UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

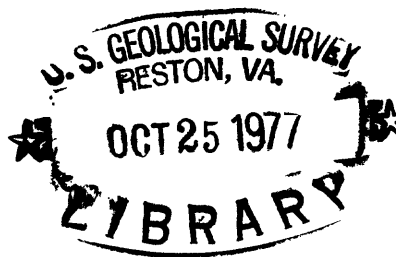PRELIMINARY STUDY OF SOURCES AND PROCESSES

OF ENRICHMENT OF MANGANESE IN WATER FROM

UNIVERSITY OF RHODE ISLAND SUPPLY WELLS

By William D. Silvey and Herbert E. Johnston

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UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

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V. E. McKelvey, Director

CONTENTS

ILLUSTRATIONS

TABLES

FACTORS FOR CONVERTING ENGLISH UNITS TO METRIC UNITS

The following factors may be used to convert English units published herein to metric units.

Multiply English units	By	To obtain metric units
Length		
inches (in)	25.4	millimeters (mm)
	2.54	centimeters (cm)
	.0254	meters (m)
feet (ft)	.3048	meters (m)
miles (mi)	1.609	kilometers (km)
Volume		
gallons (gal)	3.785	liters (L)
	3.785	cubic decimeters (dm^3)
	3.785 x 10^{-3}	cubic meters (m^3)
million gallons (10^6 gal)	3785	cubic meters (m^3)
	3.785 x 10^{-3}	cubic hectometers (hm^3)
cubic feet (ft^3)	28.32	cubic decimeters (dm^3)
	.02832	cubic meters (m^3)
Flow		
gallons per minute (gal/min)	.06309	liters per second (L/s)
	.06309	cubic decimeters per second (dm^3/s)
	6.309 x 10^{-5}	cubic meters per second (m^3/s)
Mass		
ounces	28.3527	grams (gm)
	28.3527 x 10^3	milligrams (mg)
	28.3527 x 10^6	micrograms (µg)
Temperature		
degrees Fahrenheit (°F)	5/9 (°F -32)	degrees Celsius (°C)

PRELIMINARY STUDY OF SOURCES AND PROCESSES OF ENRICHMENT OF MANGANESE IN WATER FROM UNIVERSITY OF RHODE ISLAND SUPPLY WELLS

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ABSTRACT

Concentrations of dissolved manganese in water pumped from two University of Rhode Island supply wells located about 50 feet from Thirty Acre Pond in the Chipuxet River valley in southern Rhode Island began to increase markedly between 1965 and 1967, after having yielded water containing little or no manganese for about 14 years. The wells are about 10 feet apart and are screened at different depths in stratified glacial drift, one from 50 to 70 feet, the other from 111 to 131 feet below land surface. A third well screened from 113 to 138 feet below land surface and located about 280 feet from the pond has yielded water containing little or no manganese since its construction in 1958. Concentrations of dissolved iron in water pumped from all three wells have been generally less than 0.3 milligrams per liter throughout their pumping history.

Field investigations during 1974 and 1975 by the U.S. Geological Survey in cooperation with the Rhode Island Water Resources Board indicate that oxides and other forms of manganese that occur as stains and coatings on aquifer materials may be the most important source of the manganese contained in the well water. Organic-rich sediments on the bottom of the pond and river, through which infiltration is induced when the supply wells are pumped, constitute a significant but seemingly less important source material.

Manganese enrichment in water in the well field seems to be related to the infiltration of surface water through the organic-rich sediments on the bottom of the pond and river. Data from an observation well screened from 3.5 to 5.8 feet below a 1.5-foot layer of organic material in the pond show that highly oxidized water in the pond becomes strongly reduced when passing through the organic sediments. The reduced infiltrate dissolves manganese and iron from aquifer materials and probably also from the lower layers of organic sediments. Concentrations of iron and manganese in the water from this observation well were as high as 40 and 1.2 milligrams per liter, respectively. Because concentrations of manganese were as high as 3.3 milligrams per liter in the deepest supply well, it is assumed that concentrations of manganese must either increase as infiltration moves to greater depths in the aquifer or that greater concentrations are developed beneath other parts of the pond. Also, because the supply wells yield water containing little or no dissolved iron, iron must be removed from solution by precipitation, or some other process, as the infiltrated water moves to greater depths in the aquifer.

Hydrologic analysis indicates that most of the infiltration induced from the pond and from the Chipuxet River which flows through it is diverted to the two supply wells that yield water high in manganese. The low manganese content in water from the well farthest from the pond is attributed to the fact that this well pumps relatively little of the water induced into the aquifer from the pond and river.

INTRODUCTION

This report describes progress during 1974 and 1975 of a study of manganese enrichment of ground water in the University of Rhode Island (URI) well field at Thirty Acre Pond in South Kingstown, Rhode Island (fig. 1). The study was made by the U.S. Geological Survey as part of its cooperative program with the Rhode Island Water Resources Board (RIWRB).

The problem of manganese enrichment is one that has affected water from several heavily pumped industrial and municipal supply wells that tap stratified glacial drift in Rhode Island. Concentrations of manganese in water from most of the affected wells have increased gradually, over a period of months or years, from initial levels typically less than 0.05 mg/L to levels ranging from several tenths to as much as 8 mg/L.

Manganese in water in concentrations that do not cause unpleasant taste is not regarded to be toxicologically significant. However, concentrations in excess of a few tenths of a milligram per liter are undesirable in public supplies and in many industrial supplies. Brown and others (1970, p. 111) note that waters containing manganese in concentrations less than 0.1 mg/L seldom prove troublesome, but that those containing more than 0.5 mg/L may form objectionable deposits on cooked food, laundry, and plumbing fixtures. The U.S. Public Health Service (1962) recommends that the concentrations of manganese in drinking and culinary water not exceed 0.05 mg/L.

Manganese can be removed from water by various methods, but attempts to remove manganese from water pumped from several Rhode Island wells has reportedly been costly and only marginally effective. Several supply wells have been abandoned because of high manganese levels.

At the request of the Rhode Island Water Resources Board, the Geological Survey began a reconnaissance in 1972 to determine whether a detailed investigation of the problem might result in sufficient understanding of the geochemistry of manganese in glacial aquifers to aid in (1) establishing criteria for predicting the occurrence of undesirable concentrations of manganese at potential well sites and, (2) establishing procedures to avoid or control manganese enrichment of water pumped from existing wells. Water samples from 12 municipal and industrial water-supply wells that tap stratified glacial deposits in various parts of the State were collected and analyzed for more than 40 physical and chemical properties, including the concentrations of total organic carbon, heavy metals, and pesticides (U.S. Geological Survey, 1975a). Analysis of these data suggested that infiltration of surface water, especially organically enriched streamflow, into the stratified drift might be a factor involved in manganese enrichment of ground-water supplies. It was concluded that further study of the problem would probably yield results of practical significance to ground-water users.

In March 1974, a study plan was outlined to test the following hypotheses regarding the routes and mechanisms for manganese enrichment in water from heavily pumped wells:

1. Manganese deposited in streambeds is dissolved either by (a) bacterial decomposition of associated organic matter, or (b) reduction of manganese oxide, and is carried into ground-water bodies by infiltrating water from the stream when the water table is lowered by pumping.
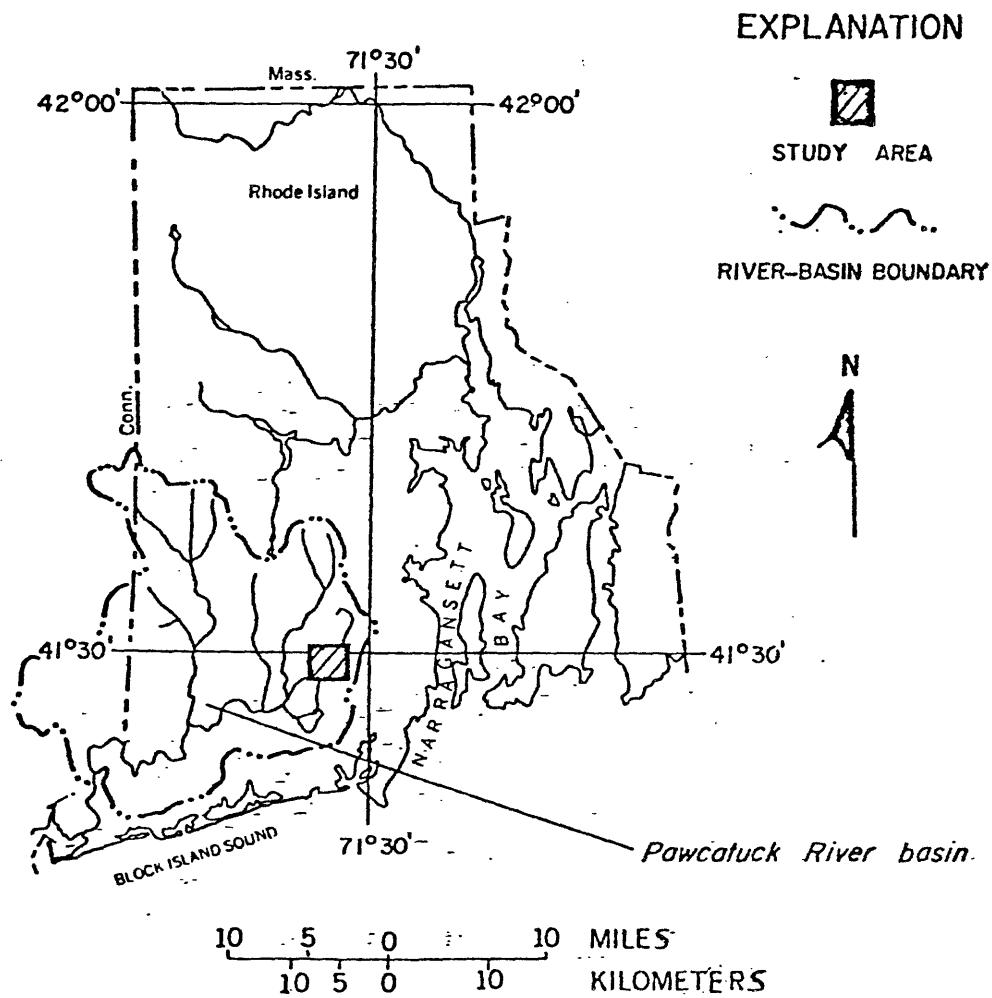
Figure 1.--Map showing location of the study area.

2. Manganese oxide coatings and other forms of manganese on surfaces of aquifer sand and gravel are dissolved when a reducing environment results from decomposition of organic matter that has been carried into the aquifer by infiltrating water.

3. Seasonal or discharge-related peaks of dissolved manganese in streamflow provide a source of high manganese concentrations in the infiltrated water after attenuation by movement at differing rates toward pumped wells.

4. Water high in manganese content in the local bedrock is induced to move toward wells in stratified drift by the alteration of flow paths resulting from pumping.

During the spring and summer of 1974, before formal study of the problem began at the URI well field, chemical analyses were made of water samples taken from 15 RIWRB test wells drilled in sand and gravel aquifers in the Chipuxet, Beaver, and Wood River subbasins of the Pawcatuck River basin. Eight of the samples were taken from wells in areas of natural ground-water flow, seven from wells within the cone of influence of the URI supply wells. These data are published in U.S. Geological Survey (1975b); data for the wells near the URI well field are also given in table 2 of this report.

The University of Rhode Island well field was selected for study as part of an on-going USGS-RIWRB cooperative ground-water investigation in the Pawcatuck River basin. The primary objective of the study was to determine the source of manganese in water pumped from supply wells; a secondary objective was to provide a preliminary evaluation of the physiochemical factors responsible for the gradual enrichment of manganese in the well water. To accomplish these objectives the following steps were taken: (1) the ground-water-flow pattern resulting from cyclic pumping of supply wells was approximated, (2) sediment samples collected from the bottom of Thirty Acre Pond, from the Chipuxet River, and from the swampy flood plain of the river were analyzed for iron and manganese content, (3) sediment samples obtained from several depths in test wells drilled near the supply wells in the spring of 1974 were also analyzed for iron and manganese content, and (4) water samples collected periodically from the pond, two supply wells, and five observation wells screened at different places in the ground-water system were analyzed for iron, manganese, and several other key properties and constituents, including dissolved oxygen and nitrogen species.

At the time of this study (1974-75), the University was being supplied with water from two large-diameter gravel-packed wells identified by USGS numbers for the Town of South Kingstown as SNW 92 and SNW 888. The wells are screened at the respective depths below land surface of 111-131 feet and 113-138 feet. A third, unused supply well, SNW 138, about 10 feet from well SNW 92, is screened from 50 to 70 feet below land surface. Wells SNW 92 and SNW 888 were constructed in 1949 and 1958, respectively, and have been in more or less continuous operation since. Supply well SNW 138 was pumped from the time of its construction, 1948, until 1971. A fourth supply well, SNW 1151, which is screened from 75 to 95 feet below land surface, was drilled in 1974 at the site of test well SNW 1133 (fig. 6). When this well is put into service in 1977, well SNW 92 will be put in standby status.

Water-quality data with which to document the history of manganese enrichment in water from the University well field are available principally from 1960. These data, obtained chiefly from the files of the Rhode Island Department of Health, are published in a report by Dickerman (1976). University maintenance personnel and others acquainted with the University water-supply system report that the well water was essentially free of manganese before 1960. A U.S. Geological Survey analysis of a water sample taken from well SNW 92 in February 1954 shows values for iron and manganese of 0.11 and 0.02 mg/L, respectively. In the mid-1960's, however, concentrations of manganese climbed to troublesome levels in water from wells SNW 92 and SNW 138 (fig. 2). Concentrations of manganese in water from supply well SNW 888 have remained anomalously low during most of its pumping history. Only two out of 31 samples from this well have exceeded 0.2 mg/L, one collected in 1960, the other in 1975.

Concentrations of dissolved iron have been low in nearly all samples collected from supply wells SNW 92, SNW 138, and SNW 888. The iron content of 31 out of 32 water samples collected from well SNW 92 since 1954 has been within the range of 0.00 to 0.35 mg/L. One sample collected in 1962 contained 0.8 mg/L. The iron content of eight out of nine samples of water collected from well SNW 138 between 1963 and 1971 ranged between 0.03 and 0.24 mg/L, whereas one sample taken in 1971 contained 0.9 mg/L. The iron content of one sample of water taken from well SNW 888 in 1960 was a rather high, 2.0 mg/L, but the content of 30 samples taken since then has ranged between 0.00 and 0.15 mg/L.

Pumping from the well field was not metered until 1973. Estimates of total annual pumpage available in USGS files for several years before 1973, together with records of metered pumpage, are listed below.

Year	Pumpage, in millions of gallons
1953	54
1954	no record
1955	100
1956	91
1957	94
1958	91
1959	85
1960	113
1961	70
1962	131
1963-72	no record
1973	239 (3 months estimated)
1974	212
1975	232

During this study, supply wells SNW 92 and SNW 888 were generally pumped several hours each day from 350 to 450 gal/min. Monthly pumpage from the wells is shown in figure 3. Variations in pumpage from month to month result chiefly from variations in student population.
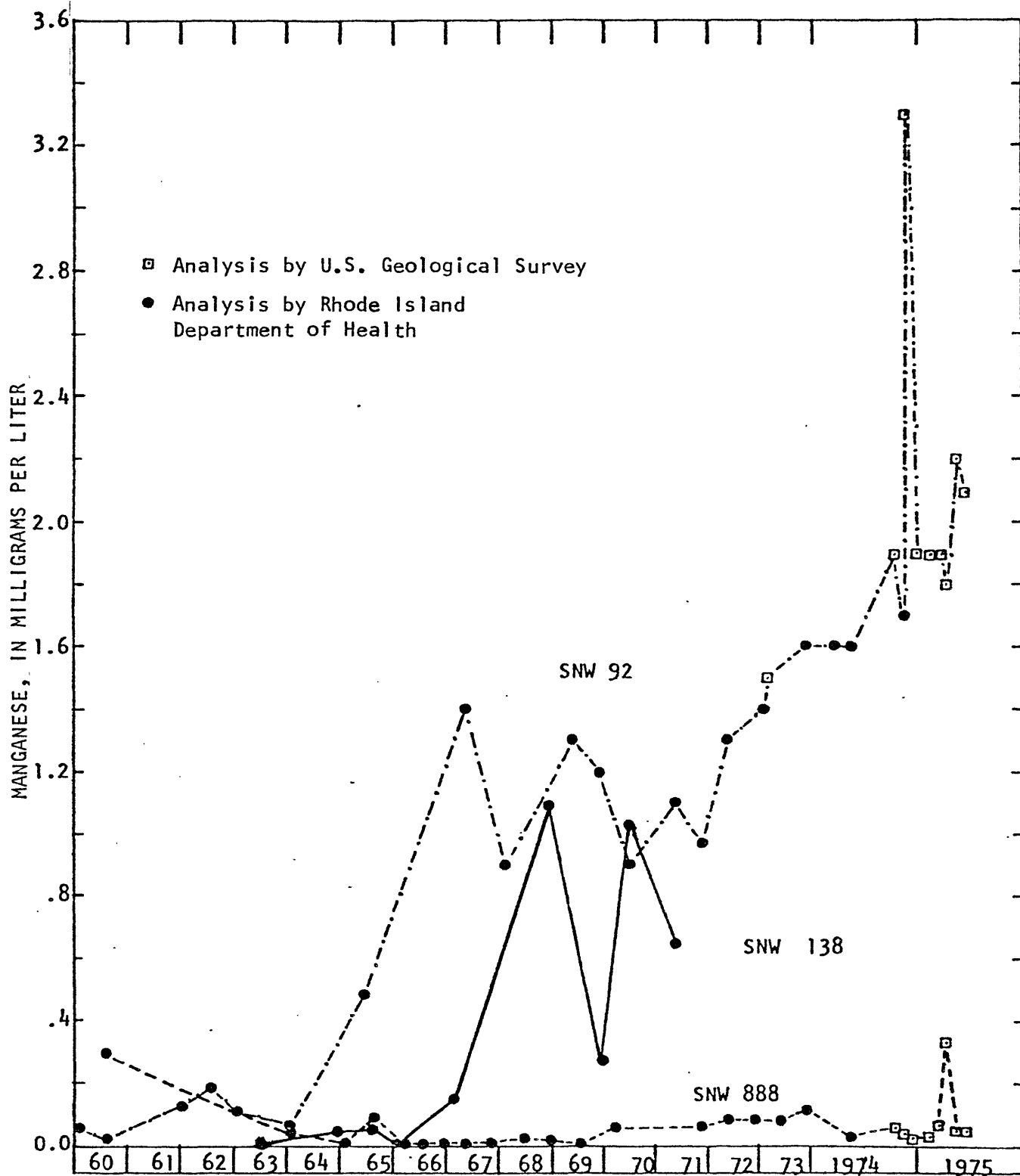
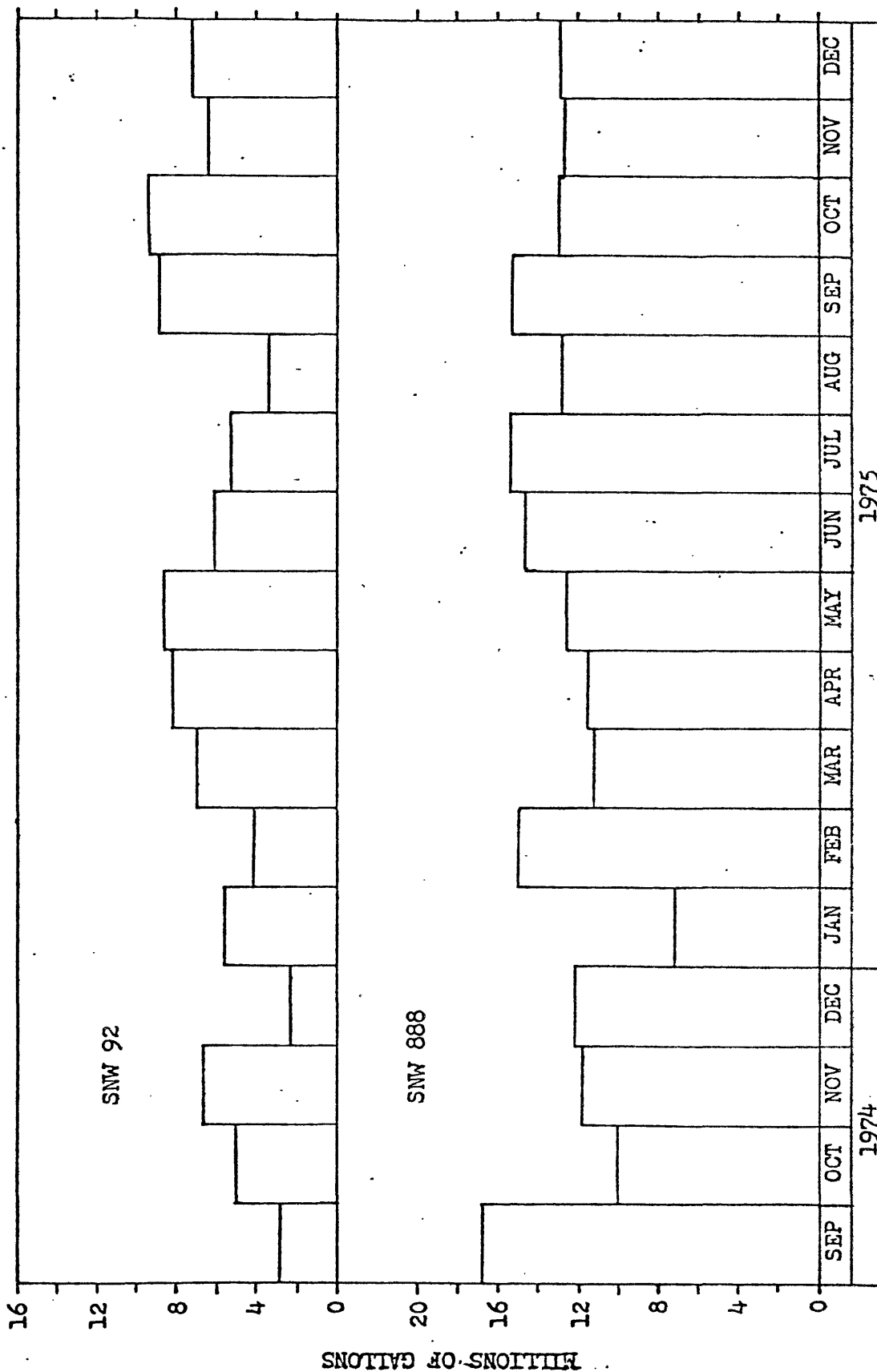Figure 2.-Manganese content of water from University supply wells during 1960-75.

Figure 3.—Monthly pumpage from University supply wells during 1974-75.

GEOHYDROLOGIC FRAMEWORK AND GROUND-WATER FLOW

. Supply wells in the URI well field tap stratified drift, which partly fills and conceals a narrow bedrock channel in the Chipuxet River valley. The drift strata are lenticular and interbedded. A lenticular body of coarse sand and gravel in the lower part of the drift is separated from overlying coarse sediments by a zone of fine-grained sediments of variable thickness. Bedrock underlying the drift is mapped as granite gneiss, which is composed chiefly of quartz, feldspar, and minor amounts of biotite (Moore, 1964). The drift is derived largely from rocks of similar granitic composition.

The drift is recharged by direct infiltration of precipitation and, to a lesser extent, by subsurface inflow from till and bedrock. Most of the subsurface inflow probably occurs near the edge of the drift. The hydraulic conductivity of the bedrock is relatively low, and it is unlikely that substantial amounts of water move from the bedrock into the drift immediately beneath the URI well field.

The hydraulic characteristics of the drift in the vicinity of the URI well field are known from analyses of data from an aquifer test during which well SNW 1133 was pumped. (See fig. 6 for location.) Computed values for storage coefficient suggest that confined conditions exist in the lower part of the aquifer. On the other hand, the occurrence of drawdown in observation wells screened in the top of the drift within a few minutes after pumping began indicates an unconfined system and that there are large differences between vertical and lateral hydraulic conductivity.

Transmissivity of the aquifer in the well field was computed to be 25,800 ft^2/day (cubic feet per foot per day) using methods described in Ferris and others, 1962. Lateral hydraulic conductivity, obtained by dividing transmissivity by the 15-foot screened interval in the pumped well (SNW 1133), is 1,720 ft/day. The coefficient of vertical leakage, which is the ratio of vertical hydraulic conductivity to the thickness of the strata through which flow is vertical, was computed to be 0.0114 ft/day/ft. Taking the thickness through which flow is essentially vertical as the 60 feet of saturated sediment over the well screen in well SNW 1133, gives a value for vertical hydraulic conductivity of 0.7 ft/day. Hydraulic conductivity, thus, is as much as 2,500 times greater horizontally than vertically.

Note that the value for lateral hydraulic conductivity probably represents a maximum for the coarse-grained sediments. The lateral hydraulic conductivities of beds of clay, silt, and fine, silty sand are much lower, and lateral movement of water through these materials under the same hydraulic gradient will be much slower. Also, the vertical leakage coefficient is an average value for the entire well field. The leakance value probably varies considerably from place to place within the well field, owing to considerable variations in the thickness of layers of clay, silt, and fine, silty sand, which offer the greatest impedence to vertical flow.

Under natural conditions, water in the vicinity of the URI well field flows continuously from the stratified drift into Thirty Acre Pond and the Chipuxet River. When wells are pumped, however, some of the potential discharge to the pond and river is diverted to wells, and, if pumping continues long enough, infiltration is induced into the stratified drift from the pond and river.

Observations made during the aquifer test on well SNW 1133 indicate that the cone of pumping influence spreads laterally in the lower part of the aquifer more than 1,000 feet within a few minutes after pumping starts, extending beneath the pond and river as well as beneath adjacent land areas. Time-drawdown graphs for shallow observation wells, two of which were driven through the pond bottom, indicate that water also begins to move vertically from the water table, pond, and river toward the stratigraphic zone in which the pumping wells are screened within a few minutes after pumping starts. It was also observed that water levels in deep observation wells begin to stabilize about 6 hours after pumping starts and are essentially stable after 24 hours. Once the steady-state condition is reached, removal of water from the strata screened by pumping wells is approximately balanced by vertical leakage through the overlying strata from the water table, pond, and river.

The pattern of ground-water flow resulting from the cyclic pumping from the two supply wells during the period of this study was determined by semi-quantitative methods. Total pumpage from each of the supply wells was assumed to have been withdrawn continuously, or, at an average rate of 118 gal/min from well SNW 92 and 255 gal/min from well SNW 888. An elliptical pattern of nearly steady-state drawdown observed in several observation wells while well SNW 888 was pumping at 500 gal/min was adjusted for a pumping rate of 225 gal/min. The same pattern of drawdown, adjusted for a pumping rate of 118 gal/min, was superimposed on well SNW 92. The combined drawdown resulting from the overlapping cones gave the pattern shown in figure 4. The approximation of average drawdown indicates that most of the infiltration from the pond and river is diverted to supply well SNW 92 and that most of the water reaching well SNW 888 is ground water that was moving from the aquifer to the pond and river.

Flow along selected paths in the vertical dimension, in response to pumping, is illustrated schematically in figure 5. Actual flow paths are likely to be more tortuous than those shown, owing to cyclic pumping and to abrupt changes in vertical and lateral hydraulic conductivity in different parts of the stratified-drift aquifer. The indicated travel times for water to move from the water table or from the bottom of the pond to well intakes are based on computations using aquifer coefficients given previously and hydraulic gradients determined from figure 4. However, the travel times should be considered merely as crude approximations. They are provided to demonstrate that infiltrated surface water reaching a well intake at any given instant will consist of molecules of water that have entered the aquifer through the soil or through the pond and river bottom over a considerable period of time. The quality of water reaching supply-well intakes, therefore, will be intermediate between extremes in quality in the pond and river or in different parts of the aquifer.

IRON AND MANGANESE CONTENT OF SEDIMENT SAMPLES

Samples of organic sediment were collected in December 1975 from the bottom of Thirty Acre Pond and the Chipuxet River and from the swampy flood plain of the river near supply well SNW 888. Samples of aquifer material from different depths in 2-1/2-inch diameter test wells drilled by the drive and wash method in the spring of 1974 were also obtained. These were analyzed in the laboratory by an acid-leach method to

Figure 4.--Approximate drawdown and pattern of flow that would occur in the lower part of the aquifer if total pumpage from SNW 92 and SNW 888 from October 1974 to December 1975 were withdrawn continuously at 118 and 255 gal/min, respectively. Stippled area is approximate area through which vertical flow is diverted to SNW 92.

Figure 5.—Section showing idealized ground-water flow paths and approximate travel times required for particles of recharge to flow vertically from the water table or pond bottom to the zone of horizontal flow and then laterally to well intakes, under conditions shown in figure 4.

determine their iron and manganese content. The locations of the sampling sites are shown on figure 6, and results of the analyses are given in table 1.

The data indicate that substantial quantities of iron and manganese are contained in both the organic sediments and aquifer materials. They show also that iron is much more abundant than manganese. The concentration of iron averages more than 25 times as great as the concentration of manganese in both the organic and aquifer sediments. The concentrations of iron and manganese are three times as great in the organic sediments as in aquifer materials, but the apparent quantities of iron and manganese contained in the aquifer are much greater owing to its much larger volume.

It is estimated that infiltration occurs through a pond and river area of about 13 acres. The infiltrated water enroute to well SNW 92 passes through a thickness of organic-rich sediment of about 1.5 feet and an aquifer thickness of about 100 feet. The volume of organic sediment through which infiltration passes is, thus, about 8.5×10^5 ft^3, whereas the aquifer volume is roughly 566×10^5 ft^3, or more than 65 times as great.

Assuming a bulk density of 1.2 gm/cm^3 (grams per cubic centimeter) for the organic-rich sediment (the sediment is 80 to 85 percent water, by weight), the mass of the sediment is calculated to be 1.2 gm/cm^3 $\times$ 2.41 $\times$ 10^{10} cm^3 = 2.892×10^{10} gm. Taking the average manganese concentration of the sediment to be the average of the values given in table 1, or 161 µg/g (1.61×10^{-4} gm/gm), the manganese content of the organic-rich sediment through which infiltration passes to well SNW 92 is 2.892×10^{10} gm $\times$ 1.61×10^{-4} gm/gm = 46.56×10^5 gm.

Similarly, if a bulk density of 1.6 gm/cm^3 is assumed for aquifer sediment, the mass of this sediment is calculated to be 1.7 gm/cm^3 $\times$ 160×10^{10} cm^3 = 256×10^{10} gm. Taking the average manganese concentration of the sediment to be the average of the values given in table 1, or 50 µg/g (5×10^{-5} gm/gm), the manganese content of the aquifer sediment through which infiltration passes to well SNW 92 is 256×10^{10} gm $\times$ 5×10^{-5} gm/gm = $1,280 \times 10^5$ gm, or about 28 times more than the manganese content of the organic-rich sediment.

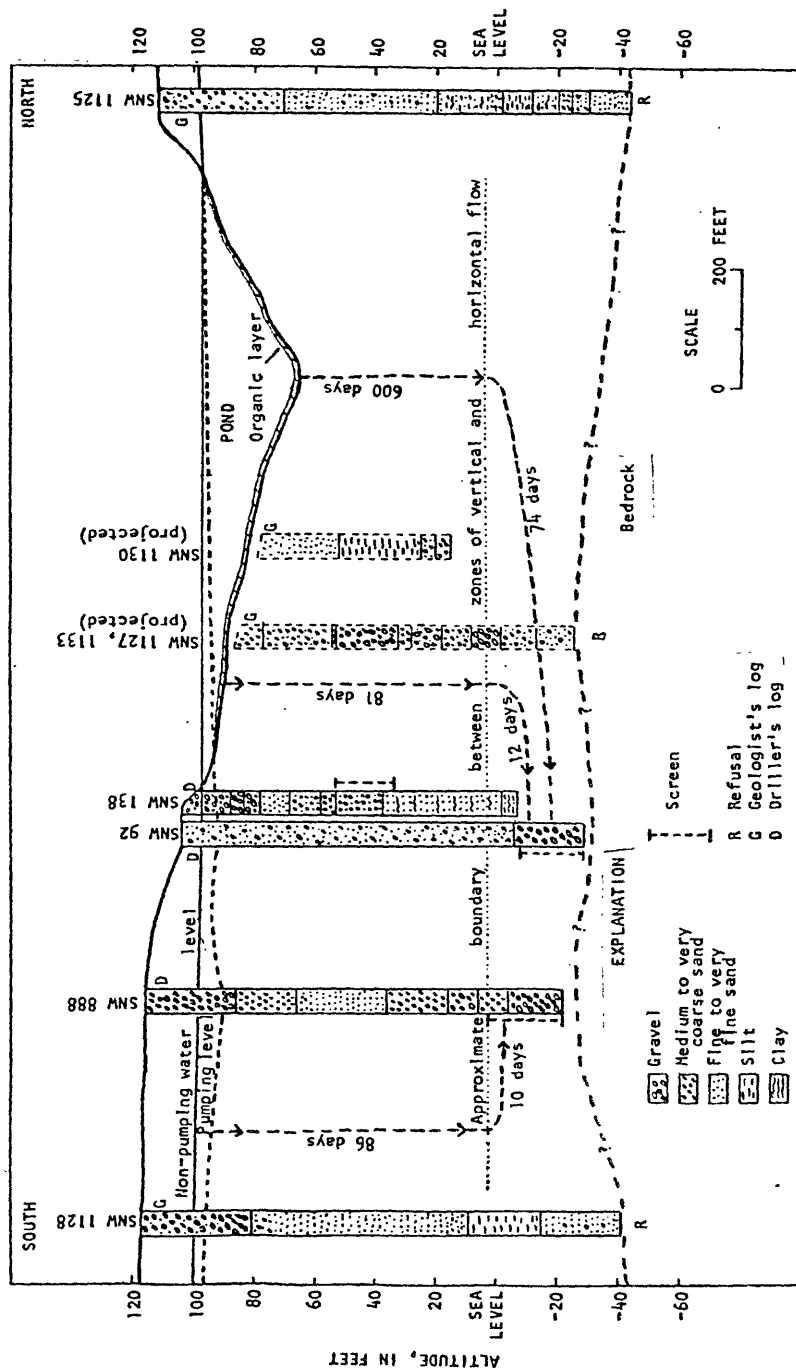During this study, annual pumpage from well SNW 92 was about 231×10^6 liters, and the water had a manganese content of about 2 mg/L. The manganese content of the water pumped from this well during 1 year was then 231×10^6 L $\times$ 2 mg/L = 462×10^6 mg, or 4.62×10^5 gm.

For perspective, a manganese removal rate of 4.62×10^5 gm per year could be sustained by the organic-rich sediment for about 10 years (assuming no additional accumulation during this period), whereas, the same rate of removal could be sustained by the aquifer sediment for nearly 300 years.

COLLECTION AND ANALYSES OF WATER SAMPLES

The locations of wells sampled for this study are shown on figure 6. Lithologic logs and the altitudes of the screened intervals of these wells are shown in figure 7. Chemical analyses of the water are summarized in table 2; analyses of individual samples are given in tables 3 and 4. The data include analyses of water from several test wells drilled in the well field during the spring and summer of 1974.

N

EXPLANATION

○   ●

Shallow Well   Deep well
and number   and number
(SNW prefix omitted. Circled
wells sampled periodically)

■

Sediment Sampling Site

Thirty Acre
Pond

1135

1149   A   B   D   1130

92   1127, 1133

E

1148

F   C

888

1132   1150

1131, 1137

River

Chips

1141

1128

ROAD

PLAINS

SCALE
0   500 FEET

Figure 6.--Map of University well field showing location of sampling sites.

Table 1.--Iron and manganese content of sediment samples from
the aquifer, swamp deposit, pond bottom, and river bottom
(See figure 6 for location of sampling sites.)

Sampling site	Date collected	Depth of sample[1] (feet)	Material	Iron (µg/g)	Man-gan-ese (µg/g)
Aquifer samples from 2-1/2-inch diameter drive-wash wells					
SNW 1127	5- 5-74	61-68	Fine to very fine sand; some silt; trace of clay; light brown	2,300	101
SNW 1127	5- 5-74	136-142	Fine to very fine sand; little medium sand; light brown	2,300	65
SNW 1128	5- 8-74	142-147	Fine to very fine sand; little silt and clay; light brown	1,700	64
SNW 1130	5- 7-74	72-78	Silt; some clay; little fine sand; gray-brown	1,100	53
SNW 1130	5- 7-74	99-104	Medium to coarse sand; little fine sand; light brown	550	19
SNW 1131	5- 7-74	11-16	Fine to coarse sand and gravel; light brown	2,000	47
SNW 1131	5- 7-74	42-47	Fine to very fine sand; little silt; light brown	490	28
SNW 1131	5- 7-74	120-125	Medium to coarse sand; little fine to very fine sand and silt; light gray	790	19
Pond bottom, river bottom, and swamp deposit samples					
A Pond	12-12-75	2.0-2.6	Silty, organic muck and partly decomposed vegetation	4,000	180
B Pond	12-12-75	.6-2.4	do.	4,300	41
C Swamp	12-12-75	1.3-2.1	Sandy, organic muck	4,300	24
D Pond	12-12-75	.8-1.2	Sand and gravel	1,500	33
E Pond	12-12-75	3.0-3.7	Silty, organic muck and partly decomposed vegetation	6,900	130
F River	12-12-75	3.4-4.4	do.	8,300	560

[1]Depths of samples from the wells and from the swamp were measured from land surface. Depths of samples from the pond and from the river bottom indicate depth to the top and bottom of organic sediment layer below water surface.

Figure 7.--Lithologic logs of wells referred to in text.

Table 2.—Summary of surface-water and ground-water-quality data in the University of Rhode Island well field

(Analyses by U.S. Geological Survey except SNW 1129 which was done by Rhode Island Department of Health. Values are in milligrams per liter, except as indicated.)

Range of values for samples collected periodically October 1974-December 1975

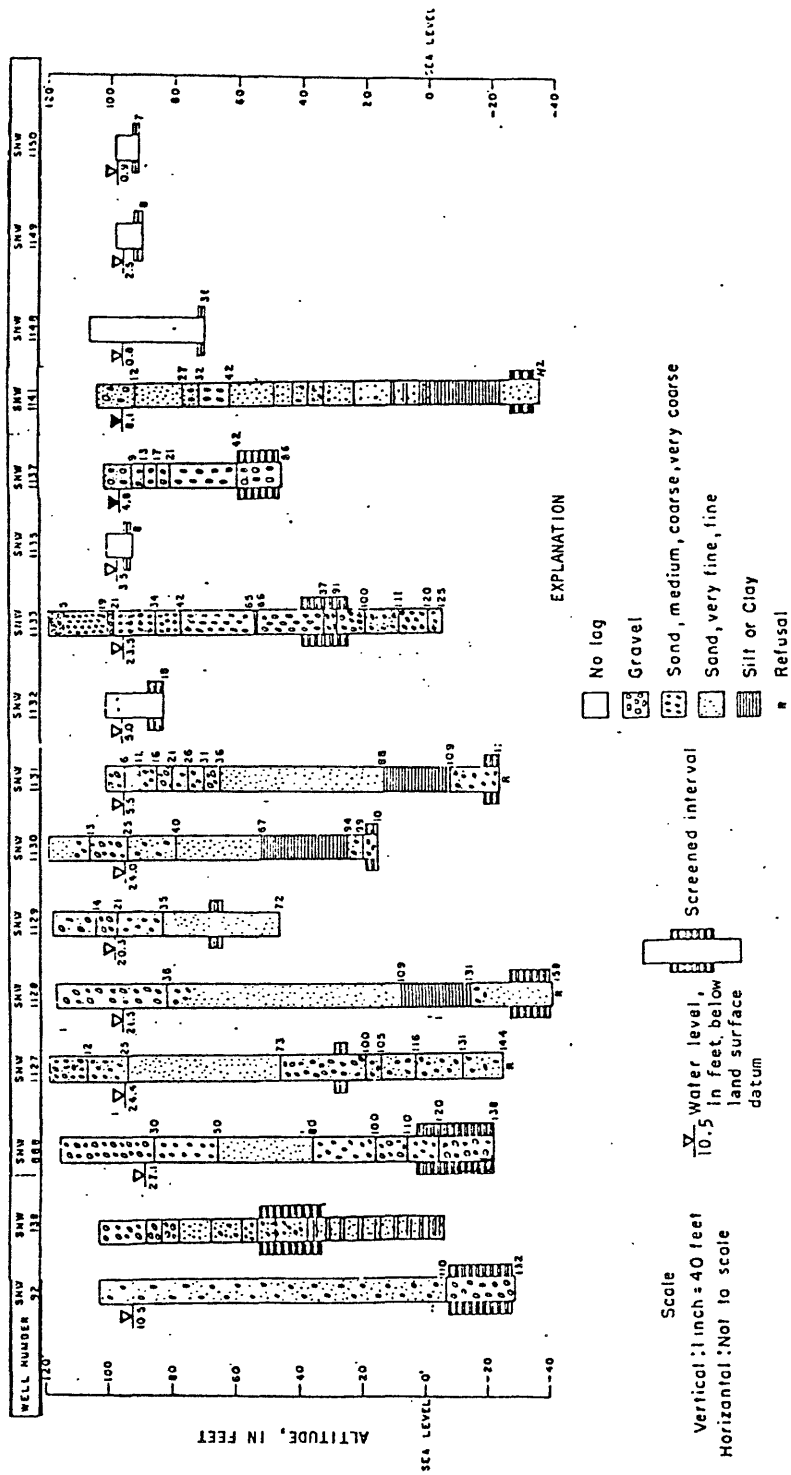| Well no.	Altitude of screen, in feet, above or below mean sea level	Number of analyses	Dissolved Iron	Dissolved Manganese	Alkalinity (as $CaCO_3$)	Total Chloride	Total Nitrite (as N)	Total Nitrate (as N)	Total Nitrogen (as N)	Total Kjeldahl Nitrogen (as N)	Total Organic Carbon	Specific conductance (micromhos per centimeter at 25°C)	Dissolved oxygen	pH (units)	Temperature (°C)
POND		7	0.06-0.28	0.02-0.1	0-17	11-14	0.00-0.01	0.17-0.47	0.50-1.0	0.08-0.57	2.3-14	79-104	7.2-12.4	6.0-7.2	1-26.5
SNW 92	-8 to-28	11	.25-.35	1.8-3.3	10-17	9.4-16	.00-.01	.15-.64	.18-.76	.00-.17	.0-13	99-127	.5-2.8	5.7-6.2	10-10.5
SNW 888	3 to-22	11	.01-.11	.03-.34	20-23	12-42	.00-.01	1.4-1.8	1.4-2.1	.00-.27	.0-16	128-158	2.5-4.4	5.8-6.5	10.5-11
SNW 1128	-27 to-40	9	.15-3.0	.02-.25	25-39	14-23	.00-.02	.77-1.0	.91-1.5	.00-.63	.0-2.9	150-187	.7-2.9	5.9-6.6	8-11
SNW 1135	95 to 93	11	.06-.75	.03-.18	6-12	11-18	.00-.01	.01-.60	.01-1.0	.00-.96	1.3-14	81-175	1.6-9.1	5.7-6.1	5-25
SNW 1148	72 to 70	11	.0 -.05	.03-.14	7-10	13-19	.00-.01	3.8-5.2	4.1-5.4	.00-.52	.0-14	165-200	2.6-6.6	5.3-5.7	10.3-10.5
SNW 1149	92 to 90	11	22 -40	.64-1.2	51-128	8.8-15	.00-.01	.00-.03	.63-1.1	.54-1.1	2.0-16	132-225	.0-1.6	6.1-7.1	8-17.5
SNW 1150	93 to 91	11	.0 -.12	.0 -.10	5-9	11-19	.00-.01	2.3-6.6	2.5-7.0	.05-.52	.0-9.4	122-165	3.7-6.7	5.3-5.8	8-13.5

Values for individual samples collected from exploratory wells during April-June 1974

Well no.	Altitude of screen, in feet, above or below mean sea level	Number of analyses	Dissolved Iron	Dissolved Manganese	Alkalinity (as $CaCO_3$)	Total Chloride	Total Nitrite (as N)	Total Nitrate (as N)	Total Nitrogen (as N)	Total Kjeldahl Nitrogen (as N)	Total Organic Carbon	Specific conductance (micromhos per centimeter at 25°C)	Dissolved oxygen	pH (units)	Temperature (°C)
SNW 1127	29 to 25	1	.13	.02	38	9.0	.01	1.5	1.5	.02	1.5	141	2.4	6.6	10.5
SNW 1129	68 to 64	1	.31	.02	8	8	--	6.6	-	-	--	185	--	--	10.5
SNW 1130	19 to 15	1	.20	.14	31	8.5	.07	1.3	1.6	.24	--	117	3.1	6.7	11.0
SNW 1131	-19 to-24	1	.18	.38	28	5.2	.01	.00	.05	.05	5.7	90	2.7	6.3	11.0
SNW 1132	88 to 83	1	.01	.04	5.5	14	.01	3.7	3.7	.00	1.8	170	10.5	5.5	9.0
SNW 1133	39 to 24	1	0	.02	25	17	.01	1.8	1.9	.05	.6	152	3.1	6.1	10.5
SNW 1137	60 to 47	1	.05	.03	7.5	12	.01	3.2	3.3	.08	1.6	180	7.7	5.5	9.5
SNW 1141	-28 to-36	1	.14	.39	29	7.5	.01	.03	.1	.06	2.1	88	.3	6.8	10.5

Table 3.--Chemical analyses of water samples from wells and Thirty Acre Pond

Concentrations in milligrams per liter except as indicated.

(Abbreviations: ND, not determined. Method: C, centrifugal pump; P, pitcher pump; T, turbine pump. Dissolved Oxygen: M, meter value; T, titration value (modified Winkler process), values of titration in well SNW 1149 may be in error owing to intereffects of high ferrous iron content of water.)

		Sample collection				Field analyses					U.S. Geological Survey laboratory analyses									
Date	Time	Depth to water (feet)	Method	Pumping rate (gal/min)	Duration (hours)	Temperature (°C)	Specific conductance (micromhos per centimeter at 25°C)	pH (units)	Alkalinity (as $CaCO_3$)	Dissolved Oxygen	Total Chloride (Cl)	Total Organic Carbon	Total Nitrite (as NO_2)	Total Nitrate (as NO_3)	Total Nitrogen (as N)	Total Nitrogen (as NO_3)	Total Kjeldahl Nitrogen (as N)	Total Nitrite plus Nitrate (as N)	Dissolved Iron (µg/L) (1 mg/L = 1,000 µg/L)	Dissolved Manganese (µg/L) (1 mg/L = 1,000 µg/L)
Well SNW 92																				
1-31-73	--	--	T	--	--	10.4	132	6.50	--	2.3	11	--	--	--	--	3.6	--	--	90	1,500
10- 8-74	1450	--	T	350	--	10.2	107	6.1	13	2.2 T	16	0.0	0.00	0.44	0.49	2.2	0.05	0.44	260	1,900
11-15-74	1015	--	T	320	--	10.3	108	5.85	17	2.8 M	10	.6	.00	.59	.71	3.1	.12	.59	250	3,300
12-30-74	0905	8.79	T	390	1	10.5	114	5.95	17	2.15T	24	.3	.00	.59	.76	3.4	.17	.59	300	1,900
2- 4-75	1100	8.58	T	410	3	10	104	5.95	12.5	1.85T	11	.5	.00	.34	.39	1.7	.05	.34	290	1,900
3- 7-75	0925	8.61	T	420	11	10.5	127	5.7	13.5	2.25T	12	.9	.00	.47	.50	2.2	.03	.47	310	1,900
4- 3-75	1031	8.61	T	420	50	10	123	5.9	14	2.2 T	12	.4	.00	.64	.75	3.3	.11	.64	310	1,800
5-12-75	0915	8.80	T	410	2.5	10	116	6.0	14	.5 T	9.4	13	--	.18	.18	.80	.00	.18	320	2,200
6-12-75	0915	8.50	T	390	1.5	10	99	5.85	12.5	1.5 T	10	7.9	.01	.27	.28	1.2	.00	.28	340	2,100
7-23-75	0940	9.86	T	450	1.5	10	108	6.2	15	1.1 M	10	1.4	.00	.15	.20	.89	.05	.15	310	2,200
9-10-75	1145	9.49	T	405	6	10	117	5.8	15	2.3 T	--	13	.00	.31	.40	1.8	.09	.31	--	--
12-16-75	0845	8.47	T	390	2	10.2	118	5.8	10.5	1.6 T	9.9	.3	.00	.24	.25	1.1	.01	.24	350	2,500
Well SNW 888																				
10- 9-74	1100	--	T	420	--	10.5	132	6.3	23	3.6 T	42	.5	.00	1.7	1.7	7.7	.04	1.7	40	60
11-15-74	1500	--	T	360	--	10.5	133	6.0	23	4.4 M	14	.1	.00	1.8-	2.1	9.2	.27	1.8	10	40
12-26-74	1115	22.56	T	340	2	10.5	140	5.8	21	3.1 T	12	.5	.01	1.4	1.4	6.2	.01	1.4	110	30
2- 4-74	1000	22.37	T	420	84	11	144	6.15	22.5	3.2 T	16	1.7	.00	1.6	1.7	7.5	.09	1.6	30	30
3- 7-75	1020	22.32	T	325	23.5	11	158	6.15	22	3.3 T	15	.2	.00	1.6	1.6	7.2	.02	1.6	20	70
4- 3-75	1230	--	T	380	5.5	10.5	142	6.1	21	3.5 T	15	1.4	.00	1.6	1.7	7.4	.08	1.6	20	340
5-12-75	1100	22.45	T	410	38	11	148	6.4	21.5	3.2 T	14	16.	--	--	1.7	7.5	.00	1.7	10	50
6-12-75	1000	22.29	T	360	67	11	128	6.3	21	3.3 T	14	7.6	.01	1.8	1.8	8.0	.00	1.8	20	50
7-22-75	1515	22.62	T	450	27	11	132	6.5	23	2.5 M	14	4.8	.01	1.6	1.7	7.7	.13	1.6	10	50
9-10-75	1430	--	T	400	5	10.5	144	6.5	24	3.5 T	14·	-7.6	.01	1.6	1.7	7.7	.14	1.6	--	--
12-16-75	1020	--	T	400	3	10.8	149	6.0	20.5	3.4 T	14	.0	.00	1.6	1.6	7.1	.01	1.6	20	100
Well SNW 1128																				
5-30-74	1000	--	P	2	.5	10.2	187	6.60	37	1.1 M	16	ND	.02	.98	1.1	4.7	.06	1.0	1,500	250
10- 9-74	0900	--	C	30	4	10.5	140	6.2	28.5	1.9T 1.8M	18	.6	.00	.94	.95	4.2	.01	.94	150	30
11-18-74	1045	--	P	3	.5	10.5	138	6.4	37	.7 T	16	2.9	.00	1.0	1.1	4.8	.09	1.0	1,400	50
12-31-74	1500	--	P	2	.75	10	142	6.05	35	1.2 T	14	2.1	.01	.77	1.0	4.5	.24	.78	1,600	100
2- 3-75	1545	21.5	P	2	.5	10	167	6.2	39	1.1 T	17	.9	.01	.99	1.0	4.5	.02	1.0	1,800	50
3- 8-75	1315	21.30	P	2.5	.5	8	173	6.3	34.5	.8 T	19	.6	.01	.87	1.5	6.7	.63	.88	2,600	90
4- 4-75	1605	21.15	P	2.5	.5	9.5	160	6.2	34.5	.7 T	18	1.4	.01	.81	.92	4.1	.10	.82	3,000	50
5-13-75	Could not sample--well would not pump.																			
6-12-75	1545	22.63	C	5 to 15	1	11	150	6.1	27	1.6 T	20	2.2	.01	.90	.91	4.0	.00	.91	600	80
7-22-75	Could not sample--well would not pump.																			
9-11-75	0945	--	C	15	.75	10.5	165	6.2	--	2.9 M	--	2.6	--	--	--	--	--	--	--	--
12-16-75	1400	22.18	C	10	.75	10.4	169	5.9	25	1.95T	23	.0	.01	.99	1.1	4.7	.06	1.0	870	20
Well SNW 1135																				
10- 9-74	1700	--	P	2	.25	13	136	6.1	9.0	1.6 M	12	ND	.00	.60	.83	3.7	.23	.60	250	180
11-18-74	1300	--	C	8	.25	10.5	106	6.1	12	8.4 T	14	1.9	.00	.22	.26	1.2	.04	.22	110	70
12-31-74	1145	3.81	C	6	.25	5	104	5.75	8	9.1 T	13	2.1	.00	.20	.33	1.5	.13	.20	60	80
2- 3-75	1420	3.46	C	6	.25	4.5	108	5.8	8.5	6.3 T	13	1.7	.00	.17	.23	1.0	.06	.17	50	40
3- 8-75	1000	3.08	C	6	.25	5	96	5.9	7.5	8.9 T	11	1.6	.00	.29	.30	1.3	.01	.29	170	60
4- 4-75	1225	2.94	C	6	.25	7	100	5.7	6.5	8.0 T	12	2.8	.00	.96	1.0	4.6	.07	.96	110	30
5-13-75	1128	3.37	C	6	.25	13	98	5.9	6.5	7.7 T	12	9.3	--	--	.34	1.5	.02	.32	250	40
6-12-75	1110	3.30	C	4	.25	18.5	86	6.05	6.5	6.75T	12	1.3	.00	.01	.01	.04	.00	.01	390	40
7-22-75	1240	3.26	C	4	1	25	81	6.1	9.0	4.8 T	12	14	.01	.02	.29	1.3	.26	.03	750	70
9-10-75	1630	4.28	C	8	.25	18.8	104	--	--	6.5 M	--	3.2	.01	.10	.36·	1.6	.25	.11	--	--
12-17-75	1205	3.44	C	8	.25	8.8	175	5.9	12.0	3.6 T	18	.9.8	.01	.32	.39	1.7	.06	.33	740	100

Table 3.--Chemical analyses of water samples from wells and Thirty Acre Pond (Continued)

		Sample collection				Field analyses					U.S. Geological Survey laboratory analyses									
Date	Time	Depth to water (feet)	Method	Pumping rate (gal/min)	Duration (hours)	Temperature (°C)	Specific conductance (micromhos per centimeter at 25°C)	pH (units)	Alkalinity (as $CaCO_3$)	Dissolved Oxygen	Total Chloride (Cl)	Total Organic Carbon	Total Nitrite (as NO_2)	Total Nitrate (as NO_3)	Total Nitrogen (as N)	Total Nitrogen (as NO_3)	Total Kjeldahl Nitrogen (as N)	Total Nitrite plus Nitrate (as N)	Dissolved Iron (µg/L) (1 mg/L = 1,000 µg/L)	Dissolved Manganese (µg/L) (1 mg/L = 1,000 µg/L)
Well SNW 1148																				
10-9-74	1300	--	C	24	--	10.5	199	5.7	7	4.8T 6.6M	19	0.0	0.00	4.6	4.7	21	0.07	4.6	50	50
11-15-74	1230	--	C	24	0.25	10.5	178	5.3	8	3.3 T	16	.5	.00	4.7	4.8	21	.05	4.7	30	60
12-30-74	1045	12.85	C	24	.25	10.5	167	5.55	10	2.6 T	15	.4	.00	3.8	4.3	19	.52	3.8	30	80
2-4-75	1430	12.33	C	24	.25	10.5	168	5.6	9	2.8 T	17	.4	.01	4.7	4.7	21	.03	4.7	10	140
3-7-75	1130	12.26	C	24	.25	10.5	--	5.5	8	3.3 T	16	1.3	.01	4.9	5.0	22	.08	4.9	20	40
4-4-75	0930	12.32	C	24	.25	10.5	200	5.5	8.5	4.8 T	14	6.5	.00	4.7	4.8	21	.07	4.7	20	50
5-12-75	1310	12.49	C	24	.25	10.5	172	5.4	7	5.6 T	13	14	--	--	4.3	19	.00	4.3	20	50
6-12-75	1105	12.54	C	24	.25	10.5	175	5.7	9.5	5.4 T	14	.3	.00	4.0	4.1	18	.12	4.0	50	30
7-23-75	0945	12.45	C	24	1	10.3	165	5.6	9	4.5 T	14	2.8	.00	4.6	4.7	21	.11	4.6	20	50
9-10-75	1715	13.21	C	10	.25	10.5	168	--	--	6.3 M	17	1.4	.01	4.6	5.1	22	.48	4.6	--	--
12-16-75	1205	12.44	C	24	.50	10.4	188	5.5	9.0	3.1 T	17	.2	.00	5.2	5.4	24	.18	5.2	0	30
Well SNW 1149																				
10-9-74	1430	--	P	4	.33	16	192	6.6	102	.2 M	8.8	4.8	.00	.03	1.1	5.0	1.1	.03	30,000	1,100
11-15-74	1330	--	C	8	.25	13	223	6.1	128	.5 M	15	12	.00	.02	.80	3.5	.78	.02	40,000	1,200
12-31-74	0940	1.14	C	8	.25	9.25	177	6.45	86	.0 T	12	2.1	.00	.00	.67	3.0	.67	.00	26,000	930
2-3-75	1045	.56	C	8	.25	8	155	6.3	70	.0 T	15	2.3	.00	.02	.76	3.4	.74	.02	25,000	810
3-8-75	0850	.34	C	8	.25	8	132	6.55	56	.0 T	15	2.5	.01	.01	1.0	4.4	.98	.02	24,000	730
4-4-75	1055	.12	C	8	.25	8	165	6.5	51	.0 T	15	2.0	.00	.00	.54	2.4	.54	.00	26,000	720
5-13-75	1038	.56	C	8	.25	9.5	166	7.05	52	.0 T	14	16	--	--	.63	2.8	.63	.00	26,000	670
6-13-75	1007	.46	C	8	.25	13	170	6.7	58	.0 T	15	3.0	.00	.00	.71	3.1	.71	.00	22,000	640
7-22-75	1010	.58	C	8	1	16	160	6.7	76	.6 M	12	2.0	.01	.02	.90	4.0	.87	.03	25,000	780
9-10-75	1300	1.42	C	5	1.50	17.5	225	6.3	76	1.6 T	--	4.0	.00	.01	.76	3.4	.75	.01	--	--
12-17-75	1110	.68	C	8	.50	12	216	6.4	92	1.4 M	14	2.0	.01	.01	1.0	4.5	1.0	.02	39,000	920
Well SNW 1150																				
10-9-74	1200	--	C	24	1	13.5	152	5.6	7	5.2T 5.3M	19	.0	.00	5.6	5.8	26	.18	5.6	120	30
11-15-74	1430	--	C	24	.25	10	148	5.3	7	5.5 M	13	3.8	.00	4.7	4.8	21	.05	4.7	60	100
12-31-74	1305	.92	C	24	.25	9	148	5.45	8	3.7 T	12	1.8	.00	3.2	3.3	15	.09	3.2	30	40
2-3-75	1225	.30	C	24	.25	8.5	165	5.7	8.5	6.2 T	13	.7	.00	6.6	7.0	31	.36	6.6	50	30
3-8-75	1110	.22	C	24	.25	8	--	5.7	7.5	6.75T	15	.4	.01	4.1	4.6	20	.52	4.1	10	10
4-4-75	1430	.05	C	24	.25	10.5	155	5.6	8	6.75T	14	.7	.00	3.3	3.4	15	.09	3.3	20	10
5-13-75	1400	.48	C	24	.25	9	145	5.55	6	6.6 T	16	9.4	--	--	2.5	11	.09	2.4	30	20
6-12-75	1230	.62	C	24	.50	10	142	5.8	8	6.35T	16	.7	.00	2.3	2.4	11	.13	2.3	30	20
7-22-75	1430	.60	C	14	.50	13	122	5.6	5	6.0 M	11	4.4	.01	3.0	3.2	14	.20	3.0	40	5
9-10-75	1550	1.41	C	24	.33	13.5	150	--	--	6.6 M	--	9.8	.01	4.6	4.8	21	.15	4.6	--	--
12-17-75	1250	.59	C	24	.25	10.4	149	5.8	9.0	5.8 T	12	.2	.00	4.3	4.5	20	.18	4.3	0	0
Thirty Acre Pond																				
2-4-75	1330	--	--	--	--	1	84	6.4	.0	12.4 T	12	4.2	.00	.45	1.0	4.5	.57	.45	110	100
3-7-75	1220	--	--	--	--	4.5	79	6.0	4	11.8 T	11	3.3	.00	.47	.84	3.7	.37	.47	120	60
4-4-75	1300	--	--	--	--	6	81	6.15	5	11 T	12	2.3	.00	.47	.65	2.9	.18	.47	60	30
5-12-75	1400	--	--	--	--	18	86	6.1	5	10.9 T	12	14	--	--	.50	2.2	.17	.33	60	50
6-12-75	No sample taken because of turbidity caused by heavy rain.																			
7-22-75	0915	--	--	--	--	26.5	87	7.2	17	7.2 M	12	8.8	.01	.19	.55	2.4	.35	.20	280	20
9-10-75	1600	--	--	--	--	22.5	104	--	--	10.8 M	--	5.2	.01	.17	1.0	4.6	.85	.18	--	--
12-17-75	0945	--	--	--	--	3.6	86	6.3	6.0	11.2 T	14	5.6	.01	.42	.51	2.3	.08	.43	270	40

Table 4.--Chemical analyses for selected additional constituents in samples collected May 12, 1975

(Concentrations in milligrams per liter except as indicated.)

Well number	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Carbon Dioxide (CO_2)	Sulfate (SO_4)	Fluoride (F)	Total Phosphorous (P)	Dissolved Solids (Residue at 180°C)	Dissolved Solids (Sum of constituents)	Noncarbonate Hardness	Hardness (Ca, Mg)	Turbidity (JTU)
Thirty Acre Pond	3.8	7.5	1.6	6.7	1.3	8	0	10	14	0.2	0.01	62	51	19	25	2
SNW 92	19	11	2.1	6.1	1.5	17	0	27	23	.5	.04	84	84	22	36	--
SNW 888	17	15	3.2	9.3	1.8	26	0	17	21	.5	.00	111	95	29	51	--
SNW 1135	7.6	6.9	1.9	7.2	1.3	8	0	16	18	.2	.00	65	59	19	25	--
SNW 1148	8.7	19	3.7	9.6	1.8	10	0	64	48	.1	.00	137	106	54	63	--
SNW 1149	11	8.5	1.7	6.6	1.2	15	0	2.1	15	.3	.01	111	92	16	28	--
SNW 1150	7.3	15	2.0	8.6	1.1	8	0	36	28	.1	.00	96	82	39	46	--

Wells sampled periodically included the following: (1) supply wells SNW 92 and SNW 888, which are screened near the base of the stratified drift aquifer; (2) a 2-1/2-inch diameter well, SNW 1128, screened near the base of the aquifer; (3) a drive-point well, SNW 1150, screened from 5.2 to 7.5 feet below the bottom of a 1-1/2-feet thick layer of organic-rich material in the swampy flood plain of the river; (4) a drive-point well, SNW 1148, located between the two supply wells and screened in the upper one-third of the aquifer; (5) a drive-point well screened from 1.7 to 4.0 feet below the pond bottom (the pond water averaged only a few inches in depth at this well) where a cover of organic matter was absent, except for a thin leaf matte that was present during the fall; and (6) a well point, SNW 1149, screened from 3.5 to 5.8 feet below the sandy pond bottom where the bottom is covered with a layer of silty, organic muck mixed with partly decomposed vegetal matter 1.5 feet thick.

The drive-point wells are 1-1/4-inch diameter galvanized pipe onto which are threaded stainless steel screens. Well SNW 1128 is steel pipe with a galvanized steel screen. Screens in supply wells SNW 92 and SNW 888 are made of Everdur bronze, which has a nominal composition of copper (96 percent), silicon (3 percent), and manganese (1 percent).

The wells were pumped for at least 15 minutes before samples were taken. Samples of pond water were taken from the pond surface near well SNW 1149, where water was 2 to 3 feet deep. At the time of collection, the temperature, specific conductance, pH, dissolved-oxygen content and alkalinity of the water were determined. Samples collected for iron and manganese determination were pressure filtered through a 0.1 micron membrane and were acidified with nitric acid. These samples, together with untreated, chilled samples were shipped to the Geological Survey Central Laboratory in Albany, NY, where analyses were made for iron, manganese, chloride, nitrate, nitrite, organic nitrogen, and total organic carbon. A more comprehensive set of analyses was made on the samples collected in May 1975 (table 4).

According to the flow patterns shown in figures 4 and 5, water samples from wells SNW 1127, 1130, 1133, and 1148 on the east side of the river should have consisted chiefly of "native" ground water moving toward the pond and river; samples from well SNW 1149 should have cosisted chiefly of infiltrated pond water; and samples from wells SNW 92, 888, 1128, 1135, and 1150 should have consisted of mixtures of "native" ground water and infiltrated surface water. Samples from wells SNW 1131, 1132, 1137, and 1141 on the west side of the river should have been exclusively "native" ground water. Water-quality data are in general agreement with this pattern of subsurface flow, as indicated in the following sections.

Specific Conductance

Specific conductance provided a relative measure of the mineral content of the water samples. The variation in specific conductance of water at different depths in the aquifer and from the pond is shown in figure 8.

Because the pond and river water during late summer and fall consist largely of seepage from the stratified glacial deposits in the Chipuxet River valley, measurements of specific conductance of the river during these periods provides an indication of the average specific conductance of ground water in the stratified-drift aquifer. Records from a U.S.
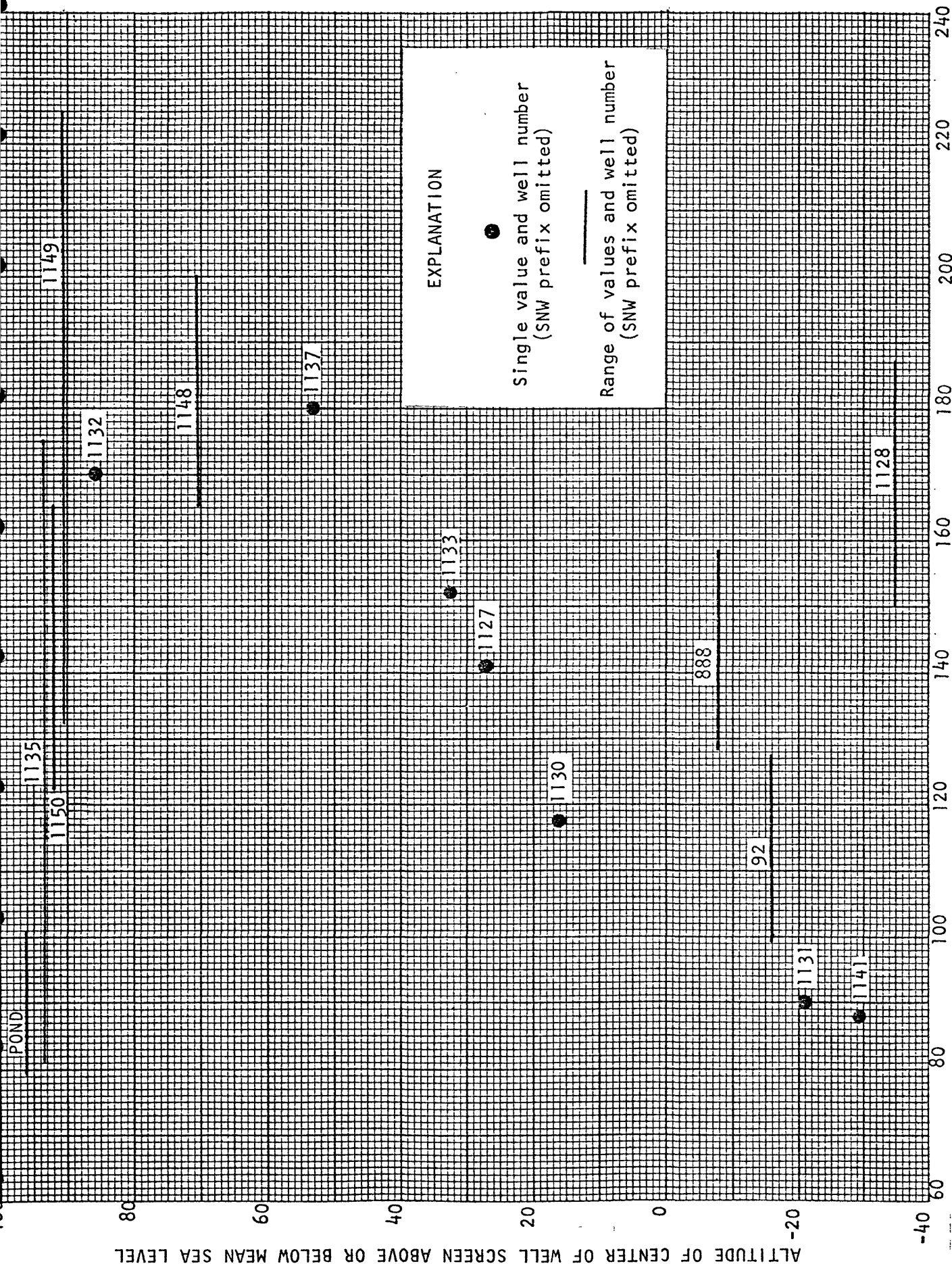
Figure 8.--Specific conductance of ground water versus depth in the aquifer

Geological Survey continuous-recording specific conductance monitor, 3,000 feet downstream from the URI well field at State Highway 138, show that specific conductance during August, September, October, and November of 1974 and 1975 averaged about 120 micromhos (U.S. Geological Survey, 1975b and 1976). Taking the average to be 120 micromhos, figure 8 shows that much of the water in the URI well field, especially in the upper part of the aquifer, is above average in mineral content. The above-average mineral content of water in the upper part of the aquifer probably resulted from leaching of fertilizers applied to fields on both sides of the river.

Differences in specific conductance of water at different depths in the aquifer seem to result from mixing of pond and river infiltration, shallow ground water contaminated by fertilizers, and "native" ground water in the lower part of the aquifer, as these waters move to the supply-well intakes.

The greatest range in specific conductance was measured in samples from wells SNW 1135 and SNW 1149 which are screened just below the pond bottom. A graph of specific conductance versus time (fig. 9) suggests that the mineral content of water in these wells may vary seasonally.

Nitrate

The average nitrate content of water in the stratified drift in the Chipuxet River valley is probably about the same as the maximum content of 0.47 mg/L measured in samples from the pond. If so, nitrate concentrations of 3 to 7 mg/L measured in samples from several relatively shallow wells indicate that the upper part of the aquifer on both sides of the river has become enriched in nitrate. The source of the nitrate is probably fertilizer that has been applied to private and University turf plots on the east side of the river and to potato fields on the west side of the river.

The relatively high nitrate content (2.3 to 6.6 mg/L) of water immediately beneath the swamp from well SNW 1150 indicates that water from this well consists chiefly of nitrate-contaminated water that is flowing toward the river. The wide range in nitrate content of the well water may result from alteration of flow paths caused by pumping the supply wells; that is, the lower concentrations may occur when some pond and river infiltration moves past this well toward supply-well intakes.

Very low nitrate levels (0.0 and 0.03 mg/L) were measured in samples from two deeply screened wells (SNW 1131 and SNW 1141) on the west side of the river. Water in these wells may represent "native" water that is relatively uncontaminated by fertilizers. Very low nitrate levels (0.00 to 0.03 mg/L) were also measured in samples from well SNW 1149 screened just below organic pond-bottom sediments. The low concentration of nitrate in water from this well probably results from reduction of nitrate contained in infiltrating pond water (0.17 to 0.47 mg/L) as it moves through these organic sediments. The absence of nitrite, a reduced species of nitrogen, in the samples indicates that nitrate nitrogen may have been converted by biochemical reactions to nitrogen gas, which is then lost to the atmosphere.

The distribution of nitrate at depth in the aquifer is shown in figure 10. Downward movement of low nitrate water from the pond apparently accounts in part for the low nitrate content of water pumped from
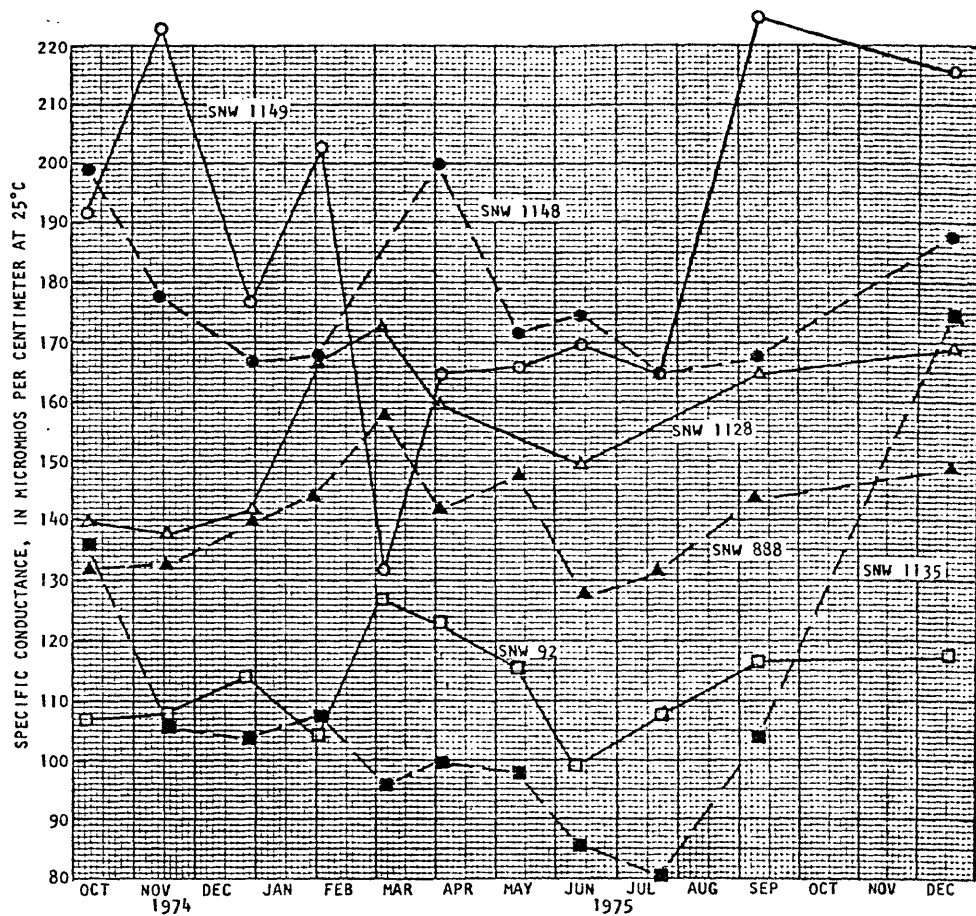
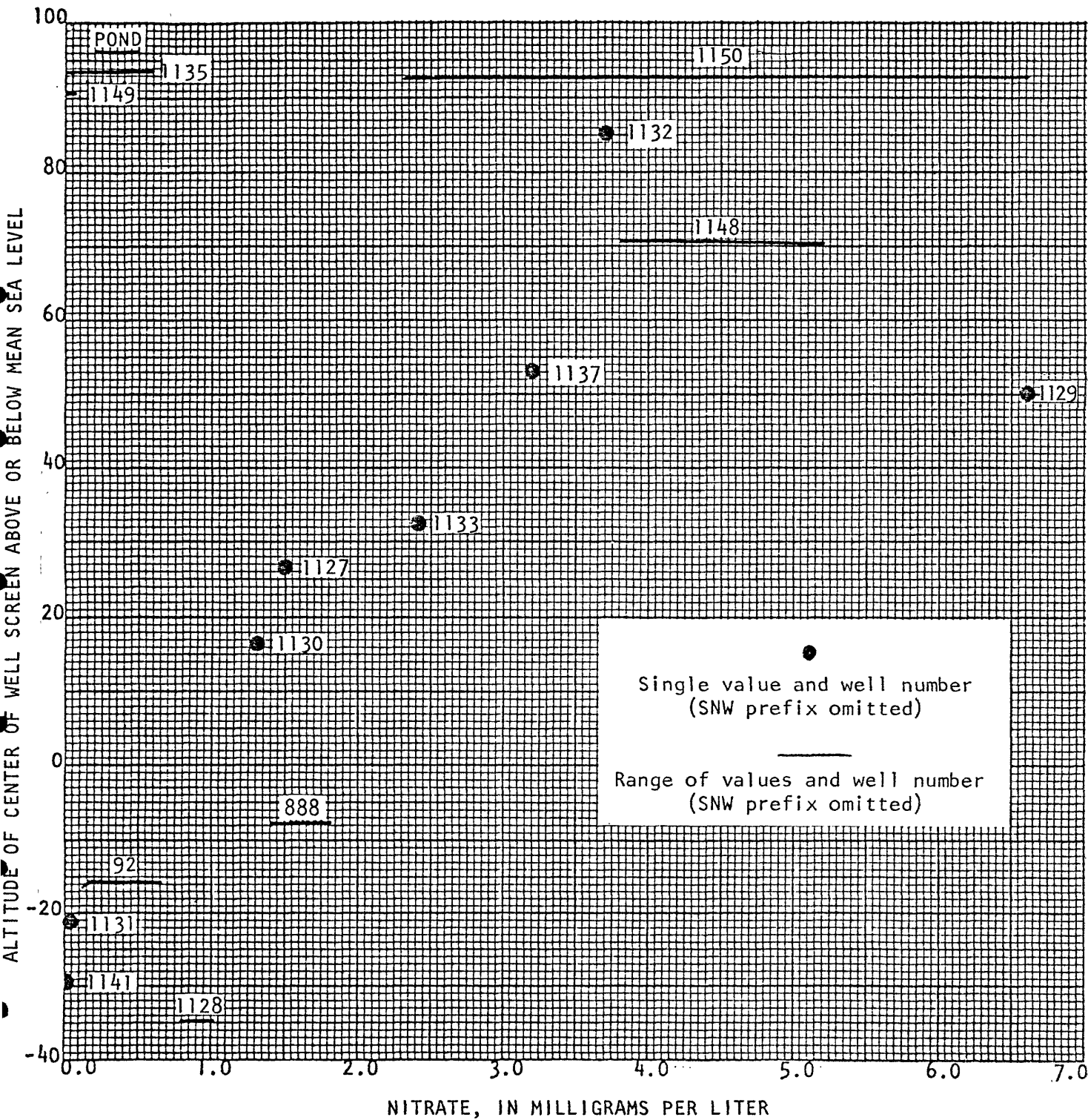Figure 9.--Specific conductance of ground water versus time

Figure 10.--Nitrate content of ground water versus depth in the aquifer

supply well SNW 92. Downward movement of high nitrate water from the upper part of the aquifer apparently also accounts for the somewhat elevated nitrate content of samples obtained from well SNW 888.

Temperature

Water temperature data obtained from wells sampled periodically do not all fit the flow concept described earlier. The temperature of water from well SNW 92, for example, fluctuated no more than 0.5°C during the measurements. If this well intercepts most of infiltration of pond water, as suggested, it would be expected that the temperature of the water pumped from it would fluctuate over a wider range than 0.5°C, in response to annual temperature fluctuation in the pond and river of as much as 26°C. The narrow temperature range observed in water from well SNW 92 is, in fact, what one would expect to see if the well water contained little or no pond infiltration. The temperature of water from supply well SNW 888, which the authors believe pumps chiefly "native" ground water and a smaller percentage of pond and river infiltration than well SNW 92, fluctuated over a range of 1°C.

Dissolved Oxygen

The concentration of dissolved oxygen in ground water indicates ability to maintain manganese and iron in solution. Water containing dissolved oxygen in concentrations of several milligrams per liter is generally too highly oxidized to contain high concentrations of dissolved manganese and iron. Depletion of dissolved oxygen in water, as a result of oxidation of organic matter or of some other oxygen consuming reaction, however, may cause the water to become so reduced that it is able to maintain several milligrams per liter of iron and(or) manganese in solution.

A comparison of the dissolved-oxygen versus dissolved-manganese content of water samples collected for this study (fig. 11) shows that concentrations of manganese as high as 0.1 mg/L occurred in water having a wide range in dissolved-oxygen content (0.0 to 12.4 mg/L). Manganese concentrations greater than 0.1 mg/L, however, occurred only in waters having a dissolved-oxygen content of less than 4 mg/L.

In the case of supply wells SNW 92 and SNW 888, note that waters having a low dissolved-oxygen and high dissolved-manganese content will mix instantaneously at the well intakes with waters having a higher dissolved-oxygen and lower dissolved-manganese content. The concentrations of dissolved oxygen and manganese in water from these wells, therefore, is largely dependent on the relative volumes of water of different quality that enter the wells along different flow paths.

Iron

Concentrations of iron in samples from the pond and from all wells except SNW 1128, SNW 1135, and SNW 1149 were low (0.0 to 0.35 mg/L). High concentrations of iron in several samples from well SNW 1128 may have resulted in part from dissolution of iron from its galvanized steel screen. This is suggested by the apparent variation in the concentration of iron with the volume of water pumped from the well. On six occasions when samples were taken after only 60 to 90 gallons was pumped from the well with a pitcher pump, iron concentrations of the samples ranged from 1.4 to 3.0 mg/L. On three other occasions, when samples were taken after
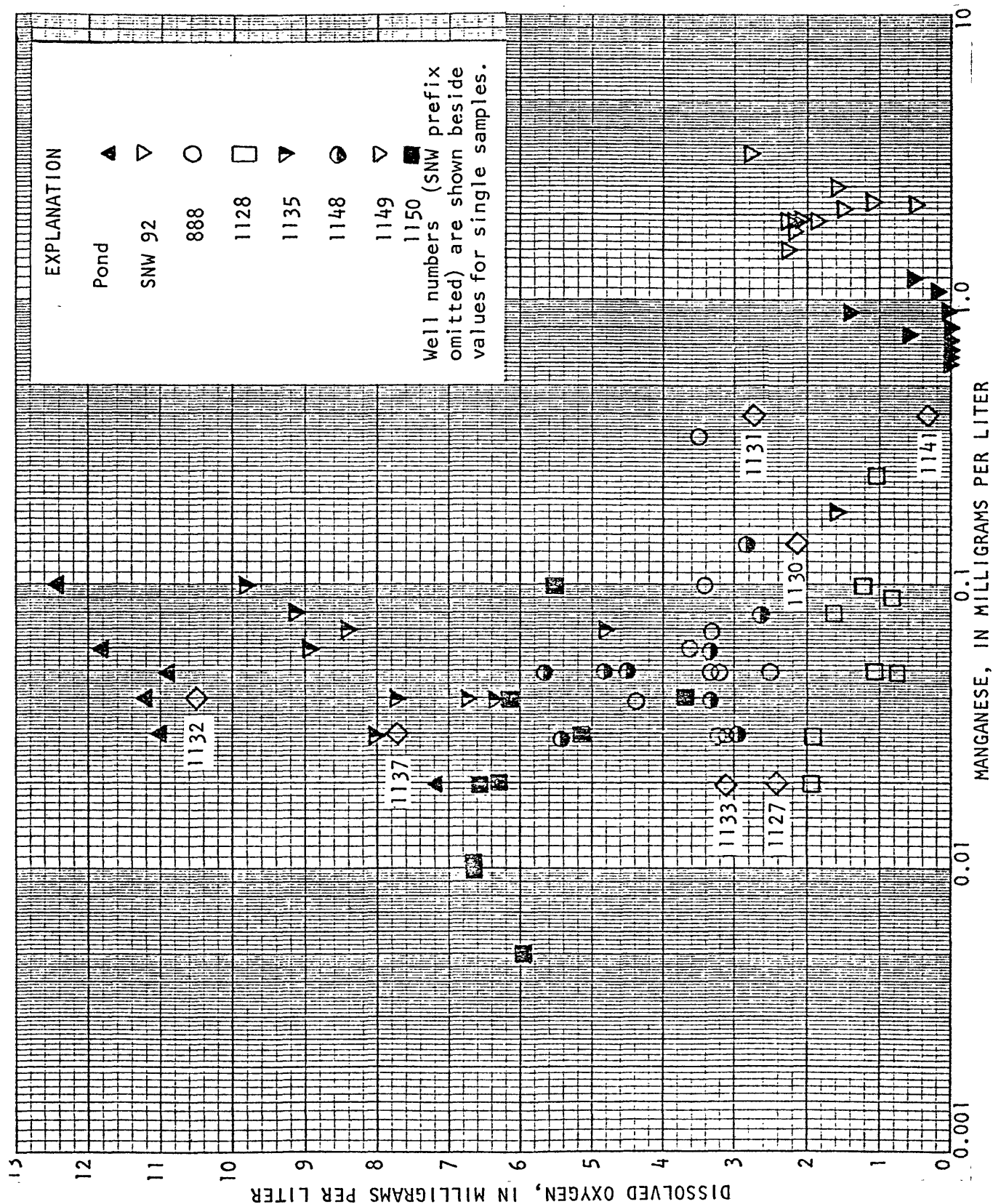
Figure 11.--Dissolved manganese versus dissolved oxygen content of ground-water samples

withdrawing 600, 750, and 6,200 gallons, the respective iron concentrations of the samples were 0.6, 0.87, and 0.15 mg/l, respectively. High concentrations of iron in wells SNW 1135 and SNW 1149 may include some iron dissolved from the galvanized pipe to which the stainless steel screens are attached. However, most of the iron in samples from these wells, especially the excessive concentrations (22 to 40 mg/L) in those from well SNW 1149 are probably derived from dissolution of iron from pond bottom sediments and(or) from aquifer materials through which pond infiltration moves enroute to supply-well intakes. Inasmuch as iron concentrations in water from supply wells SNW 92 and SNW 888 generally did not exceed 0.35 mg/L, it is apparent that most of the dissolved iron present in the infiltrated water a few feet below the pond bottom is removed from solution by precipitation or by some other mechanism before reaching the supply wells.

Manganese

Concentrations of dissolved manganese measured during this study were highest in water samples from deeply screened supply well SNW 92 (1.8 to 3.3 mg/L) and from well SNW 1149 (0.64 to 1.2 mg/L) screened just beneath a layer of organic pond bottom sediments. The content of manganese in the other deeply screened supply well, SNW 888, was comparatively low (0.03 to 0.34 mg/L). Manganese in water from well SNW 1135, also screened just below the pond bottom but where an organic layer was absent except for a thin leaf matte in the fall, ranged from 0.03 to 0.18 mg/L. Possibly of significance are samples obtained from deeply screened wells SNW 1131 and SNW 1141 on the west side of the river that contained manganese concentrations of 0.38 and 0.39 mg/L, respectively. The authors believe that neither of these wells intercept flow paths containing pond and river infiltration. The manganese content of water from all other wells was within the range of 0.00 to 0.25 mg/L.

The maximum concentrations of manganese measured in supply wells SNW 92 and SNW 888 were the highest values recorded since they were put into production. Supply well SNW 138, screened near the middle of the aquifer, also yielded water containing as much as 1.1 mg/L manganese when it was in production.

Because water pumped from supply well SNW 92 consists of a mixture of waters that have moved to the well intake along different flow paths from different parts of the aquifer and from the pond and river, it may be assumed that the manganese content of water moving along some flow paths is greater than 2 or 3 mg/L. Data obtained from well SNW 1149 indicate that the flow paths most likely to contain excessive concentrations of manganese are those that carry pond and river infiltration to well SNW 92. Although concentrations of manganese measured in water from well SNW 1149 did not equal or exceed those in water from well SNW 92, higher concentrations may be generated beneath other parts of the pond and river or concentrations may increase as infiltrated water moves to greater depths in the aquifer.

Water-quality data for well SNW 1149 indicate that changes in the physiochemical character of the pond water as it moves through the organic bottom sediments into the aquifer cause manganese to be dissolved from the organic sediments and(or) aquifer materials. Samples of pond water taken at the surface near well SNW 1149 contained high concentrations of dissolved oxygen (7.2 to 12.4 mg/L), low but significant concen-

trations of nitrate nitrogen (0.17 to 0.47 mg/L), and comparatively low concentrations of dissolved iron (0.06 to 0.28 mg/L) and manganese (0.02 to 0.1 mg/L. In contrast, the water pumped from well SNW 1149 was nearly devoid of dissolved oxygen (0.0 to 1.6 mg/L), contained essentially no nitrate nitrogen (0.0 to 0.03 mg/L), and contained very high concentrations of dissolved iron (22 to 40 mg/L) and, as noted above, high concentrations of dissolved manganese. These data indicate that oxidized pond water is reduced as it flows through the organic sediments. The reduced water is apparently then able to dissolve iron and manganese derived from biochemical decomposition of organic matter and(or) from oxides and other forms of iron and manganese present as coatings and stains on aquifer materials.

The time variation in manganese content of water from the two supply wells, an observation well that yields water containing relatively little pond infiltration, and a well that yields water constituted almost entirely of pond infiltration is shown in figure 12. The peaks in concentrations of manganese may be related to seasonal intensification of the reducing conditions that cause manganese (and iron) to become dissolved. These intensified conditions may result in part from increased pond water temperatures, during the summer, which would increase the rate of oxygen depletion in organic bottom sediments. Die off and decay of aquatic vegetation and decay of leaves that accumulate on the pond bottom during the fall may also contribute significantly to depletion of dissolved oxygen in water being infiltrated. It is also possible that a reducing environment occurs in deeper parts of the pond during the summer as a result of temperature stratification and stagnation.

The possibility of seasonal temperature stratification and attendant oxygen depletion in deeper parts of the pond needs to be defined. It could be that concentrations of manganese in excess of 2 to 3 mg/L enter the aquifer beneath these parts of the pond. Should this be the case, artificial aeration of water in deep parts of the pond during the summer might reduce the concentrations of manganese in the water being infiltrated. Although figure 5 suggests that the rate of vertical flow is highest closest to the pumping wells, this may not be the case. If, for example, vertical hydraulic conductivity at the vertical flow path 250 feet north of well SNW 92 were as much as 10 times less than the average value used in computing the rate of flow and if the vertical flow path beneath the deepest part of the pond 800 feet north of well SNW 92 were 10 times greater, the rate and volume of infiltration would be 10 times greater beneath the deep part of the pond. Stratigraphic data (fig. 7) show that there is considerable variation in the thickness of fine-grained units from place to place in the sediment column and therefore that vertical hydraulic conductivity may be much higher in some places than others.

An area of the pond beneath which high concentrations of manganese may be generated is a hole about 30 feet deep about 800 feet northeast of well SNW 92. If seasonal temperature stratification of water occurs at depth in this hole, contact of the stagnant water with organic bottom sediments may create a relatively large body of more strongly reduced water capable of dissolving higher concentrations of manganese than those observed beneath shallower parts of the pond. This possibility warrants investigation. If such a situation exists, manganese concentrations in ground water might be reduced by artificially aerating the stagnant body of pond water.
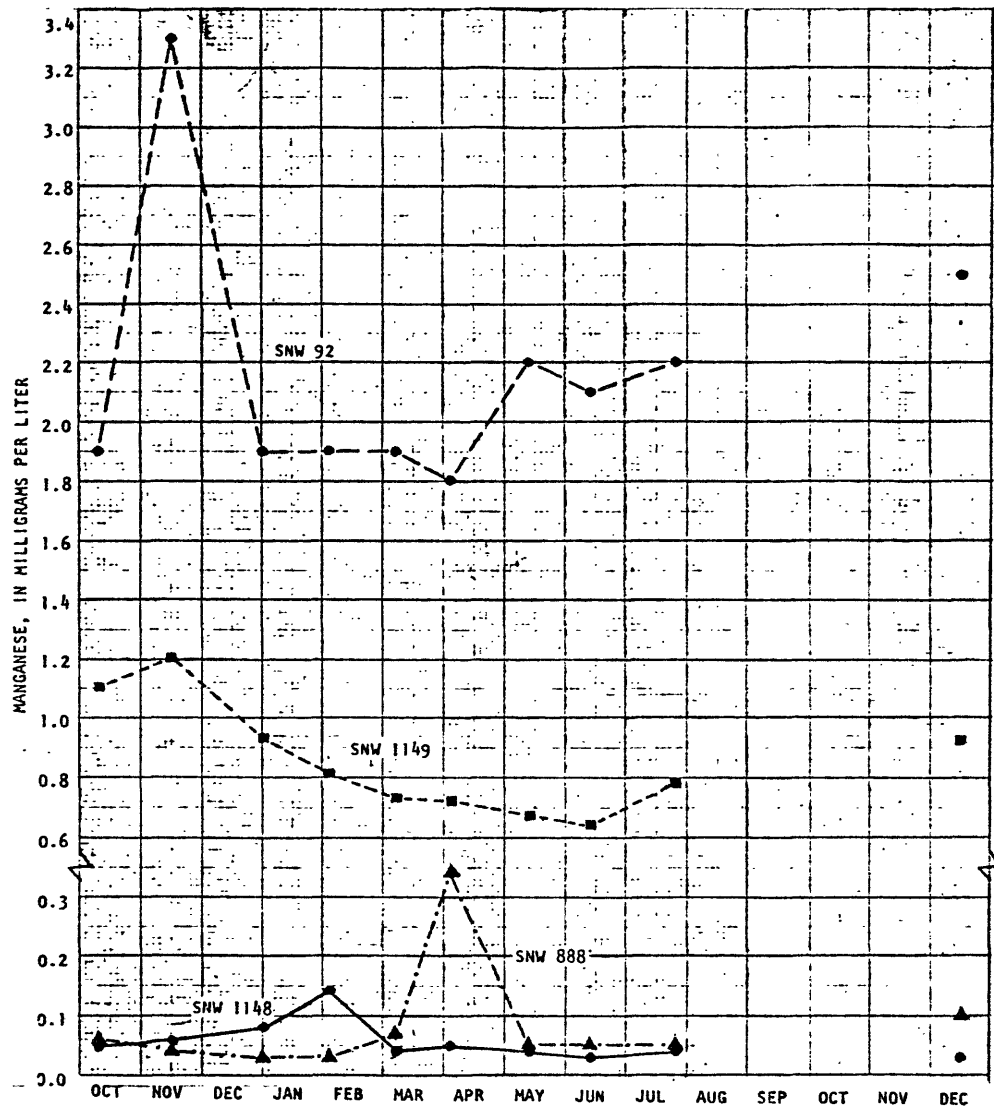
Figure 12.--Variation in manganese content of water with time

Peaks in the concentration of manganese in water from supply wells and observation wells seem to be related to seasonal variations in reducing conditions beneath the pond and river bottom. This could be due to one or both of the following conditions; (1) the reducing environment may be intensified at the end of the growing season owing to decay of leaves that have fallen into the water and to die-off and decay of aquatic vegetation, or (2) seasonal stratification of water in deeper parts of the pond may cause a seasonally intense reducing environment in this part of the pond.

No water samples were obtained from bedrock underlying the study area, but theoretical considerations and indirect evidence would seem to rule out water in bedrock as the source of high concentrations of manganese in the supply wells. The hydraulic conductivity of the bedrock is too low for it to supply more than a small fraction of the water pumped from the supply wells. Thus, for bedrock to be the source would require that water in the bedrock contain dissolved manganese much in excess of 2 to 3 mg/L. The authors are unaware of any bedrock wells in Rhode Island that yield water containing dissolved manganese substantially in excess of these concentrations. In a study of the relation of ground-water chemistry to bedrock lithology in Rhode Island, Hermes and Murphy (1971) showed that the manganese content of ground water at 30 of 31 sites of diverse lithology ranged from less than 0.01 to 0.31 mg/L, and the median concentration was less than 0.05 mg/L. One well sampled yielded water with a manganese content of 2.8 mg/L. Moreover, because the water in bedrock flows naturally into stratified drift as it moves to areas of discharge, excessive concentrations of dissolved manganese would be expected near the base of the stratified drift. No such high concentrations have been observed in test wells drilled in the Chipuxet River basin.

During this preliminary study, Prof. William E. Kelly, University of Rhode Island, offered the hypothesis (personal commun., Jan. 1976) that manganese contained in leachate from a landfill about 4,000 feet northeast of the well field is a potential source of the high concentrations of manganese in the University supply wells. A concentration of manganese as high as 73 mg/L has been measured in an unfiltered water sample bailed from a 2-1/2-inch diameter observation well screened immediately beneath the landfill, and the leachate plume has been traced north-northwestward from the landfill a distance of about 1,200 feet to the east shore of Hundred Acre Pond (Kelly, 1975). Concentrations of manganese as high as 0.84 mg/L were measured in filtered (0.45 micron membrane) water samples taken in November 1973 from test wells drilled in the center of the leachate plume near the shore of Hundred Acre Pond (Dickerman, 1976). Kelly suggests that slugs of leachate containing concentrations of manganese higher than 2 mg/L may be travelling through the aquifer and that some of the leachate, rather than discharging into Hundred Acre Pond, continues to move in the subsurface beneath Hundred Acre Pond and the Chipuxet River to the well field at Thirty Acre Pond, a distance of about 4,000 feet.

If the landfill leachate, rather than infiltration from the pond, is the cause of the manganese enrichment in water from well SNW 92, it would explain the lack of temperature fluctuation in well SNW 92 and might also explain the elevated content of manganese in water near the base of the aquifer on the west side of the Chipuxet River. Variations in manganese content of water pumped from well SNW 92 would also be consistent with a leachate source for the manganese.

The hypothesis is plausible and deserves further consideration. Nevertheless, the weight of evidence currently available indicates that the process of infiltration of surface water through organic bottom sediments is a more plausible explanation of the cause of manganese enrichment in the University well field. It is a process likely to be involved in the enrichment of manganese in other well fields where landfill leachate is not a factor.

SUMMARY

Hydrologic analysis indicates that cyclic pumping from University supply wells SNW 92 and SNW 888 causes infiltration of pond and river water to be induced into the stratified-drift aquifer. An approximation of the pattern of ground-water flow that would result if pumping were continuous rather than cyclic indicates that most of the infiltrated water is diverted to well SNW 92 and that well SNW 888 yields mostly "native" ground water primarily from aquifer storage.

Water-quality data provide some evidence in support of this estimated pattern of flow. Water in the upper part of the aquifer on both sides of the river is apparently contaminated by nitrate nitrogen derived from fertilizers. Downward movement of this water has caused above-normal concentrations of nitrate nitrogen in water from well SNW 888. Pond and river water infiltrating through organic-rich bottom sediments contains virtually no nitrate nitrogen and little or no dissolved oxygen. Downward movement of this water is apparently partly responsible for the low concentrations of nitrate nitrogen and dissolved oxygen in water from well SNW 92. Water-temperature data from well SNW 92 seem to be in conflict with the hydrologic analysis. The temperature of its water was between 10° and 10.5°C throughout the period of sampling. It was expected that the temperature of water from this well would vary seasonally over a somewhat larger range in response to seasonal fluctuations of temperature in the pond of as much as 26°C. Further study of the relationship between the temperature of water pumped from well SNW 92 and that of infiltration induced from the pond and river is necessary to clarify this relationship.

Theoretical considerations and indirect evidence seem to preclude bedrock as a source of the high concentrations of manganese in supply well SNW 92. Relatively little of the water pumped from SNW 92 is likely to be derived from the bedrock owing to the bedrock's low hydraulic conductivity, and available data indicate that concentrations of manganese in water derived from bedrock are too low to account for the high concentrations measured in water from well SNW 92.

Chemical analyses of water samples taken near the surface of the pond indicate that streamflow is probably not a direct source of manganese in the supply wells. Although concentrations as high as 0.1 mg/L were measured in the pond samples, the pond and river water seem to be too highly oxidized to contain concentrations of as much as 1 mg/L.

The most likely sources of the manganese are the organic-rich sediment on the bottom of the pond and river and the aquifer materials. Chemical analyses of these materials show that they both contain substantial concentrations of manganese and iron and that iron is much more abundant than manganese. Concentrations of manganese and iron are higher in the organic-rich bottom sediments than in aquifer materials, but quantities of iron and manganese are greater in aquifer materials because

of their larger volume. It is estimated that if all of the manganese contained in organic-rich bottom sediments through which infiltration occurs were dissolved, there would be enough manganese to supply the content of manganese in the water currently being pumped from supply well SNW 92 for about 10 years. In contrast, it is estimated that there is enough manganese contained in aquifer materials through which infiltration passes to support the same rate of manganese removal for nearly 300 years.

Physiochemical changes in infiltrated water as it moves through the organic-rich sediments on the bottom of the pond and river seem to be responsible for manganese enrichment of water pumped from supply wells. Dissolved oxygen and nitrate nitrogen contained in the infiltrating water are depleted as it moves through the organic layer, causing the water to change from an oxidized to a reduced state. The reduced infiltrate is able to maintain in solution high concentrations of manganese and iron derived from biochemical alteration of the organic matter and(or) from dissolution of oxides and other forms of manganese and iron present as coatings and stains on aquifer materials. Concentrations of dissolved manganese and iron as high as 1.2 and 40 mg/L, respectively, were measured in water samples obtained at a depth of 3.5 feet below the pond bottom. Because water pumped from well SNW 92 contained much lower concentrations of iron (0.25 to 0.35 mg/L) and significantly higher concentrations of manganese (1.8 to 3.3 mg/L), iron must be removed from solution by precipitation or some other process before reaching the well, and manganese concentrations must either increase as the infiltrated water moves deeper into the aquifer or higher concentrations must be generated beneath other parts of the pond. Furthermore, if infiltration through organic sediments is truly the cause of high concentrations of manganese in the supply wells, water along some flow paths between the pond bottom and the screen in well SNW 92 must contain manganese concentrations in excess of 2 to 3 mg/L. This is to be expected because a large part of the water pumped from well SNW 92 presumably consists of "native" ground water, having a manganese content similar to that in water pumped from supply well 888 (0.03 to 0.34 mg/L).

Leachate containing high concentrations of manganese from a landfill northeast of the University well field has been suggested as possible source of the manganese in water from wells SNW 92 and SNW 138. This possibility deserves further study. The locations and depths of wells available for this study were not suitable for evaluating this hypothesis.

CONTINUING STUDY

Study of the problem of manganese enrichment in ground water in the University of Rhode Island well field is continuing to determine whether manganese concentrations increase as pond infiltration moves to successively greater depths in the aquifer and to further evaluate apparent cyclic variations in the manganese content of the ground water.

Periodic sampling of observation wells is continuing, and four (4) 1-1/4-inch diameter wells constructed with pvc casing have been installed in the vicinity of SNW 1149. The wells are screened at approximately 6-8, 13-15, 20-22, and 36-40 feet. A porous cup sampler (soil lysimeter) has been placed in the organic-rich pond bottom sediment adjacent to the wells.

The four wells, porous cup sampler, pond water, and supply well SNW 92 were sampled twice per week during August through November 1976 and will be sampled weekly until June 1977.

Field measurements consist of temperature, conductivity, dissolved oxygen, pH, and redox potential. Samples are being filtered through 0.1 m membrane filters in the field.

Laboratory measurements consist of soluble manganese (Mn), ferrous iron (Fe^{2+}), and total soluble iron (Fe); alkalinity and nitrate; and once every 2 or 3 weeks samples are being analyzed for major ions, nutrients, and organic carbon.

Selected wells in the URI well field are being sampled periodically throughout the study period (August 1976 to June 1977). The wells sampled and sampling frequency will be determined during the study. The wells may include SNW 92, 888, 1128, 1135, 1148, and 1150. The new supply well, SNW 1151, will be sampled periodically also, if it is put into production during the study.

Samples of pond and river sediment as well as aquifer materials will be subjected to organic analyses to determine if iron and manganese are associated with organic water and whether the source of organic carbon is terrestrial debris, aquatic biota, or landfill pollution. Organic extracts will be analyzed for their iron and manganese content.

A hydrographic survey of Thirty Acre Pond and associated bottom material will be made in order to determine the chemical properties of the water and sediment and to estimate the relative importance of the pond benthic system on the underlying aquifer.

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