, when the 2- and 4-month soil-moisture measurements were taken (curves 2 and 3 in fig. 28b), 3.0 and 21.6 inches of head were observed in the basin, respectively. This suggests that the majority of the head loss occurs at the basin floor, which indicates surface control.

This assumption is supported by the vertical hydraulic conductivity of the 0- to 1-ft and the 0- to 5-ft depths. Vertical hydraulic-conductivity values at selected times during the 176-day test were calculated from head increases and are presented in table 11. Most noticeable is the reduction in hydraulic conductivity (K) with rising basin stage. Values of K for the 0- to 1-ft depth range from 2.1 to 28 ft/d, whereas the values for the 0- to 5-ft zone range from 6.1 to 47.9 ft/d. It is evident that, by the end of the test, the basin surface was transmitting less water to the unsaturated zone, which in turn caused basin stage to increase. If recharge operations were to continue, this would have been an appropriate time to restore infiltration capacity by letting the basin floor dry and(or) scarifying the soil surface.

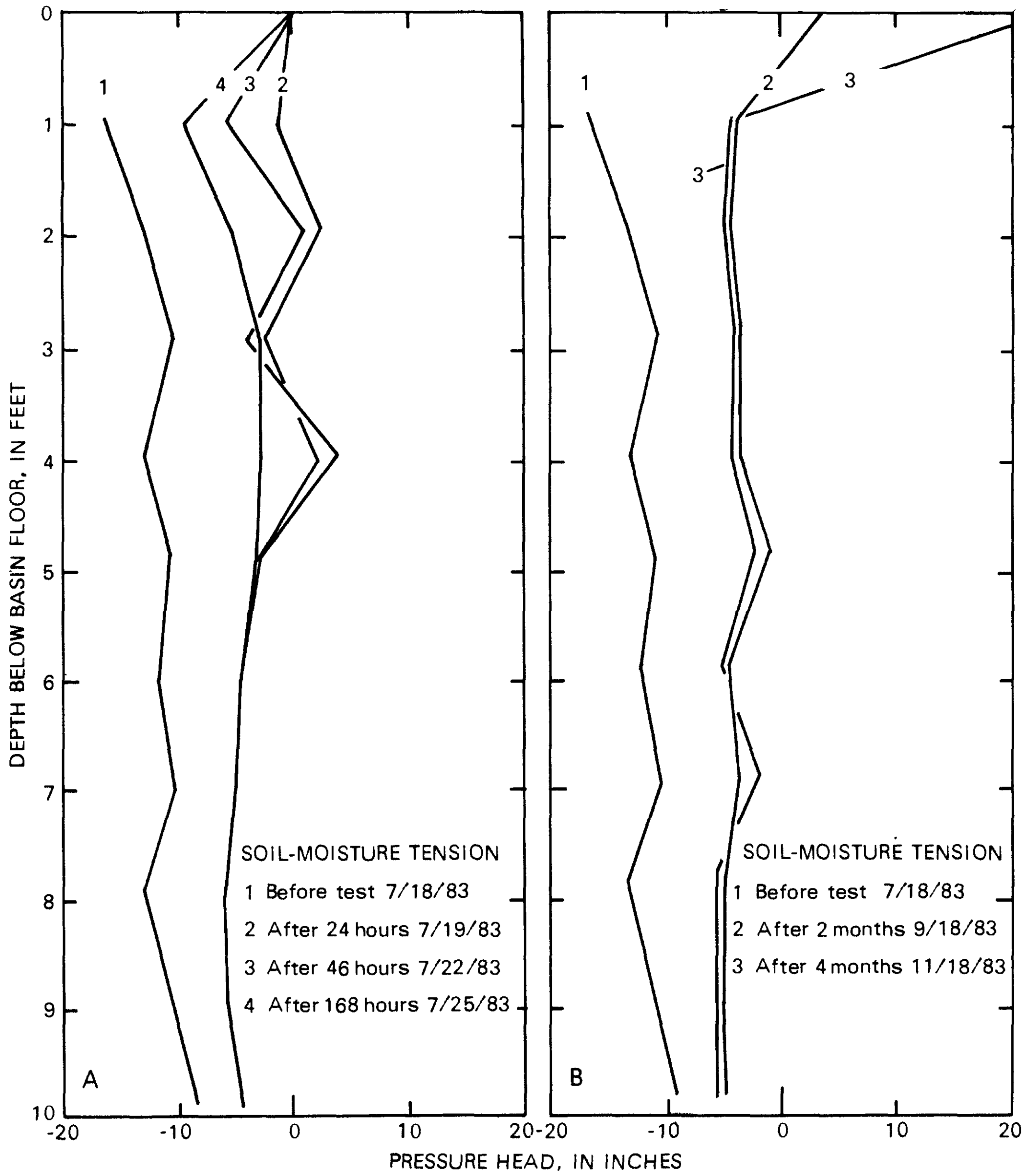


Figure 28.--Pressure heads within the unsaturated zone during 5-month recharge test at basin 2: A, before test, and after 24, 96, and 168 hours of recharge; B, before test and after 2 and 4 months of recharge.

Field measurements of soil-moisture tension reveal the location and extent of the zone controlling infiltration. Although basins 2 and 3 are only 50 ft apart, differences in their surficial and subsurficial characteristics significantly affect recharge efficiencies.

Table 11.--Hydraulic data on the 0- to 5-foot and 0- to 1-foot depth intervals below floor of basin 2 during 5-month recharge test

Date	Time of day	Time since test began (days)	Pressure head, (inches of water) Upper boundary	Pressure head, (inches of water) Lower boundary	Hydraulic gradient	Infiltration rate adjusted to 60 °F (ft/h)	Vertical hydraulic conductivity at 60 °F (ft/d)
		A. 0- to 5-ft interval (thickness 58.8 inches)					
7-25-83	1250	7	0	-2.75	1.05	2.09	47.7
8-16-83	0100	29	3.6	-2.81	1.11	.91	19.7
10-10-83	2300	84	21.36	-2.04	1.40	.90	15.4
12-20-83	2400	155	31.20	-2.43	1.57	.65	9.9
1- 9-84	1500	176	40.00	-3.27	1.74	.44	6.1
		B. 0- to 1-ft interval (thickness 11.4 inches)					
7-25-83	1250	7	0	-8.95	1.79	2.09	28.0
8-16-83	0100	29	3.6	-3.14	1.59	.91	13.7
10-10-83	2300	84	21.36	-1.23	2.98	.90	7.2
12-20-83	2400	155	31.20	-3.11	4.01	.65	3.9
1- 9-84	1500	176	40.00	-4.95	4.95	.44	2.1

Movement of Wetting Front

Neutron geophysical logs were obtained within and adjacent to basin 2 (locations are shown in fig. 23, p. 46) during the 5-month recharge test as in the 72-hour test at basin 3. A series of neutron logs taken during the first 2 hours of the test is given in figure 29. The first slug of reclaimed water reached the water table in just over 2 hours, which would indicate the average interstitial velocity to be 12 ft/h. This velocity is verified by the response to recharge at an observation well 10 ft north of basin 2. When the test began at 1230 hours, the water level in the well was 66.50 ft above sea level. Between 1415 and 1430 hours, the water level rose 0.20 ft from 66.63 to 66.83 ft above sea level, which indicates that reclaimed water had reached the water table. During the next several hours, the water level rose about 0.10 ft every 15 minutes to a height of 70.54 after 48 hours.

Neutron access tubes 9, 10, and 11 (fig. 23) were also logged to detect vertical and lateral movement of water throughout this 5-month test. The logs from access tubes 10 and 11, which are 12 and 24 ft north of basin 2 (fig. 30B, 30A) show insignificant lateral movement within the unsaturated zone, even after 3 months, and the log from neutron access tube 9, 6 ft from the retaining wall (fig. 30C), indicates only a 5-percent soil-moisture buildup after 3 months. These results, as at basin 3, verify that horizontal movement in the unsaturated zone is insignificant in relation to vertical flow.

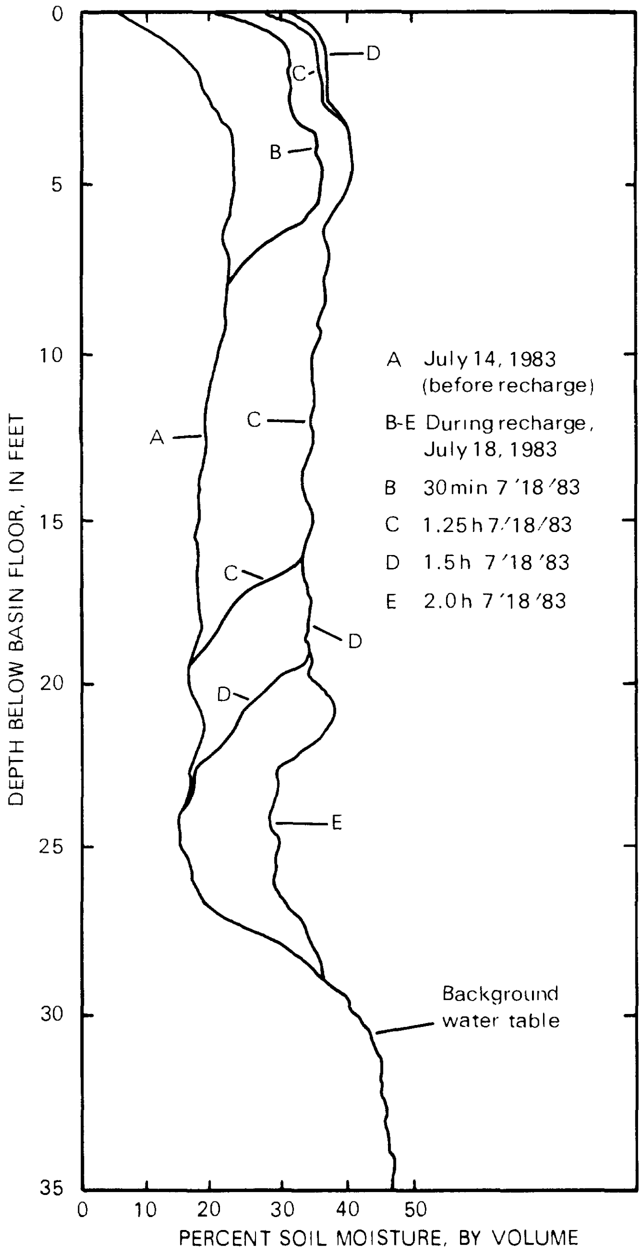


Figure 29.

Soil-moisture logs from basin 2 before recharge and during recharge on July 18, 1983.

Water Quality in Unsaturated Zone at Basin 2

An attempt was made to use the same sampling schedule for this test as had been used at basin 3 to provide comparable results. Therefore, most of the soil-water samples to be used for chemical analysis were obtained during the first 5 days of recharge. One sample of reclaimed water entering the basin was collected hourly beginning July 18 at 1400 hours and ending at 1100 hours on July 22, 1983, and composited. One sample was also collected from each lysimeter (all four lysimeters collected sufficient volumes) on July 18, 20, and 22 and one from an observation well (N9821) beneath the manhole on the same dates. Another suite of samples was collected just before the test ended in December 1983, to determine what long-term changes in water quality occurred during the 5 months of basin operation. On December 12, 1983, a sample was collected from each lysimeter and from the observation well beneath the manhole. A basin composite sample was derived from hourly samples beginning at 1000 hours December 12 and ending at 1000 hours on December 13, 1983.

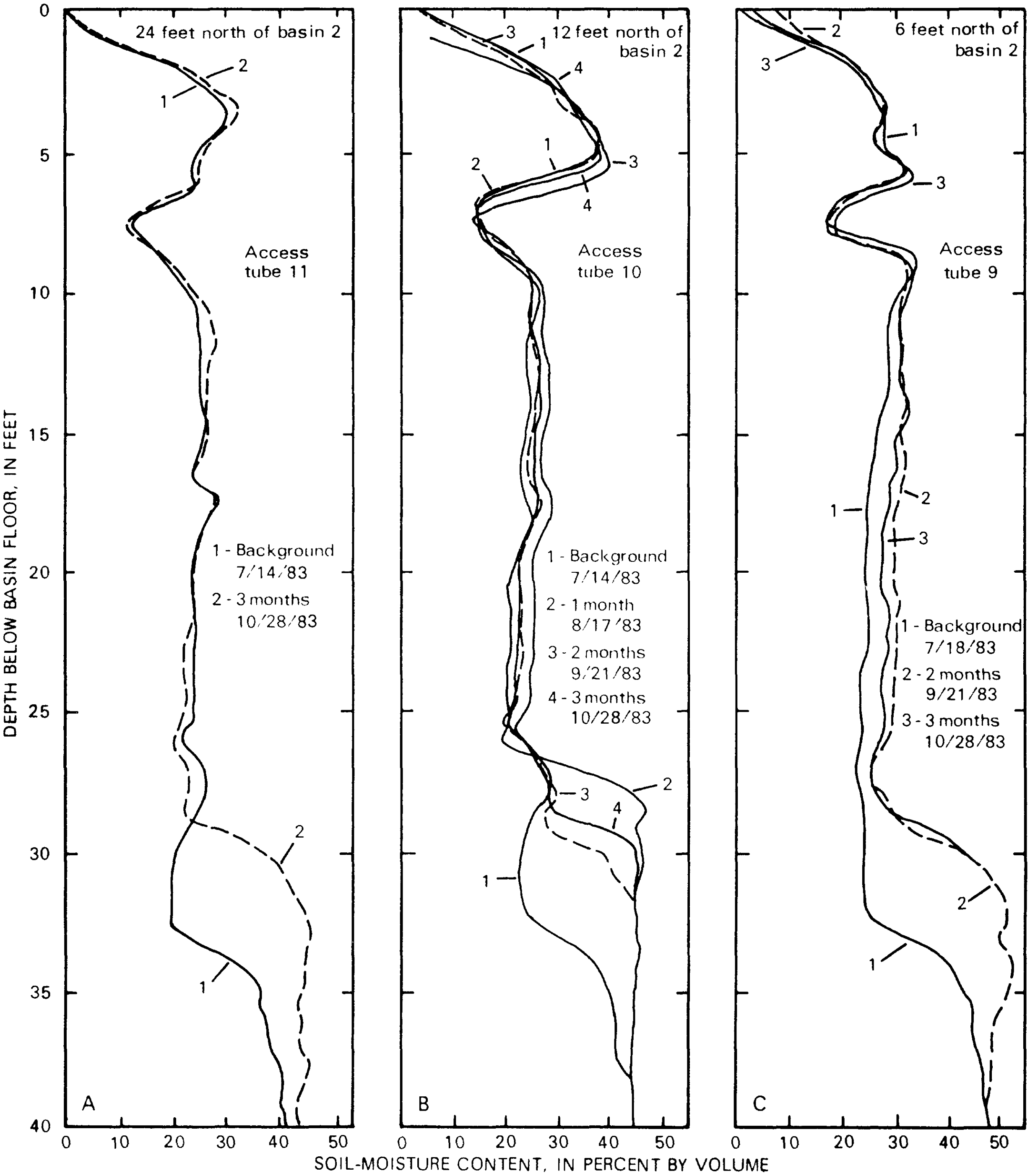


Figure 30.--Soil-moisture logs obtained selected distances from basin 2 during recharge test of July 18, 1983: A, neutron access tube 11, 24 ft north of basin 2; B, neutron access tube 10, 12 ft north of basin 2; and C, neutron access tube 9, 6 ft north of basin 2. (Locations are shown in fig. 23.)

The results, summarized in table 12, indicate that concentrations of most chemical constituents changed little during passage through the unsaturated zone. The concentrations are similar to those found during the 72-hour test at basin 3. Some constituents showed a small fluctuation on the first sampling date as a result of dilution with native water remaining in the unsaturated zone before recharge; other constituents showed no change in concentration. After the first sampling date, concentrations of most constituents were unaltered. Of interest, however, is the fate of phosphorus through time. During the first week of the 5-month test, as in the 72-hour test, phosphorus was actively adsorbed within the unsaturated zone. After several days, however, the adsorptive capacity of the unsaturated zone decreased; hence, the phosphorus concentrations increased with depth within the unsaturated zone. On December 12, 1983, the final sample showed soil water within the unsaturated zone and ground water beneath the basin to contain much higher phosphorus concentrations than ambient ground water.

The stability of chemical constituents during transit to the water table at basins 2 and 3 can be attributed to three main factors: (1) the nonreactive nature of the quartzose sand and gravel that forms the upper glacial aquifer gives only a small potential for exchange reactions; (2) the short retention time within the unsaturated zone (12 ft/h in basin 2 and 6 ft/h in basin 3) minimizes the time in which chemical exchange reactions or degradation by microbiological activity can occur; and (3) reclaimed water is highly treated before recharge, which makes additional filtration or chemical alteration in the unsaturated zone unlikely. Thus, the chemical concentration of reclaimed water is not altered or modified to any significant degree by contact with the unsaturated zone.

Table 12.--Chemical analysis of reclaimed water from basin, unsaturated zone, and water table beneath basin 2 during 5-month recharge test.

Date	Constituent	Basin composite	Lysimeters (Unsaturated zone)				Observation well
			1	2	3	4	
	A. INORGANIC CATIONS AND ANIONS						
7-18-83	Calcium (mg/L)	54	28	34	31	30	43
	Magnesium (mg/L)	9.4	2.9	2.3	2.6	2.6	4.9
	Potassium (mg/L)	12	5.6	9.5	18	25	15
	Sodium (mg/L)	91	85	77	55	74	72
	Chloride (mg/L)	130	120	120	99	120	110
	Fluoride (mg/L)	0.2	0.1	0.1	0.1	0.1	0.1
	Sulfate (mg/L)	72	81	80	67	84	56
	pH	7.1	6.2	6.3	7.7	6.3	6.8
	Specific conductance (μS/cm)	820	668	652	921	673	682
7-20-83	Calcium (mg/L)		53	51	52	52	49
	Magnesium (mg/L)		9.5	9.5	9.7	9.6	6.9
	Potassium (mg/L)		12	12	12	12	17
	Sodium (mg/L)		110	110	110	110	100
	Chloride (mg/L)		150	150	150	150	150
	Fluoride (mg/L)		0.2	0.2	0.2	0.2	0.2
	Sulfate (mg/L)		72	72	73	72	72
	pH		7.7	7.8	7.7	7.7	7.3
	Specific conductance (μS/cm)		921	921	921	912	891

- continued -

Table 12.--Chemical analysis of reclaimed water from basin, unsaturated zone, and water table beneath basin 2 during 5-month recharge test. (*continued*)

Date	Constituent	Basin composite	Lysimeters (Unsaturated zone) 1	2	3	4	Observation well
	A. INORGANIC CATIONS AND ANIONS (continued)						
7-22-83	Calcium (mg/L)		52	54	53	54	52
	Magnesium (mg/L)		8.4	8.8	8.6	8.9	8.6
	Potassium (mg/L)		12	12	12	12	15
	Sodium (mg/L)		110	86	110	95	92
	Chloride (mg/L)		120	120	120	120	120
	Fluoride (mg/L)		0.2	0.2	0.2	0.2	0.3
	Sulfate (mg/L)		73	73	72	73	71
	pH		7.5	7.6	7.5	7.5	7.4
	Specific conductance (µS/cm)		864	865	866	854	853
12-13-83	Calcium (mg/L)	52	53	53	53	54	50
	Magnesium (mg/L)	8.8	8.8	8.8	8.7	8.9	7.3
	Potassium (mg/L)	13	13	13	13	13	11
	Sodium (mg/L)	100	96	99	100	100	--[a]
	Chloride (mg/L)	120	120	130	120	130	--[a]
	Fluoride (mg/L)	0.5	0.6	0.6	0.6	0.6	--[a]
	Sulfate (mg/L)	81	81	81	81	81	74
	pH	7.3	6.8	6.9	7.1	7.1	7.2
	Specific conductance (µS/cm)	863	870	867	866	874	859

[a] analyses not performed

Date	Constituent	Basin composite	Lysimeters (Unsaturated zone) 1	2	3	4	Observation well
	B. NITROGEN, CARBON, AND PHOSPHORUS SPECIES (in mg/L)						
7-18-83	Nitrogen, total as N	1.4	1.9	2.7	2.9	2.5	1.8
	Nitrogen, total NH_4^+ as N	0.02	<0.01	0.02	0.02	<0.01	<0.01
	Nitrogen, total $NO_2 + NO_3$ as N	1.2	1.7	2.5	2.4	2.3	1.6
	Nitrogen, total organic as N	0.18	--	0.18	0.48	--	--
	Carbon, organic total	2.1	3.6	4.3	7.9	2.9	2.3
	Phosphorus, total	0.30	0.04	0.03	0.04	0.02	0.03
7-20-83	Nitrogen, total as N		1.5	1.6	1.5	--	1.8
	Nitrogen, total NH_4^+ as N		<0.01	0.01	<0.01	<0.01	<0.01
	Nitrogen, total $NO_2 + NO_3$ as N		1.3	1.3	1.3	1.3	1.6
	Nitrogen, total organic as N		--	0.29	--	--	--
	Carbon, organic total		1.4	0.8	0.8	--	2.7
	Phosphorus, total		0.02	0.03	0.04	0.04	0.10

(continued)

Table 12.--Chemical analysis of reclaimed water from basin, unsaturated zone, and water table beneath basin 2 during 5-month recharge test.
(continued)

		Basin	Lysimeter				Observation
Date	Constituent	composite	1	2	3	4	well
	B. NITROGEN, CARBON, AND PHOSPHORUS SPECIES (in mg/L) (continued)						
7-22-83	Nitrogen, total as N		1.0	1.1	1.1	1.1	1.1
	Nitrogen, total NH_4^+ as N		<0.01	<0.01	0.01	<0.01	<0.01
	Nitrogen, total $NO_2 + NO_3$ as N		0.9	0.9	0.9	0.9	0.9
	Nitrogen, total organic as N		--	--	0.19	--	--
	Carbon, organic total		1.5	1.2	1.0	1.1	1.6
	Phosphorus, total		0.14	0.13	0.04	0.05	0.05
12-13-83	Nitrogen, total as N	--	--	--	--	--	.7
	Nitrogen, total NH_4^+ as N	.26	0.05	0.22	0.06	0.06	0.03
	Nitrogen, total $NO_2 + NO_3$ as N	<0.1	0.2	0.2	0.2	0.2	0.4
	Nitrogen, total organic as N	0.24	--	--	--	--	--
	Carbon, organic total	5.8	2.9	2.0	2.4	2.0	1.2
	Phosphorus, total	0.85	0.34	0.32	0.33	0.33	0.26
	C. HEAVY METALS (in μg/L)						
7-18-83	Lead	20	17	8	12	15	43
	Chromium	10	20	10	20	10	10
	Iron	280	470	300	570	440	2500
	Nickel	20	16	27	29	9	18
	Manganese	10	40	80	20	20	70
	Zinc	70	150	340	370	80	60
7-20-83	Lead		12	6	4	12	34
	Chromium		<10	10	10	10	10
	Iron		50	60	50	100	2600
	Nickel		18	6	2	9	18
	Manganese		<10	<10	<10	<10	60
	Zinc		630	30	30	20	20
7-22-83	Lead		9	4	7	6	11
	Chromium		10	10	10	20	20
	Iron		230	110	100	150	370
	Nickel		4	3	9	6	6
	Manganese		<10	10	<10	<10	10
	Zinc		20	20	20	10	20
12-13-83	Lead	14	2	3	5	4	1.3
	Chromium	10	10	10	20	20	20
	Iron	100	90	80	160	80	160
	Nickel	5	5	3	<1	4	9
	Manganese	10	10	10	10	10	<10
	Zinc	40	40	30	60	20	160

(continued)

Table 12.--*Chemical analysis of reclaimed water from basin, unsaturated zone, and water table beneath basin 2 during 5-month recharge test.* (*continued*)

Date	Constituent	Basin composite	Lysimeter				Observation well
			1	2	3	4	
	D. LOW-MOLECULAR-WEIGHT ORGANIC COMPOUNDS [All values are in μg/L; dashes indicate value below detection limit]						
7-18-83	Dichloromethane	--	0.2	0.2	0.1	0.2	0.2
	Trichloromethane	--	0.2	0.3	0.2	0.3	0.3
	1,1,1-Trichloroethane	--	--	--	--	--	--
	Bromodichloromethane	1.1	0.6	0.6	0.4	0.8	0.7
	Dibromochloromethane	4.5	4.6	4.4	2.9	5.8	4.7
	Tribromomethane	15.4	22.3	21.3	14.4	26.4	22.7
7-20-83	Dichloromethane		0.4	0.2	0.3	<0.3	0.2
	Trichloromethane		0.6	0.3	0.8	0.5	0.3
	1,1,1-Trichloroethane		--	--	--	--	--
	Bromodichloromethane		2.1	0.9	2.0	2.0	1.0
	Dibromochloromethane		6.1	10.8	12.6	12.4	6.3
	Tribromomethane		47.3	26.9	45.4	46.4	34.5
7-22-83	Dichloromethane		0.4	<0.3	0.1	<0.3	0.2
	Trichloromethane		0.3	0.4	0.3	0.3	0.3
	1,1,1-Trichloroethane		--	--	--	--	--
	Bromodichloromethane		1.4	1.0	1.5	1.0	1.3
	Dibromochloromethane		3.5	7.0	6.2	7.4	6.6
	Tribromomethane		29.0	25.8	31.8	29.9	29.0
12-13-83	Dichloromethane	--	6.0	0.2	0.1	0.1	0.2
	Trichloromethane	--	0.7	0.8	0.8	0.6	0.4
	1,1,1-Trichloroethane	3.0	--	--	--	--	--
	Bromodichloromethane	3.0	0.9	1.1	1.0	1.0	1.2
	Dibromochloromethane	--	1.4	1.5	1.8	1.6	2.4
	Tribromomethane	--	2.1	2.7	2.6	2.5	1.1

Results of Soil Analysis

Soil samples from selected depths within the unsaturated zone provided information on ion-exchange reactions that occur within the unsaturated soil during recharge. Two suites of samples were collected from soil ports installed through the manhole wall and were analyzed for cation-exchange capacity, pH, exchange acidity, exchangeable cations, and acid-soluble metals.

One suite of samples was obtained before recharge at basin 2 and therefore represents background conditions; the second suite was collected at the end of the 5-month test and revealed physical and chemical changes that had taken place within the unsaturated zone as a result of exposure to reclaimed water. Soil samples were collected at 2.5-ft, 5.3-ft, 8.2-ft, and 11-ft depths, which coincide with the plane of capture of the gravity lysimeters. Therefore these samples can be considered representative of the same depths as the soil-water samples discussed in the preceding section.

Results of the two samplings (table 13) show varied net increases and decreases in exchangeable cations and acid-soluble metals. For example, potassium concentrations in unsaturated material before recharge ranged from 0.025 meq/100 g to 0.335 meq/100 g, but after 5 months of recharge, the range had decreased to 0.015 to 0.042 meq/100 g. This reduction can be attributed to the higher concentrations of sodium in reclaimed water. (As mentioned earlier, the ratio of sodium to potassium in samples of background pore water from the unsaturated zone was 3:1, but during recharge, it increased to 8:1. This increase in sodium forces potassium to move from its exchange sites into the percolating water.) This effect would also explain the increase in potassium in pore-water samples from lysimeters in both basin 3 (table 10A) and basin 2 (table 12A). This phenomenon was greatest in the first few days of recharge at basin 3, when the system was undergoing the greatest stress; after several days, when the system was nearing equilibrium, potassium concentrations in unsaturated material samples were no longer much higher than in reclaimed water. The increase in calcium in the unsaturated zone also played a role in removing potassium during recharge. Further evidence of this exchange was found by analysis of exchangeable sodium and calcium in the earth material. Sodium concentrations in the unsaturated material before recharge ranged from <0.01 to 0.045 meq/100 g, but after 5 months of recharge, they ranged from 0.047 to 0.076 meq/100 g (table 13). Similarly, calcium concentrations in the unsaturated material before recharge ranged from 0.125 to 0.295 meq/100 g and, after recharge, they ranged from 0.135 to 0.45 meq/100 g (table 13).

Lead also showed some change. Lead concentrations in the unsaturated material before recharge ranged from 1.25 to 2.80 µg/g, but after 5 months, they ranged from 1.4 to 5.0 µg/g (table 12C). The higher concentration near land surface coincides with the decrease in concentrations in pore-water samples, which indicates that lead is adsorbed in the upper 2 ft of earth material. This phenomenon also indicates that the lead-adsorbing capacity of the material did not diminish after 5 months of recharge.

Table 13.--Chemical properties of soil samples from unsaturated zone beneath basin before and after 5-month recharge test at basin 2

Depth below basin floor (ft)	Soil ph		Exchangeable cations (meq/100 g)							
			Calcium		Magnesium		Sodium		Potassium	
	2-15-82	12-13-83	2-15-82	12-13-83	2-15-82	12-13-83	2-15-82	12-13-83	2-15-82	12-13-83
2.5	7.95	7.4	0.295	0.45	0.017	0.067	0.045	0.076	0.055	0.042
5.3	7.90	7.4	0.130	0.215	0.005	0.039	0.01	0.055	0.05	0.023
8.2	8.00	7.65	0.185	0.190	0.006	0.025	0.01	0.050	0.335	0.024
11.0	8.05	7.6	0.125	0.135	0.0015	0.021	<0.01	0.047	0.025	0.015

Depth below basin floor (ft)	Acid-Soluble Metals (µg/g)							
	Zinc		Cadmium		Lead		Nickel	
	2-15-82	12-13-83	2-15-82	12-13-83	2-15-82	12-13-83	2-15-82	12-13-83
2.5	49.0	20.0	0.19	.1	2.80	5.0	1.5	4.0
5.3	15.2	12.3	0.11	.1	1.30	2.1	1.5	2.0
8.2	4.85	14.3	0.19	.1	1.85	2.0	<1	1.15
11.0	23.45	3.7	0.04	.1	1.25	1.4	<1	.03

Soil analyses performed by Cornell University, Department of Agronomy.

EFFECTS OF ARTIFICIAL RECHARGE ON LOCAL GROUND-WATER SYSTEM

During the 15-month artificial-recharge period (October 6, 1982 through January 9, 1984), measurements of ground-water mounding, velocities, and hydraulic gradients, as well as artificial-recharge rates and volumes, were made to determine what influence artificial recharge had on the ground-water system beneath the site. Most of the information gathered pertains to basin operation because 80 percent of the total recharge volume was returned to the ground through the seven shallow basins.

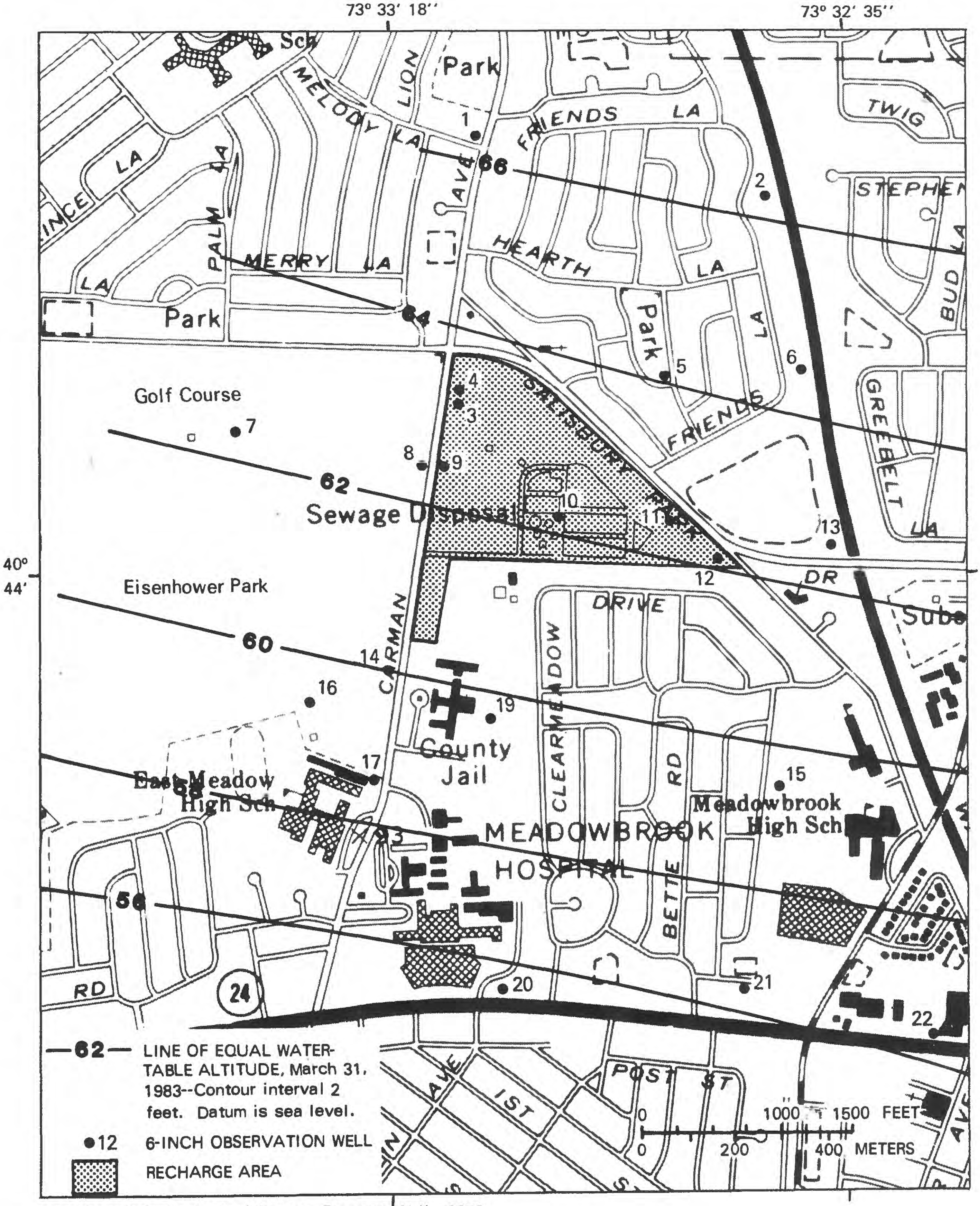
Ground-Water Mounding

As few as one but no more than four basins or wells were in use at any time (table 6). Recharge rates at basins ranged from 200 to 800 gal/min; those at wells ranged from 250 to 340 gal/min. A map of background water-table altitudes is shown in figure 31. The gradient before recharge was calculated to equal 0.0019.

The highest measured ground-water mound of 6.70 ft (fig. 32A) occurred when 4 Mgal/d was applied through basins 2, 5, 6, and 7 after 30 consecutive days (July 26 to August 26, 1982). When 2 Mgal/d was applied through basins 1, 5, 6, and 7, a mound of 4.3 ft was detected after 14 days (October 15 to October 29, 1982); with only basin 2 in operation at 1 Mgal/d, a mound of 3.95 ft developed after 5 days. With injection wells and recharge basins operating simultaneously at 2 Mgal/d at each site, two distinct mounds developed. The highest point of the ground-water mound was 3.5 ft above static near the basins and more than 2 ft above static in the vicinity of the injection wells (fig. 32B). A map of observed change in the regional water-table altitude after 11 days of continuous recharge through basins and wells is shown in figure 32C. Throughout the various recharge schemes tested at the facility, ground-water mounding was not significant and was much less than originally anticipated.

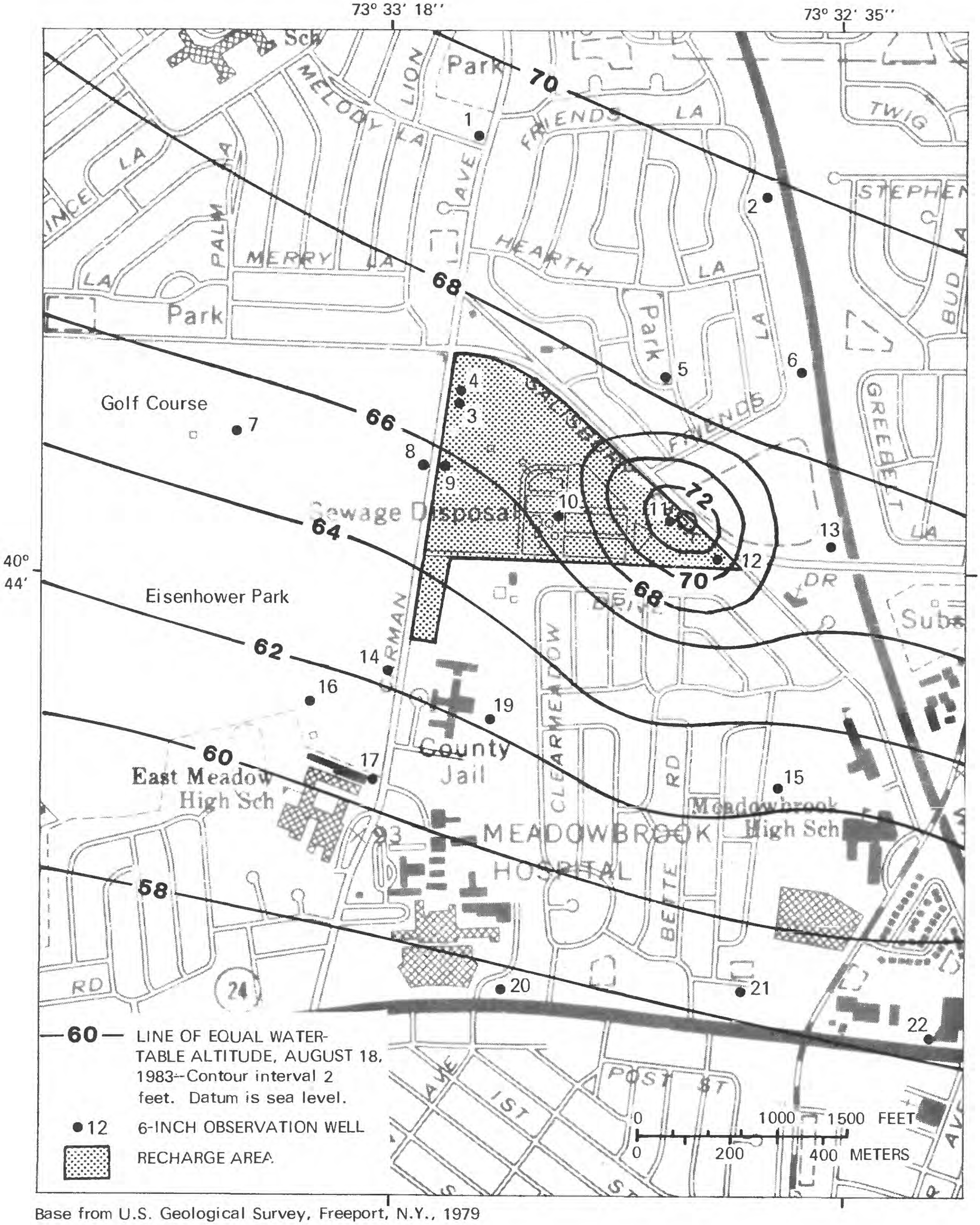
Water-Level Increases

The upper hydrograph in figure 33 (p. 68) depicts water levels in three wells affected by natural and artificial recharge from December 1, 1981 to December 1, 1983. Well N9196 (11A) and well N9198 (11C) are 200 ft deep (in Magothy aquifer) and 50 ft deep (in upper glacial aquifer), respectively, and are near the geographic center of the recharge facility. Well N1616 is a 68-ft-deep well 6 mi north of the recharge area that reflects the regional water-level trend in an area unaffected by artificial recharge. The increase in water levels from the early to middle part of 1983 in well N1616 reflects above-average precipitation, when half the yearly average rainfall of 44 inches fell during the 3-month period from March through May 1983. Also noticeable in this hydrograph is the minimal water-level increase in the deep well (11A) in response to artificial aquifer recharge.



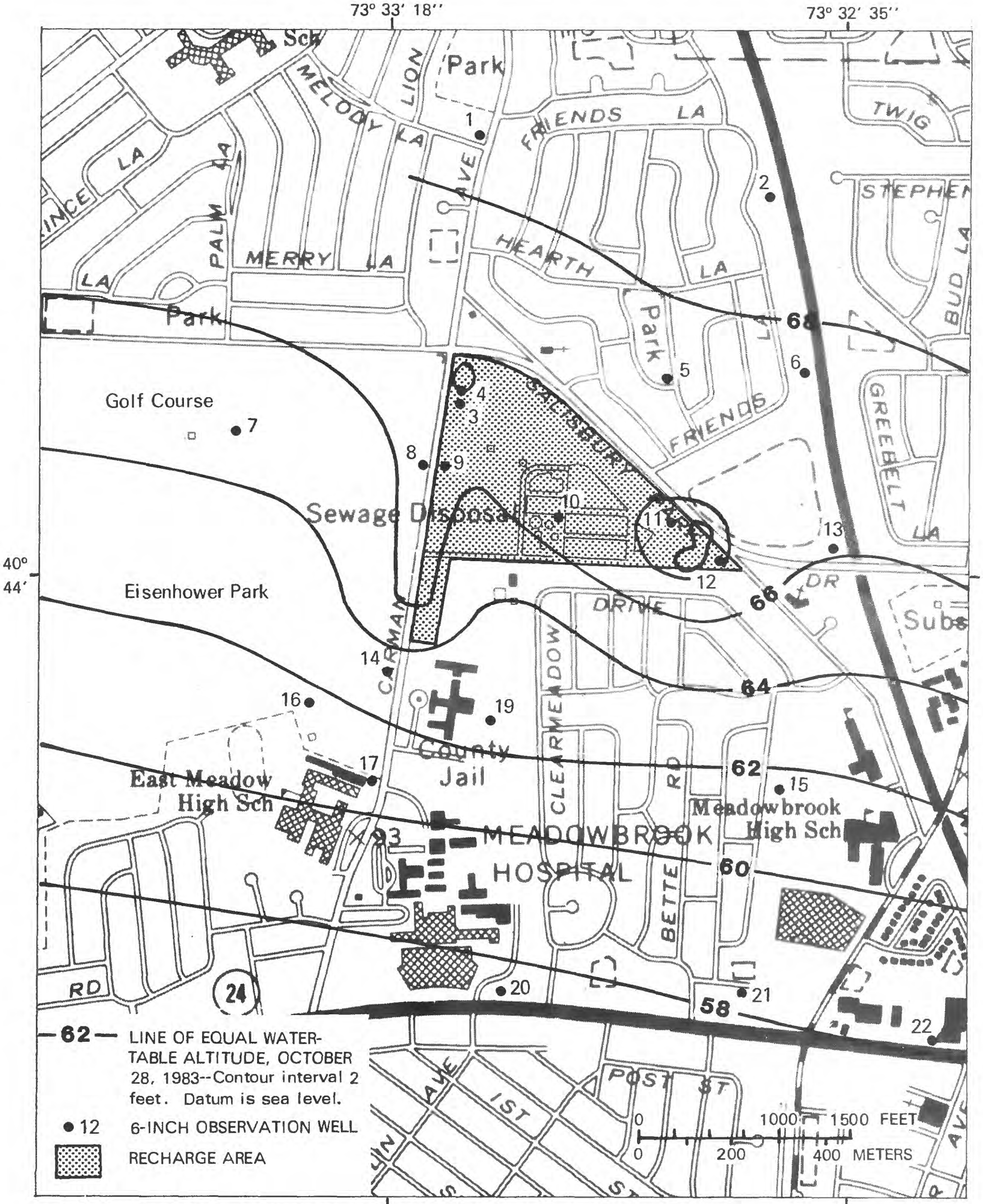
Base from U.S. Geological Survey, Freeport, N.Y., 1979

Figure 31.--Water-table altitude on March 31, 1983, before start of April 18 recharge test.



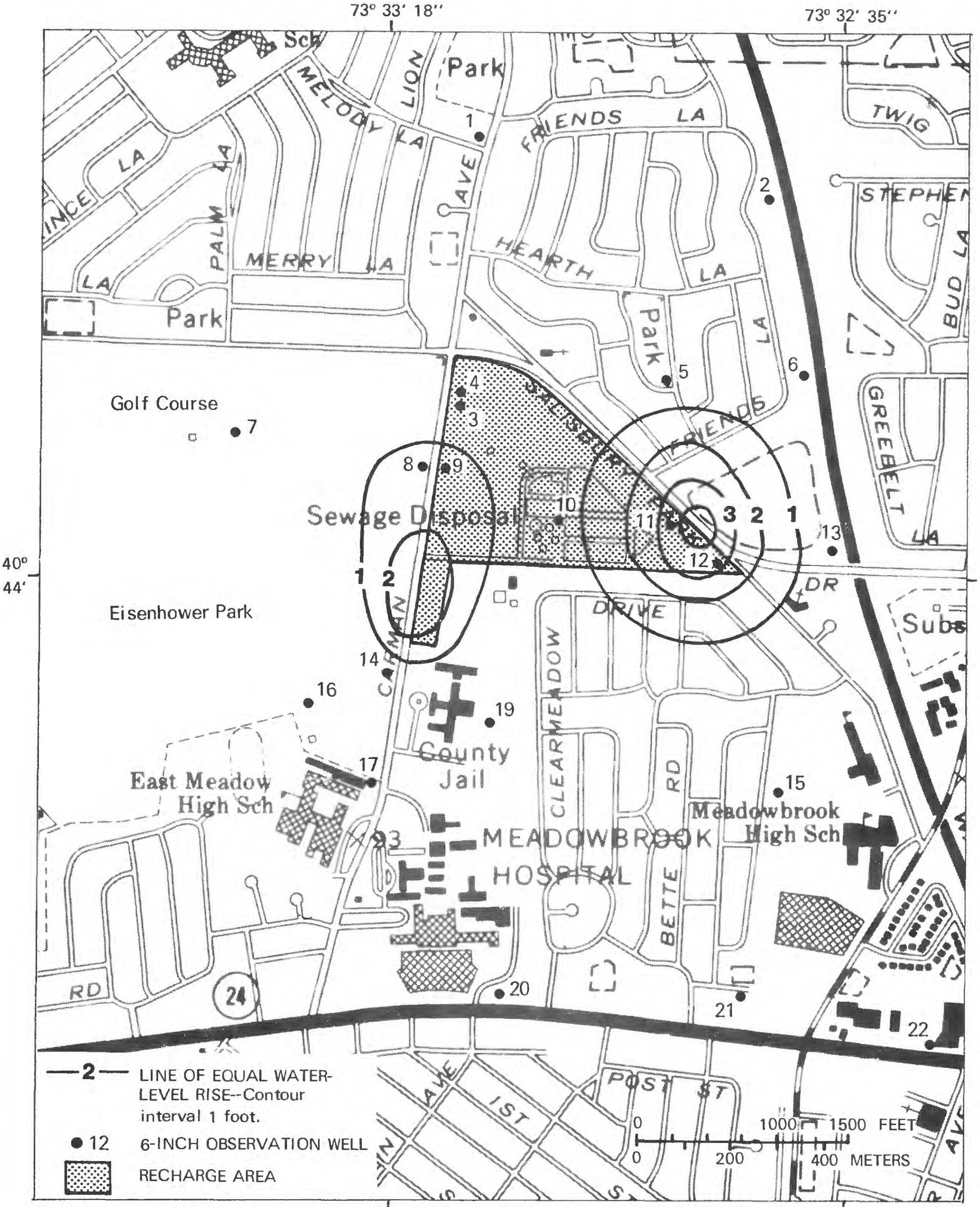
Base from U.S. Geological Survey, Freeport, N.Y., 1979

Figure 32A.--Ground-water mounding after 30 days of recharge at 4 Mgal/d.



Base from U.S. Geological Survey, Freeport, N.Y., 1979

Figure 32B.--Head buildup after 9 days of injection by wells and 7 months of recharge through basins.



Base from U.S. Geological Survey, Freeport, N.Y., 1979

Figure 32C.--Change in water-table altitude after 11 days of recharge at 4 Mgal/d.

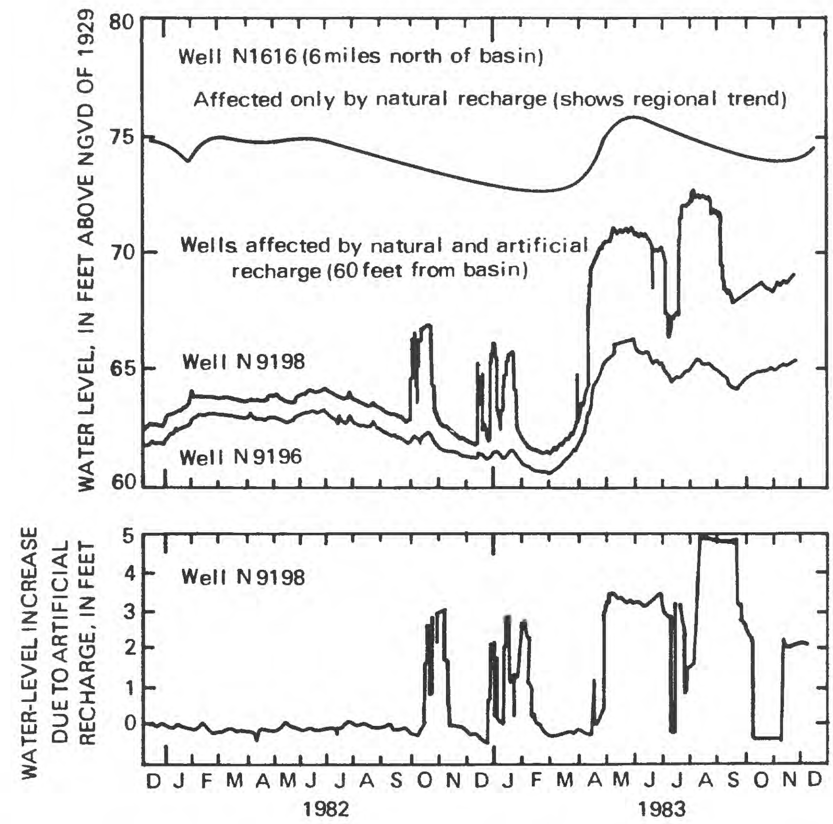


Figure 33.--Hydrographs of observation wells, 1982-83: Well N1616 (68 ft deep) shows regional pattern 6 mi north of basin, and wells N9198 (45 ft deep) and N9196 (200 ft deep) show effects of natural and artificial recharge 60 ft from basin. (Well locations are shown in fig. 9.)

Rate and Duration of Application

One of the important factors in recharge is the rate at which reclaimed water is applied to the basin floor or to the injection well. High recharge rates and extended basin-operating periods were used when conditions allowed. However, when basins accepted reclaimed water for periods longer than 1.5 months, ponding increased as a result of clogging, mainly by biological mechanisms. This phenomenon is common when water is applied at a high rate for an extended period. For example, a rate of 700 gal/min was maintained at basin 2 (fig. 25, p. 52) for nearly 4 months (August through November 1983). During this time, water stage steadily increased. When the flow rate was drastically reduced from early December through the remainder of the test, the stage continued to increase. High infiltration rates could be maintained more effectively if recharge durations were considerably shorter and the basin surfaces were scarified periodically to restore infiltration capability.

Extended operation, especially during summer, provided the conditions for the growth of insect populations. Reducing the length of recharge periods and removing vegetation from the basin floor should decrease the potential for excessive insect propogation while still maintaining high recharge rates.

On the whole, artificial-recharge experiments with basins and injection wells caused inconsequential ground-water mounding. Observations of ground-water levels and ponding within recharge basins, and of injection-well operation, revealed no serious impediments to ground-water recharge with reclaimed water. At this facility, the upper glacial aquifer can accept more than 4 Mgal/d of reclaimed water through the recharge basins and wells. To increase the performance of recharge basins, a simple basin-maintenance program consisting of resting cycles and(or) basin-floor modification can be followed. To increase the performance of injection wells, a weekly or biweekly redevelopment program would be necessary. The physical and biological factors that cause clogging can be circumvented if such a schedule is maintained.

EFFECTS OF ARTIFICIAL RECHARGE ON GROUND-WATER QUALITY

To determine alterations in ground-water quality as well as the areal distribution of reclaimed water at and near the injection site, water samples were taken periodically and analyzed for inorganic compounds, nutrients, and trace organic constituents.

One useful method of defining the approximate extent or shape of the plume formed by reclaimed water is through specific-conductance measurements. Dissolved solids such as sodium and chloride in reclaimed water in greater concentrations than in ambient water generates higher values of specific conductivity in observation wells affected by reclaimed water. The onsite measurements permitted immediate confirmation of plume location. The median value of specific conductance in both the upper glacial and Magothy aquifers before recharge was 300 µS/cm (table 1), and the median value in pure reclaimed water is 850 µS/cm. This wide disparity was used as an indicator of the presence of reclaimed water.

Results of Water-Quality Sampling

Three sets of water-quality data were collected during the recharge experiments to evaluate the effects of introducing reclaimed water to native aquifer water. Summaries of these sets are presented in tables 1, 3, and 14. They represent quality of (1) background (prerecharge) ground water; (2) reclaimed water (treated wastewater); and (3) ground water affected by reclaimed water. Included in the sampling were three synoptic sampling rounds made during August 1982, September 1983, and March 1984. The August 1982 samples and certain samples from September 1983 are incorporated within the background data; the March 1984 samples and some from September 1983 include wells that were affected by reclaimed water and are therefore considered "recharge" or "postrecharge."

Table 14.--Statistical summary of selected constituents of water from wells affected by injection of reclaimed water

Constituent	Median	Minimum	Maximum	Number of samples
Temperature (°C)	17.0	13.0	23.0	27
Turbidity (NTU)	1.50	.90	200	51
Specific conductance (µS/cm)	860	56.0	1,160	30
Oxygen, dissolved (mg/L)	5.80	2.80	60.0	27
Nitrogen, total (mg/L as N)	.00	.00	3.60	9
Nitrogen, dissolved (mg/L as N)	1.80	.69	6.30	30
Nitrogen, organic total (mg/L as N)	.00	.00	.68	8
Nitrogen, organic dissolved (mg/L as N)	.51	.00	1.00	10
Nitrogen, ammonia dissolved (mg/L as N)	.02	.01	1.60	54
Nitrogen, ammonia total (mg/L as N)	.02	.01	1.50	54
Nitrogen, NO2 + NO3 total (mg/L as N)	1.30	.10	14.0	54
Nitrogen, NO_2 + NO_3 dissolved (mg/L as N)	1.35	.05	14.0	54
Phosphorus, total (mg/L as P)	.05	.01	2.52	54
Carbon, organic total (mg/L as C)	1.70	.80	5.80	27
Calcium, dissolved (mg/L as Ca)	42.5	17.0	59.0	52
Magnesium, dissolved (mg/L as Mg)	7.90	2.30	13.0	52
Sodium, dissolved (mg/L as Na)	100	25.0	200	51
Potassium, dissolved (mg/L as K)	11.0	5.70	28.0	52
Chloride, dissolved (mg/L as Cl)	130	18.0	240	52
Chromium, total recoverable (µg/L as Cr)	10.0	10.0	70.0	50
Iron, total recoverable (µg/L as Fe)	70	10.0	14,100	52
Lead, total recoverable (µg/L as Pb)	10.0	.00	95.0	50
Nickel, total recoverable (µg/L as Ni)	.00	.00	40.0	28
Zinc, total recoverable (µg/L as Zn)	40.0	10.0	120	28
Dichlorobromomethane, total (µg/L)	1.05	.20	15.0	60
Carbon tetrachloride, total (µg/L)	1.00	.20	22.0	60
1,2-Dichloroethane, total (µg/L)	.40	.20	3.00	38
Bromoform, total (µg/L)	16.0	.20	50.0	60
Chloroform, total (µg/L)	1.00	.11	6.80	60
Toluene, total (µg/L)	3.00	1.00	8.00	54
Benzene, total (µg/L)	3.00	1.00	3.00	54
Butyl benzyl phthalate total (µg/L)	1.00	1.00	120	30
Tetrachloroethylene, total (µg/L)	1.00	.06	28.0	60
1,1-Dichloroethane, total (µg/L)	2.00	.10	10.0	60
1,1,1-Trichloroethane, total (µg/L)	1.00	.10	12.0	60
Chloroethylene. total (µg/L)	1.00	.10	4.00	60
2,4-Dimethylphenol, total (µg/L)	1.00	1.00	28.0	30
Di-n-butyl phthalate, total (µg/L)	2.00	1.00	65.0	30
Trichloroethylene, total (µg/L)	1.00	.10	22.0	60
Aldrin, total (µg/L)	.01	.01	.01	29
Lindane, total (µg/L)	.01	.01	.01	29
Chlordane, total (µg/L)	.10	.10	.10	29
DDD, total (µg/L)	.01	.01	.01	29
DDE, total (µg/L)	.01	.01	.01	29
DDT, total (µg/L)	.01	.01	.01	29
Dieldrin, total (µg/L)	.01	.01	.16	29

-continued-

Table 14.--Statistical summary of selected constituents of water from wells affected by injection of reclaimed water (continued)

Constituent	Median	Minimum	Maximum	Number of samples
Endosulfan, total (µg/L)	.01	.01	.01	29
Endrin, total (µg/L)	.01	.01	.01	29
Heptachlor, total (µg/L)	.01	.01	.01	29
Heptachlor epoxide, total (µg/L)	.01	.01	.01	29
PCB, total (µg/L)	.10	.10	.10	29
Mirex, total (µg/L)	.01	.01	.01	29
Silvex, total (µg/L)	--	--	--	0
Solids, residue at 180°C dissolved (mg/L)	502	314	668	29
Solids, sum of constituents, dissolved (mg/L)	.00	.00	559	17
Mercury, total recoverable (µg/L as Hg)	.50	.00	13.0	50

Plume-Water Concentrations

The chemical quality of plume water or water affected by reclaimed water is in some respects substantially different from that of ambient ground water. Sodium and chloride, for example, are four to five times higher than ambient levels although they are well within New York State drinking-water limits. Other constituents such as total nitrogen (nitrate plus nitrite as N), chlorinated hydrocarbons, insecticides, and PCB's are lower in plume water than in ambient water. The median concentration of total nitrogen in ambient water was 9.1 mg/L with a range of 0.08 to 25 mg/L, whereas the median value from 54 samples of plume water was only 1.8 mg/L.

The concentrations of some low-molecular-weight chlorinated hydrocarbons (tetrachloroethylene, 1,1-dichloroethane, 1,1,1-trichloroethane, and chloroethylene) are higher in ambient water than in plume water. For example, the median concentration of 1,1,1-trichloroethane in 84 ambient water samples was 7.9 µg/L, with a range of 0 to 217 µg/L, whereas in plume water, the median concentration of 60 samples was 1.0 µg/L.

Of the 51 constituents listed in table 14, 27 have higher median concentrations in the plume than in formation water, 19 are the same, and 7 are lower. Even though the concentrations of some constituents in plume water are higher than background levels, the values are substantially lower than the State concentration limits (table 3).

Table 15 compares four constituents of water from 11 observation wells that were sampled both before and after recharge. The four constituents (sodium, chloride, nitrate, and specific conductance) are considered primary indicators of reclaimed water. Generally, any samples with specific conductance values near 800 µS/cm indicate the presence of reclaimed water in that well. Water unaffected by reclaimed water, such as at wells N9451 and N9248, has values resulting partly from natural background variations.

Within months after the cessation of artificial recharge, the effects of mixing, dilution, and dispersion were observed in water from observation wells previously affected by reclaimed water. Results of analyses for wells N9198, N9363, and N9368, which are shallow wells near artificial-recharge sources, show these four constituents returning to prerecharge conditions (table 15).

The median sodium and chloride concentrations in the reclaimed water were approximately 115 and 157 mg/L, respectively, whereas those in ambient ground water were 22 and 27 mg/L, respectively. The chloride concentrations in wells tapping the upper glacial aquifer 2 months before recharge began and 3 months after the cessation of recharge are shown in figures 34 and 35. The effects of reclaimed water are still seen near the injection wells and recharge basins, where chloride concentrations average 85 mg/L.

Table 15.--Comparison of analyses from 11 observation wells before and after artificial recharge

[Well locations are shown in fig. 9; all values in mg/L unless noted]

	Precharge		Postrecharge		
	2-22-82	8-17-82	9-27-83	3-14-84	3-31-85
N9197					
Specific conductance (µS/cm)	363	425	960	925	861
Chloride	35	33	190	140	139
Sodium	31	31	110	130	108
Nitrate	15	16	1.4	0.27	0.8
N9198					
Specific conductance (µS/cm)	361	375	880	830	354
Chloride	39	34	150	97	23
Sodium	31	35	100	100	24
Nitrate	16	16	1.3	.4	8.2
N9360					
Specific conductance (µS/cm)	113	140	260	240	137
Chloride	17	17	49	38	28
Sodium	9.6	12	37	23	14
Nitrate	2.3	2.1	9.7	9.1	4.0
N9361					
Specific conductance (µS/cm)	334	425	340	980	475
Chloride	51	53	25	140	32
Sodium	42	46	28	130	35
Nitrate	6.3	7.2	18	.06	17.3
N9362					
Specific conductance (µS/cm)	312	400	370	730	390
Chloride	25	31	26	94	48
Sodium	23	30	24	88	33
Nitrate	17	22	19	5.0	12.0
N9363					
Specific conductance (µS/cm)	377	390	440	847	501
Chloride	57	59	54	112	60
Sodium	--	44	51	110	62
Nitrate	8.1	8.8	17	.59	10.0

(continued)

Table 15.--Comparison of analyses from 11 observation wells before and after artificial recharge (continued)

[Well locations are shown in fig. 9; all values in mg/L unless noted]

	Prerecharge		Postrecharge		
	2-22-82	8-17-82	9-27-83	3-14-84	3-31-85
N9364					
Specific conductance (µS/cm)	350	410	400	648	381
Chloride	27	29	31	85	55
Sodium	--	30	23	76	37
Nitrate	33	24	16	5.7	10.0
N9367					
Specific conductance (µS/cm)	368	380	650	800	777
Chloride	44	50	130	130	156
Sodium	32	36	90	120	106
Nitrate	12	14	1.3	.24	.45
N9368					
Specific conductance (µS/cm)	294	165	915	580	172
Chloride	31	15	150	75	15
Sodium	23	18	100	73	<3
Nitrate	8.2	3.1	1.6	.47	3.2
N9451					
Specific conductance (µS/cm)	277	375	380	275	285
Chloride	17	25	25	11	23
Sodium	20	24	30	17	18
Nitrate	13	21	14	8.5	9.1
N9248					
Specific conductance (µS/cm)	258	250	260	216	212
Chloride	33	27	23	38	28
Sodium	25	25	19	20	17
Nitrate	7.9	8.9	8.2	4.8	2.4

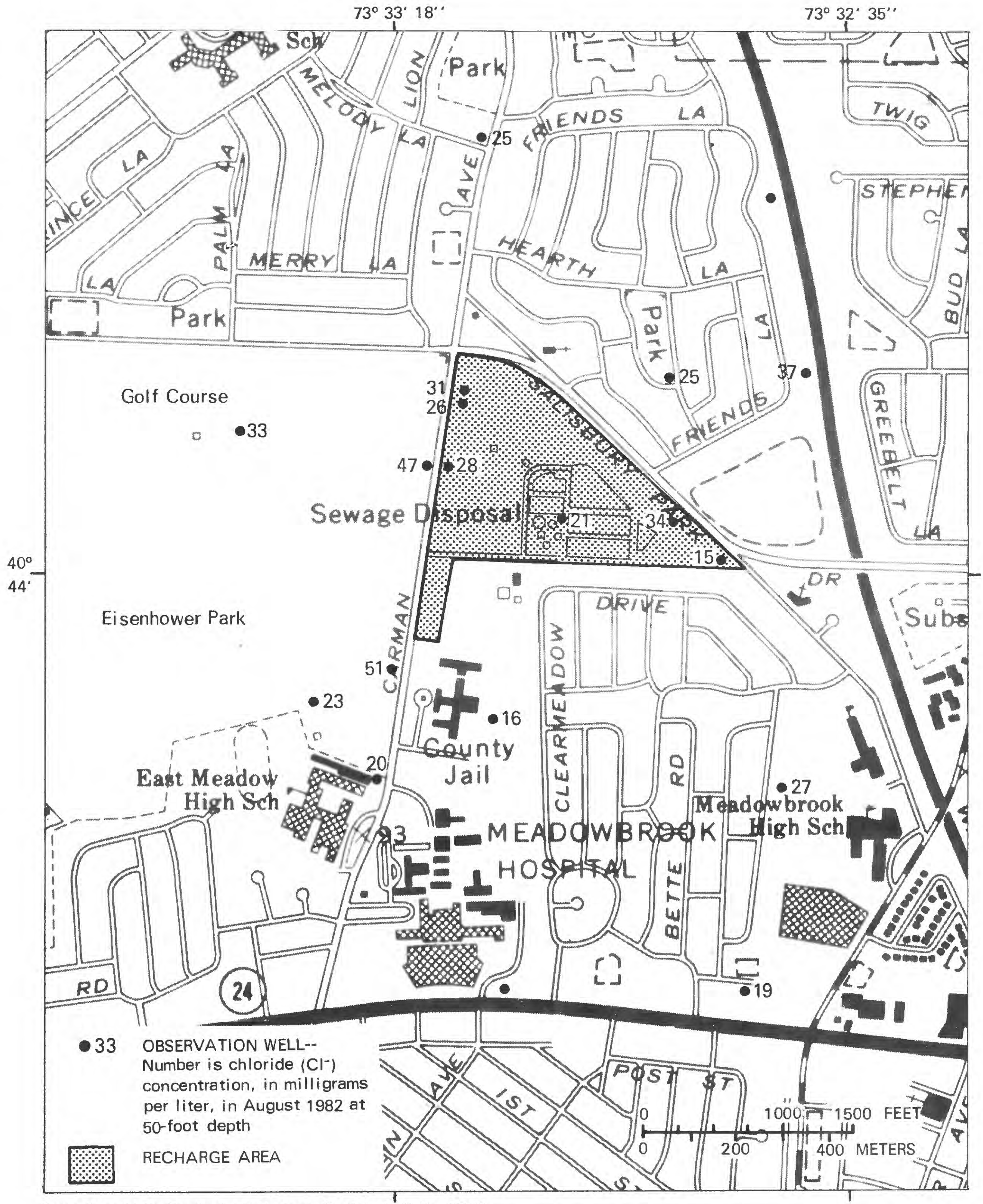
Mixing

The contrast between sodium and chloride concentration in reclaimed water and ambient ground water made them useful as tracers for monitoring the movement and mixing of reclaimed water in the aquifer. The degree of mixing between reclaimed water and ambient ground water can be estimated by methods used by Reeder and others (1976). If the chloride concentration in ambient ground water is approximately 30 mg/L and in reclaimed water is 170 mg/L, the percentage of reclaimed water in samples from observation wells can be calculated from the following simultaneous equations (Reeder and others, 1976):

$$30x + 170y = \text{concentration of mixture, and} \qquad (3)$$

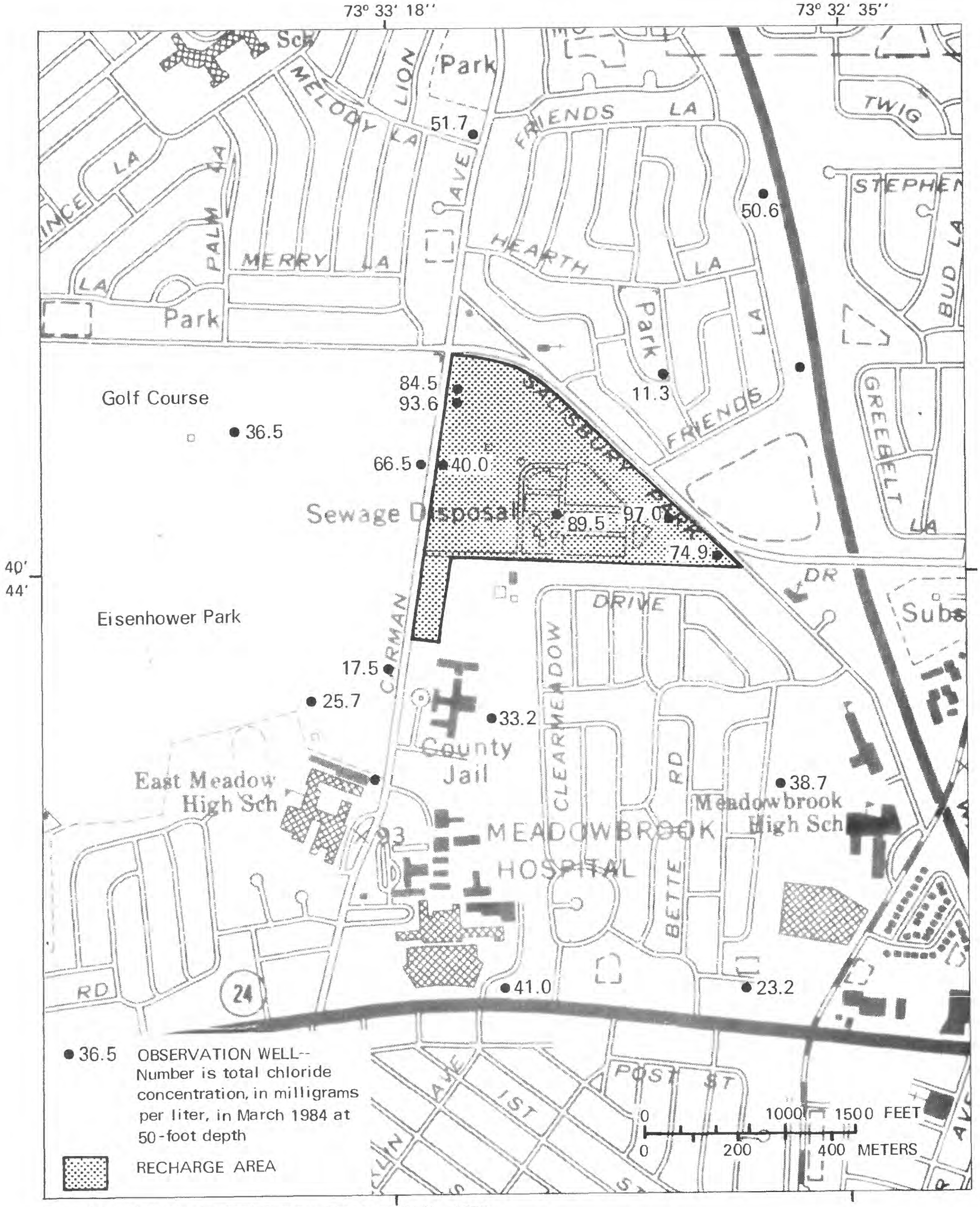
$$x + y = 1 \text{ (100 percent).} \qquad (4)$$

where: 30 is background chloride concentration, in mg/L;
170 is chloride concentration of the injected water, in mg/L;
x is percentage of native water in the sample; and
y is percentage of injection water in the sample.



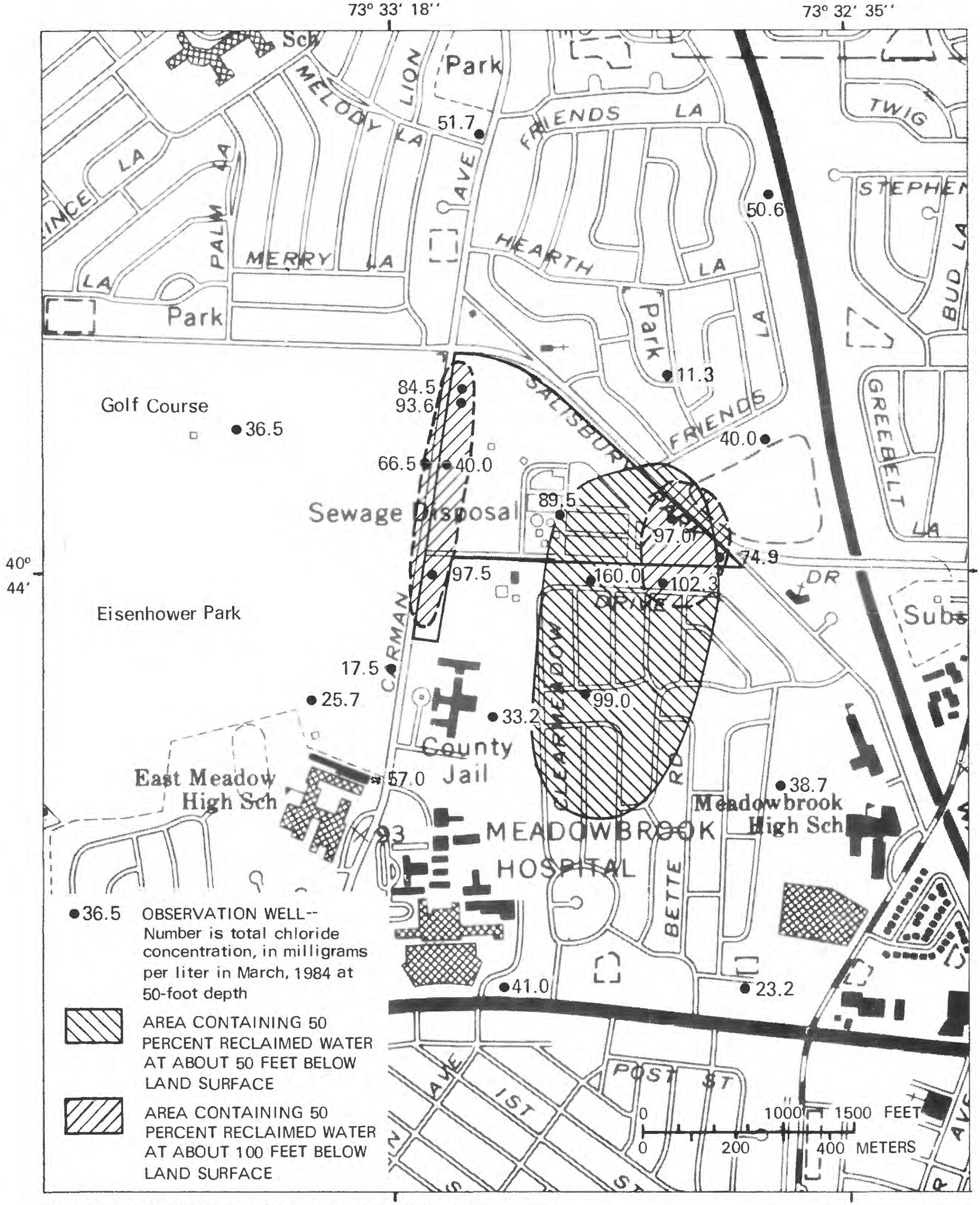
Base from U.S. Geological Survey, Freeport, N.Y., 1979

Figure 34.--Concentration of total chloride as Cl^- in shallow observation wells, August 1982 (before recharge).



Base from U.S. Geological Survey, Freeport, N.Y., 1979

Figure 35.--Concentration of chloride in observation wells, March 1984, 3 months after cessation of recharge.



Base from U.S. Geological Survey, Freeport, N.Y., 1979

Figure 36.--Percentage of reclaimed water in ground-water plume, March 1984, 3 months after cessation of recharge.

The percentage of mixing within the plume in March 1984. approximately 3 months after the cessation of recharge, is shown in figure 36. The solid line shows where the percentage of ground water that consists of reclaimed water is 50 percent at about 50 ft below land surface; the dashed lines show where the percentage is 50 at about 100 ft below land surface. No reclaimed water was detected in the aquifer 200 ft below land surface.

At 100 ft below land surface, the percentage of reclaimed water was 50 percent or greater directly under the recharge basins and in the vicinity of the injection wells. At 50 ft below land surface, the percentage of reclaimed water was 50 percent or greater only beneath and downgradient of the recharge basins. The injection-well screens are between 65 and 95 ft below land surface; thus, the wells inject reclaimed water below the 50-ft depth. Results of synoptic water-quality sampling indicate the plume of reclaimed water to be downgradient (southward) from the recharge site as well as approximately 100 ft below land surface directly beneath the recharge basin area. The plume was also detected in several 50-ft and 100-ft observation wells within 200 ft of either side of the injection wells, which are aligned in a north-south axis.

SUMMARY AND CONCLUSIONS

Aquifer-recharge experiments were conducted on Long Island in an effort to determine the feasibility of large-scale aquifer replenishment with reclaimed water. An advanced wastewater-treatment plant in south-central Nassau County produced a high-quality effluent that was piped to an artificial-recharge site at East Meadow. There, the reclaimed water was returned to the shallow ground-water reservoir through basins and injection wells.

The following conclusions were drawn from this study:

-- Large quantities of water can be transmitted to the upper glacial aquifer through shallow basins and wells. More than 800 million gallons of reclaimed water was returned to the shallow aquifer system at rates that ranged between 250 and 800 gal/min during 341 days of operation.

-- Recharge basins are a more effective means of moving large quantities of reclaimed water into the aquifer than injection wells. Under continuous operation, wells were capable of operating only 30 to 40 days before head buildup required shutdown, whereas basins were operable for up to 5 months before head buildup required shutdown. Clogging was more easily handled in basins than in wells.

-- Ground-water mounding beneath the recharge site produced no detrimental effects on the aquifer system or local community. Maximum mounding measured 6.7 ft beneath the recharge basins and approximately 2 ft in the vicinity of the recharge wells and was confined largely to the immediate area of recharge.

-- Reclaimed water undergoes insignificant chemical alteration as it passes through the unsaturated zone during recharge because (1) the aquifer material is unreactive; (2) the reclaimed water has a short residence time in the unsaturated zone; and (3) the water is highly treated before recharge.

-- The quality of ground water in the aquifer zones affected by recharge was, on the whole, improved from its original condition. Background aquifer concentrations of nitrate nitrogen and several low-molecular-weight hydrocarbons, above drinking-water standards before recharge, were reduced to concentrations well within drinking-water standards as a result of dilution. Sodium and chloride concentrations, although elevated above background levels as a result of recharge, remained well within drinking-water standards and the New York State effluent standards established for this ground-water recharge project.

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