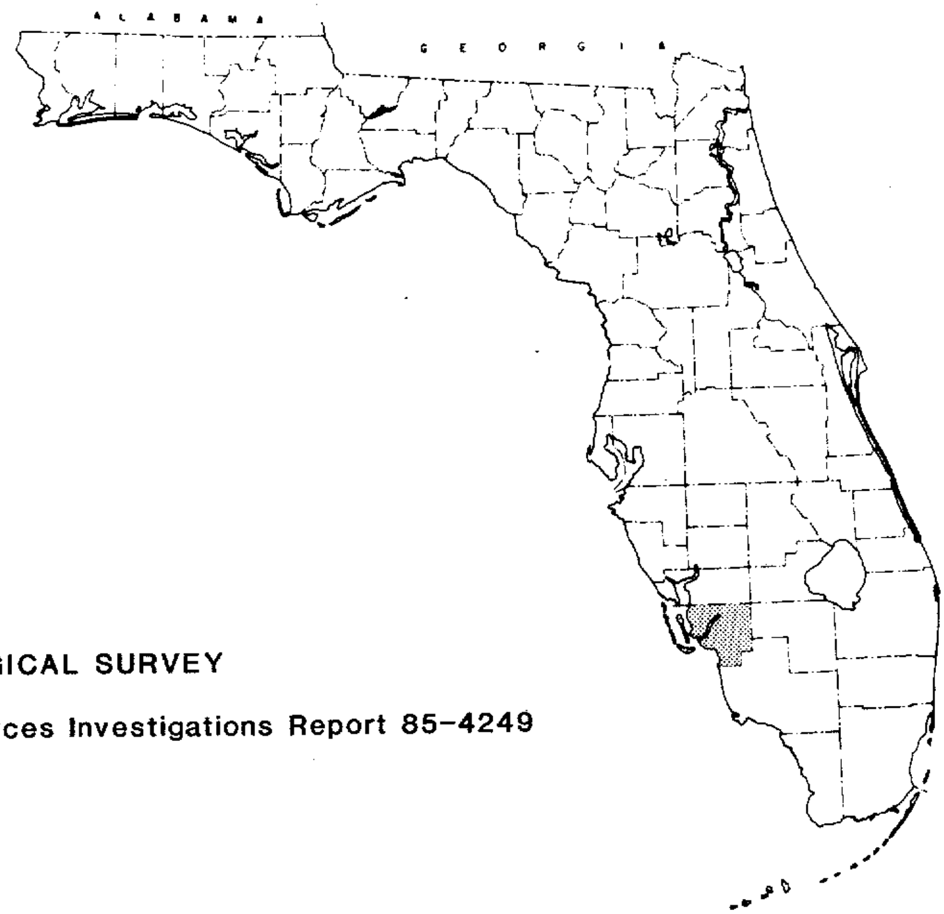
TESTS FOR INJECTING, STORING, AND RECOVERING FRESHWATER IN A SALINE ARTESIAN AQUIFER, LEE COUNTY, FLORIDA



U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 85-4249

Prepared in cooperation with

LEE COUNTY and the SOUTH FLORIDA
WATER MANAGEMENT DISTRICT

CONVERSION FACTORS

For use of readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
gallon per minute per foot (gal/min)/ft	0.2070	liter per second per meter (L/s)/m
square foot per day (ft^2/d)	0.09290	square meter per day (m^2/d)
pound per square inch (lb/in^2)	6.895	kiloposcal (kPa)

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8°C + 32$$

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Tallahassee, Florida

1986

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

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TESTS FOR INJECTING, STORING, AND RECOVERING FRESHWATER IN A SALINE ARTESIAN AQUIFER, LEE COUNTY, FLORIDA

By D. J. Fitzpatrick

ABSTRACT

An investigation was made of the suitability of a saline, artesian limestone aquifer for the injection, storage, and recovery of freshwater from the Caloosahatchee River. The tests were conducted on a well tapping a leaky artesian system that has a transmissivity of 800 square feet per day, a storage of 1×10^{-4}, and a leakance of 0.01 per day. The specific capacity of the injection well was increased through acidizing and was decreased as a result of well clogging during injection.

Three injection tests were made wherein the amounts of freshwater injected, the storage duration, and the quality of water injected varied. Analysis of the test data showed that freshwater recoverability ranged from 9.7 to 38.7 percent of the total injected. Differences were attributed principally to differences in the quality of water injected and storage duration. Repeated injection-recovery cycles probably would result in greater recoverability. Head buildup, nearly 200 feet in one test, was a prime problem related chiefly to clogging from suspended material in the injected water and to bacterial growth at the wellbore-limestone interface. Regular backflushing was required. Total head buildup decreased as a result of acidizing the injection well.

No coliforms or fecal streptococcus were noted in the recovered water. Growth of anaerobic bacteria occurred. Changes in the quality of the recovered water included decreases in concentration of dissolved organic carbon by as much as 15 mg/L (milligrams per liter), organic nitrogen by as much as 0.80 mg/L, and nitrate by as much as 0.50 mg/L. Increases were noted in ammonia by 0.40 mg/L, and iron by as much as 0.60 mg/L. These changes are consistent with the presence of an anaerobic bacterial ecosystem.

INTRODUCTION

The freshwater resources of Lee County in southwest Florida may not fully satisfy the demands of the rapidly growing population. Freshwater sources are the Caloosahatchee River and the surficial aquifer system;[1/] deep saline aquifers locally furnish water for desalination. Continued declining water levels in areas of ground-water withdrawals for public water supply have increased the potential for saline-water intrusion from the tidal reach of the Caloosahatchee River and from the deep saline artesian aquifers.

[1/]Deliberations among hydrogeologists active in southwest Florida that have occurred since this report was prepared and approved by the Director of the Geological Survey have resulted in placement of the regional base of the surficial aquifer system higher in the hydrogeologic section than shown in this report. Regionally, the base of the surficial aquifer system in southwest Florida is considered to be at the first areally persistent clay layer, which is commonly green and similar in lithology to the deeper lying clays of the Hawthorn Formation. In the Lee County area, the first clay is thin and affords seeming hydrologic continuity between the water table and the "sandstone aquifer," as evidenced by the similar configuration of the potentiometric surface of the "sandstone aquifer" with that of the water table. Therefore, on the basis of local data, this report regards the "sandstone aquifer" as part of the surficial aquifer system rather than as part of the intermediate aquifer system, which is the consensus recently arrived at based on regional considerations.

The controlled reach of the Caloosahatchee River is the source of freshwater for much of Lee County and for artificial recharge to the Fort Myers shallow municipal well field. River water is affected seasonally by migration of saline water upstream from the Gulf of Mexico, by periodic algae blooms and, in recent years, by recurring low water levels in Lake Okeechobee, the principal source of water for the Caloosahatchee River. These problems indicate the need for developing additional water sources to meet future demands.

Lee County is underlain at depths greater than 400 feet by artesian aquifers containing nonpotable mineralized water. These zones might be used for the injection, storage, and recovery of surplus freshwater from the Caloosahatchee River, or other sources. The efficiency of such an injection and recovery system would depend upon the ability of the injected zones to receive, store, and discharge the injected freshwater.

Various earlier studies have indicated that subsurface storage could be a technique for water conservation (Vecchioli and Ku, 1972; Reeder and others, 1976; Brown and Silvey, 1977; F. W. Meyer and M. L. Merritt, U.S. Geological Survey, oral commun., 1982). These studies stipulated a need for site-specific detailed information on aquifer characteristics, confining layers, ground-water quality, and injection-water quality.

In 1977 the U.S. Geological Survey, in cooperation with Lee County and the South Florida Water Management District, began an investigation of the suitability of a saline artesian aquifer in the lower part of the Hawthorn Formation and the upper part of the Tampa Formation for the injection, storage, and recovery of freshwater from the Caloosahatchee River. The test site was at the Lee County water-treatment plant in the northeastern part of the county. The investigation consisted of three phases:

1. Collection of background hydrologic and geologic information;

2. Design and construction of test facilities;

3. Completion of a series of injection, storage, and recovery tests.

This report summarizes the data obtained during the investigation, analyzes the results of the tests, and makes assessment of the suitability of injecting and storing freshwater in the saline lower Hawthorn aquifer at the Lee County water-treatment plant.

Description of Test Site

The test site is the Lee County water-treatment plant on the Caloosahatchee River, 1 mile upriver (east) from the Franklin Lock (S-79) (fig. 1). The area is sparsely populated and is mainly agricultural, although some residential development is occurring.

The Lee County water-treatment plant, which supplies much of the county, obtains untreated water from the Caloosahatchee River. The water plant for the City of Fort Myers withdraws water from the Caloosahatchee River at a

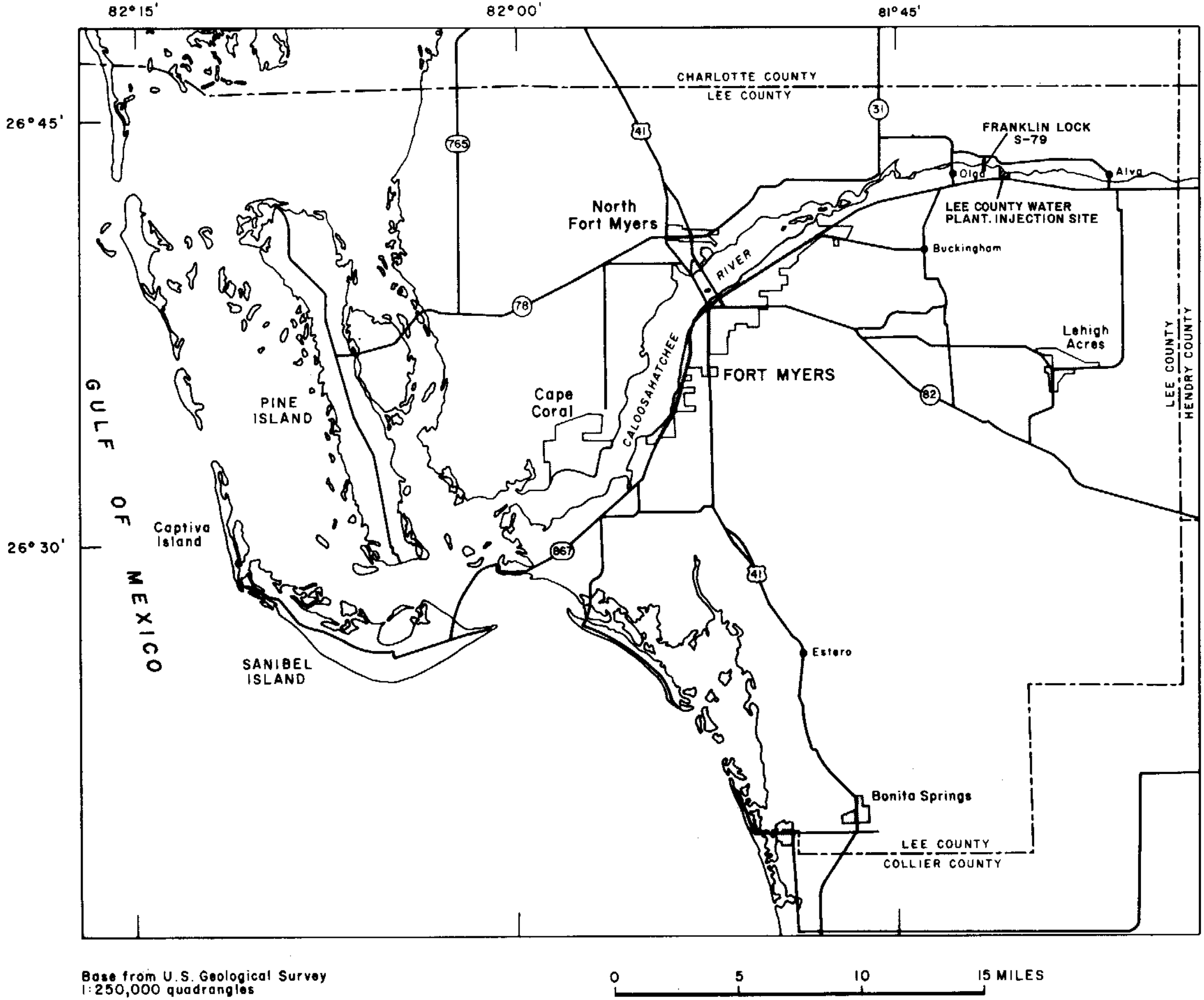

Figure 1.--Lee County, Florida, showing location of test site.

site less than 1/4 mile from the Lee County water-treatment plant. Residences near the test site generally obtain water from wells tapping shallow aquifers. Water for irrigation and livestock is also obtained from deeper wells in brackish to saline aquifers with flows 100 to 200 gal/min at the surface.

Rainfall at the test site is distributed unevenly throughout the year. About 60 percent of the average annual rainfall (54 inches) occurs from June through September.

A 705-foot test hole for hydrogeologic data (well L-2901), an injection well (L-3225), and two observation wells (L-2530 and L-3224) were constructed as part of this investigation (fig. 2). Injection well L-3225 was constructed by drilling a 16-inch hole to 450 feet and by cement grouting 445 feet of 10-inch schedule 80 PVC (polyvinyl chloride) casing. A nominal 9-inch hole was then drilled to 600 feet. Observation wells L-2530 and L-3224 were drilled to similar depth at distances of 140 and 335 feet from the injection well. Well-construction data for the test hole and three wells are given in table 1.

Acknowledgments

The author gratefully acknowledges the assistance provided by personnel in Lee County and the South Florida Water Management District. Special acknowledgment is made to Leslie Wedderburn of the South Florida Water Management District for providing a technical review of this report.

GEOHYDROLOGY

Lithology and Water Quality

The principal zone of investigation (injection zone), locally referred to as the lower Hawthorn aquifer, is a limestone of moderate permeability within the uppermost part of the Floridan aquifer system and comprises the lower part of the Hawthorn Formation and the upper part of the Tampa Limestone (fig. 3). The most permeable section of these formations in this test-site area consists mainly of white-gray, phosphatic limestone, 460 to 580 feet below land surface. Material of lower permeability composed of fine-grained, marly, phosphatic limestone interbedded with gray-green clay overlies the permeable section and forms the intermediate aquifer system. The permeable limestone is separated from the deeper permeable layers of the Floridan aquifer system by another limestone of low permeability (fig. 3).

Water from limestone in the lower part of the Hawthorn Formation is brackish to saline. Dissolved solids concentrations in water from wells L-3225, L-2530, and L-3224, which tap those limestones at the injection site, ranged from 1,520 to 1,580 mg/L, and chloride concentrations ranged from 500 to 550 mg/L (table 2). Selected chemical constituents and characteristics of the water are given in table 2, and background bacteriological data are in table 3. Coliforms and fecal streptococcus were not found, and other bacteria counts were low and not significant.

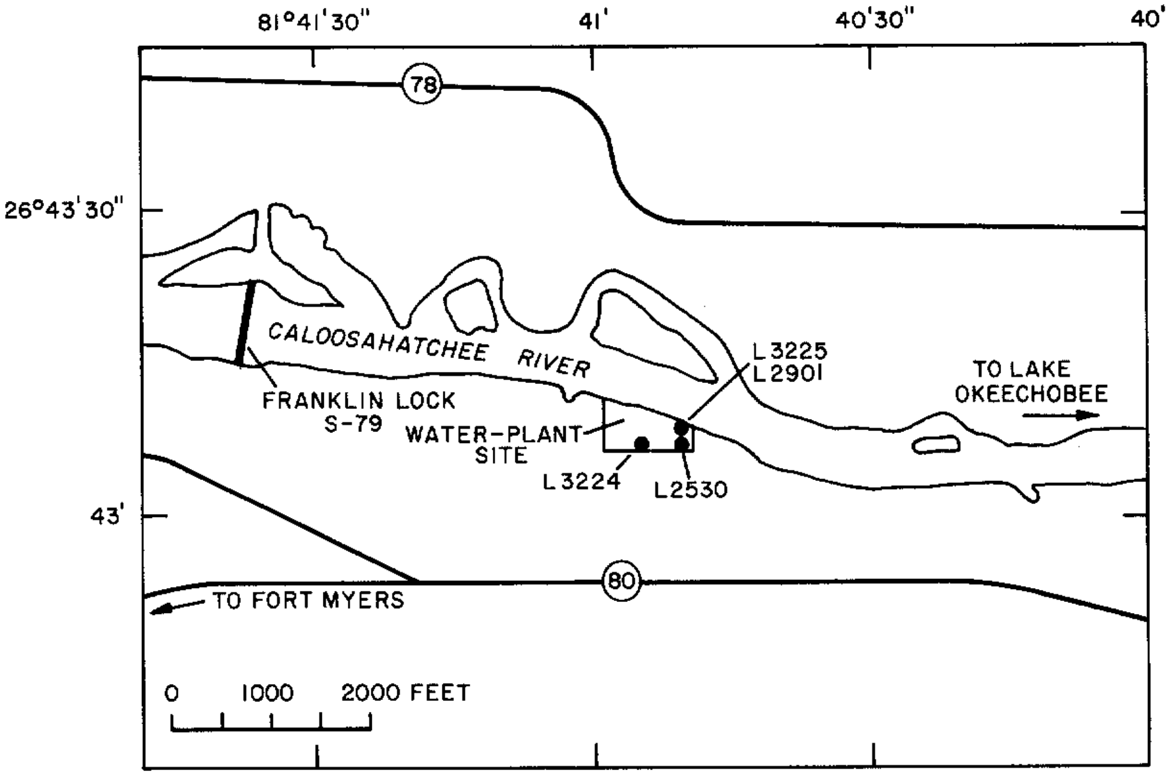

Figure 2.--Test site showing location of test hole (L-2901), injection well (L-3225), and observation wells (L-2530 and L-3224).

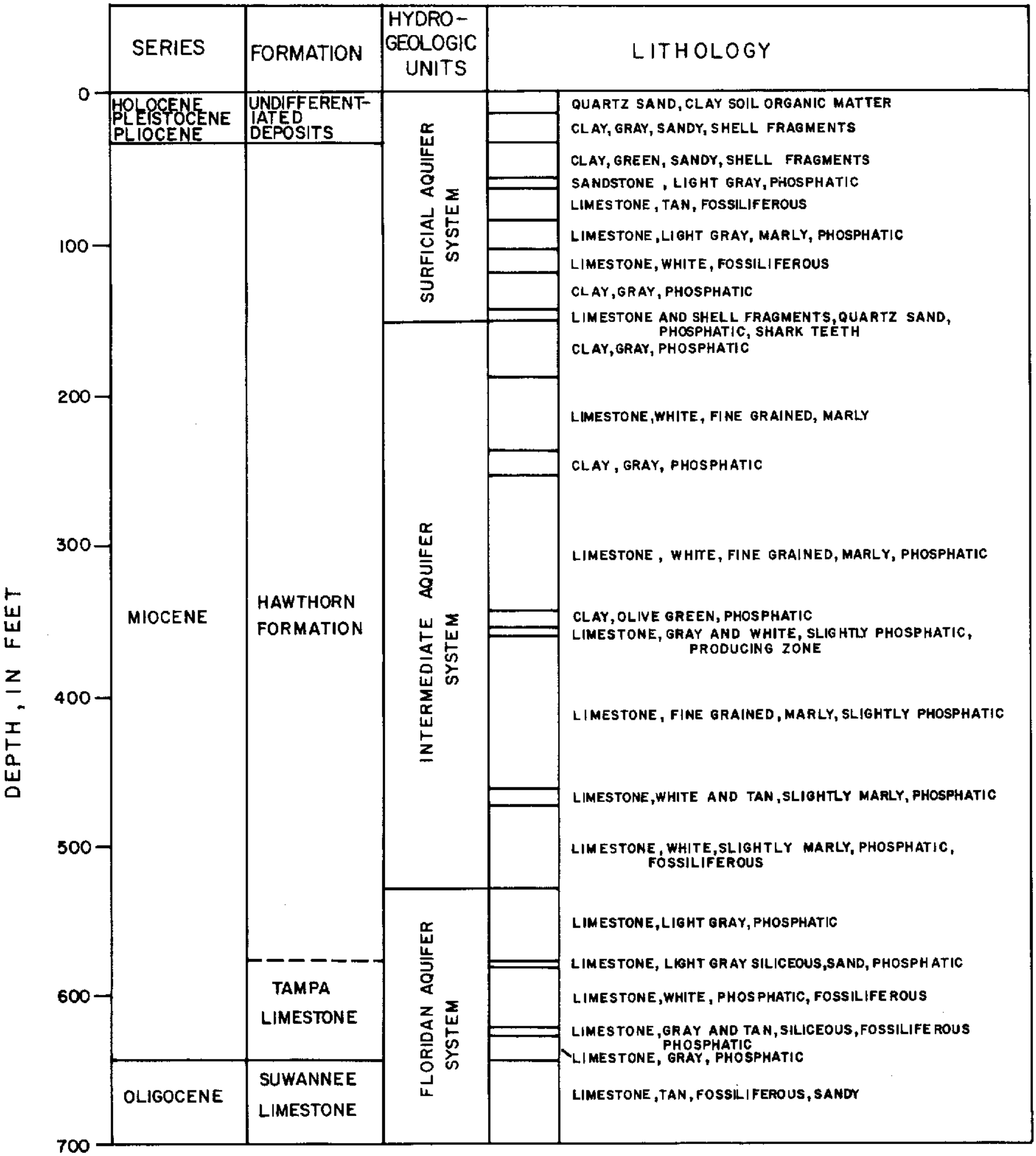

Figure 3.--Geologic log of test hole L-2901 at the Lee County water-treatment plant.

Table 1.--Well-construction data for injection well L-3225, test hole L-2901, and observation wells L-2530 and L-3224

Local well No.	Year drilled	Well depth (ft)	Depth cased (ft)	Well diameter (in.)	Altitude of land surface (ft, sea level)
L-2530	1977	615	475	4-2	7.20
L-2901	1979	705	60	6-4	10.72
L-3224	1979	620	460	4	9.99
L-3225	1980	600	445	10-9	10.72

Table 2.--Background water-quality data for injection well L-3225 and observation wells L-2530 and L-3224

[Concentrations in milligrams per liter, except where noted]

Constituent	Well L-3225	Well L-2530	Well L-3224
Major dissolved inorganics and related physical characteristics			
Alkalinity (as $CaCO_3$)	192	188	192
Calcium (Ca)	87	71	72
Chloride (Cl)	550	500	520
Fluoride (F)	1.6	1.6	1.6
Magnesium (Mg)	80	74	78
Potassium (K)	19	19	20
Silica (SiO_2)	14	13	13
Sodium (Na)	340	300	310
Sulfate (SO_4)	340	270	270
Noncarbonate hardness (as $CaCO_3$)	410	380	380
Total hardness (as $CaCO_3$)	560	500	520
Dissolved solids (residue at 180°C).	1,580	1,520	1,560
pH (units)	7.4	7.2	7.4
Temperature (°C)	26.6	26.5	26.0
Total trace elements			
Aluminum (Al)	.02	.01	.02
Arsenic (As)	.001	.001	.001
Barium (Ba)	<.05	<.05	<.05
Boron (B)	.56	.58	.62
Cadmium (Cd)	.00	.00	.00
Chromium (Cr)	.01	.01	<.01
Copper (Cu)	.00	.00	.00
Iron (Fe)	.02	.02	.02
Lead (Pb)	.001	.001	.001
Manganese (Mn)	.01	.01	.01
Mercury (Hg)	.0002	<.0001	<.0001
Molybdenum (Mo)	.001	.00	.001
Nickel (Ni)	.00	.001	.00
Selenium (Se)	.00	.00	.00
Silver (Ag)	.00	.00	.00
Strontium (Sr), dissolved	15.00	14.00	13.00
Zinc (Zn)	.01	.01	.01
Selected total nutrients and related characteristics			
Ammonia nitrogen	.35	.30	.35
Organic nitrogen	.70	.58	.55
Nitrate nitrogen	.00	.01	.00
Nitrite nitrogen	.00	.00	.01
Chemical oxygen demand	110	120	110
Phosphorus	.01	.01	.01
Total orthophosphate phosphorus	.00	.00	.00

Table 3.--Background bacteriological data for injection well L-3225 and observation wells L-2530 and L-3224

[Analyses were conducted on July 15, 1980]

	Well L-3225	Well L-2530	Well L-3224
Bacteria (colonies/100 mL)			
Fecal coliform	0	0	0
Fecal streptococci	0	0	0
Bacteria (organisms/100 mL)			
Total anaerobes	<3	<3	<3
Total aerobes	20	75	50
Denitrifiers	93	43	3
Sulfate reducers	23	<3	23
Mathanogyens producing	<3	<3	<3

Aquifer Characteristics

Limestones in the lower part of the Hawthorn Formation together with the underlying Tampa Limestone comprise the uppermost producing zones of the Floridan aquifer system at the injection site. The aquifer system is under artesian pressure, and those wells at the test site have water levels that range from 40 to 50 feet above sea level. The general gradient of the potentiometric surface of the system is southwest.

Contributions of flow to wells from limestone sections of the open wellbore are variable as shown in figure 4 by logs of fluid resistivity and temperature and by a flow profile in test hole L-2901 and well L-3225. A temperature profile of the open wellbore of test hole L-2901 (fig. 4) indicates inflow to the open wellbore in the 550- to 580-foot interval. A second zone of inflow and one of higher permeability is indicated at the interval 505 to 525 feet. A similar configuration is noted in the fluid resistivity log (fig. 4), which gives a measure of the dissolved solids concentration in the water. The change in resistivity between 550 and 580 feet corresponds to the temperature-indicated change.

Flow data for injection well L-3225 (fig. 4) were determined by measuring fluid velocity at 5-foot intervals within the open wellbore and then calculating the flow by multiplying the velocity by the cross-sectional area in the borehole at the measurement intervals. These flow profiles were determined as the well was discharging at the surface at the rate of 250 gal/min and again as water was injected at a rate of 300 gal/min. The flow profiles corroborate the temperature and resistivity data which indicate that the most permeable part is the limestone section between 550 and 580 feet in depth. Analysis of discharge data indicates that about 70 percent of the flow contribution to the well occurs from 550 to 580 feet. Minor contributions are from the remainder of the open wellbore.

During injection tests on well L-3225, the specific capacity was increased as a result of acidizings in the well and was decreased as a result of residual clogging during injection. The variations in the specific capacity at different stages of the investigation are given in table 4.

An aquifer test was made prior to the injection tests to determine aquifer characteristics. Injection well L-3225 was pumped at a constant rate of 350 gal/min for 48 hours, and water-level responses were monitored in the injection well itself and in observation wells L-2530 and L-3224 (fig. 2). Test data were analyzed using the Hantush-Jacob model with the Cooper family of curves (Lohman, 1979, p. 30). Analysis of test data indicated that the transmissivity (T), storage (S), and leakance (K'_v/b') values are as follows:

$$T = 700 \text{ to } 800 \text{ ft}^2/\text{d}$$
$$S = 1 \times 10^{-4}$$
$$K'_v/b' = 0.01 \text{ per day}$$

where $K'v$ is vertical hydraulic conductivity of the confining bed;
b' is thickness of the confining bed.

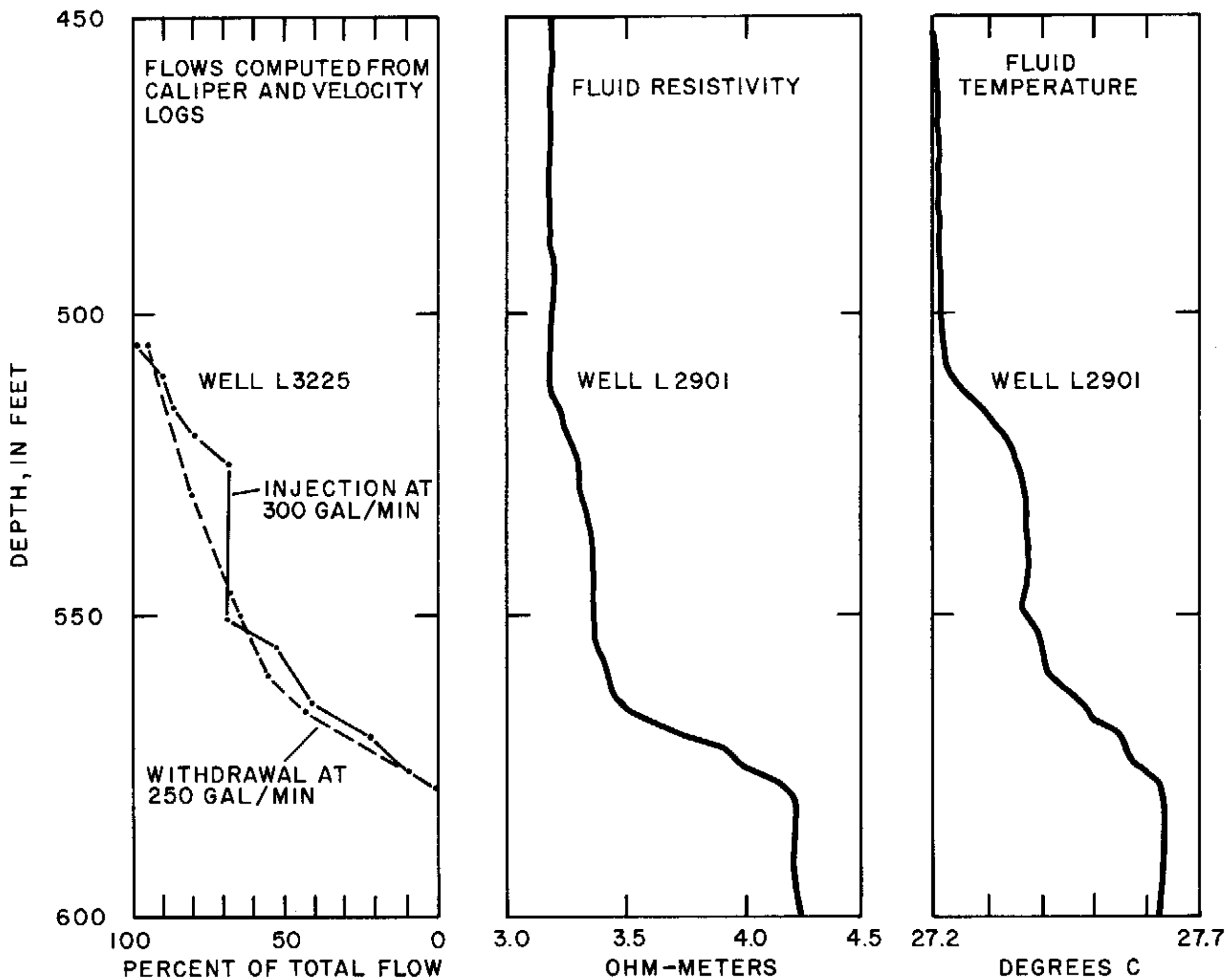

Figure 4.--Percent of total flow profile from velocity and caliper logs from injection well L-3225 and fluid resistivity and temperature logs from test hole L-2901.

Table 4.--Specific-capacity data for injection well L-3225

[Specific capacity in gallons per minute per foot of drawdown]

Project stage	Date	Specific capacity[1/]
Preinjection test (background data)	10/8/80	5.38
Following injection Test 1	12/9/80	3.84
Prior to first well acidizing	2/20/81	4.18
Following first well acidizing	2/22/81	7.89
Prior to second well acidizing	2/24/81	5.45
Following second well acidizing	8/5/81	8.91
Following injection Test 3	7/13/82	5.11

1/ Values were calculated at a flow rate of 90 gal/min.

Values indicate leaky artesian conditions and a comparatively low transmissivity. The leakance is an integrated parameter that represents movement from units above and below the permeable limestone section to which the well is open. Lithologic data indicate that most of the leakage probably occurs through the lower semiconfining layer. The permeable limestone section is separated from the deeper parts of the Floridan aquifer system by about 60 feet of gray limestone of low permeability, which is probably part of the Tampa Limestone. The overlying confining layer consists of a finer grained, marly limestone of even lower permeability.

AVAILABILITY OF FRESHWATER FOR INJECTION

The Caloosahatchee River is the source of freshwater at the test site. The freshwater reach of the river extends 42 miles from Lake Okeechobee to Franklin Lock (S-79) (fig. 1) and drains a basin of 850 mi^2 of relatively flat topography (La Rose and McPherson, 1980). Sources of freshwater in the river are discharge releases from Lake Okeechobee and basin runoff. Seasonal rainfall results in a range of freshwater discharge and water quality in the river. Examination of this discharge is essential to determine times of optimum injection-water availability and quality.

Monthly river discharge data for 1974-81 at S-79, 1 mile downstream from the Lee County water-treatment plant, are illustrated in figure 5. The period of greatest discharge was July through October; maximum flow during those wet-season months exceeded 650 Mgal/d and the minimum flow during those months exceeded 50 Mgal/d.

Salinity in the river water is the major water-quality consideration, with regard to freshwater injection. Chloride concentration, an indicator of salinity, was monitored at the bottom of the river channel at S-79; the monthly data are illustrated in figure 6. Chloride concentrations at S-79 closely approximate those in the river at the injection site. The chloride data are derived from continuous specific conductance data converted to chloride concentration by interpolation of the chloride and specific conductance relationship determined at S-79.

Chloride concentrations are highest near the end of the dry season (March to May) and lowest during the wet season (June to October). For the period of record, 1974-81, chloride concentrations did not exceed 65 mg/L during August through October, nor did the maximum concentrations exceed the secondary maximum contaminant level for drinking water of 250 mg/L (Florida Department of Environmental Regulation, 1982). Concentrations of selected chemical constituents at S-79 for 1976-79 are given in table 5 (La Rose and McPherson, 1983).

Another major water-quality consideration, with regard to injection of river water, is algal accumulation because of its effect on well clogging. Generally, algae increased in late spring and early summer and decreased during late summer and autumn (McPherson and La Rose, 1981). Considering streamflow, chloride concentration, and other water-quality constituents, the ideal period to inject river water seems to be between August and October.

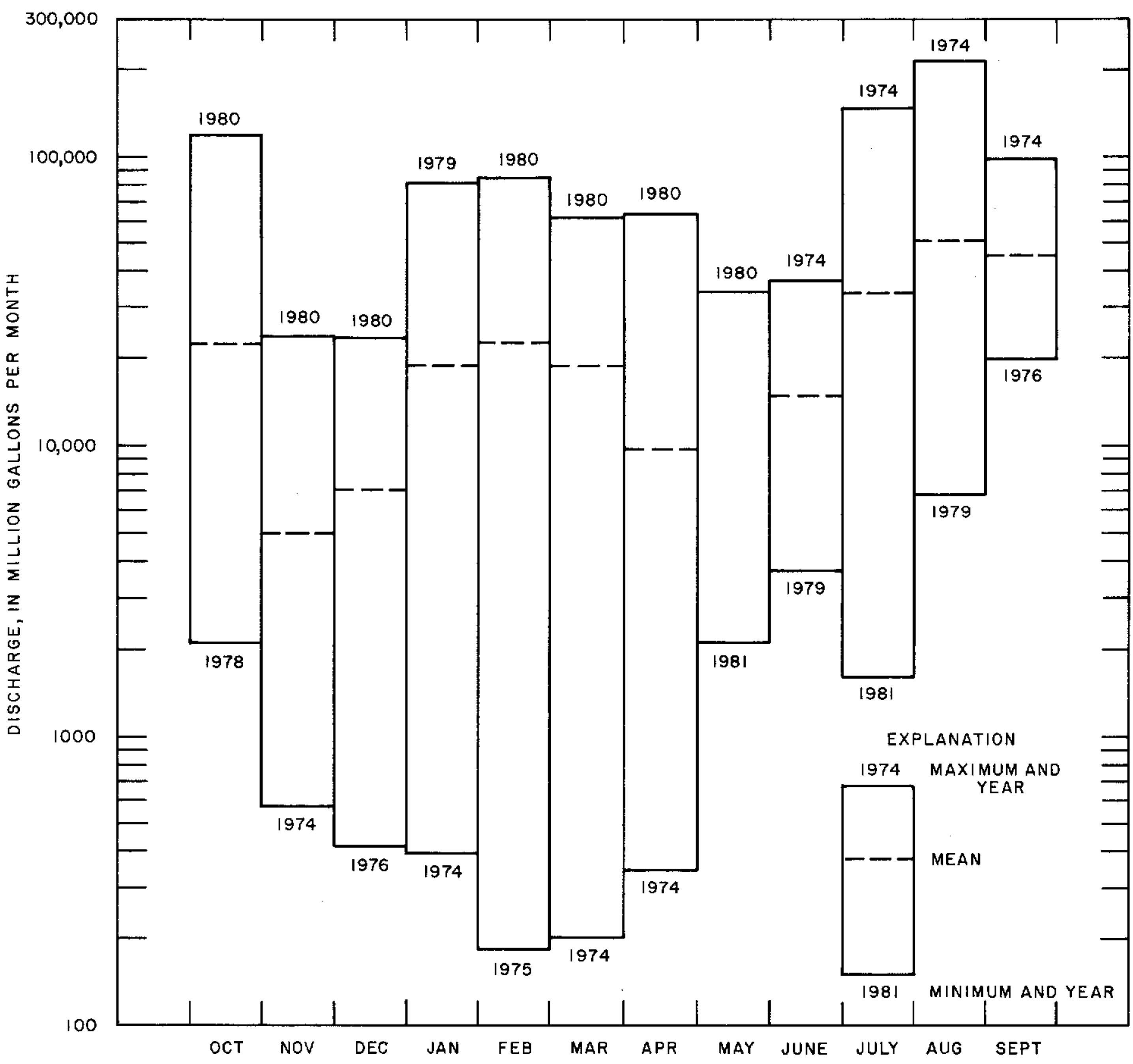

Figure 5.--Maximum, minimum, and mean monthly discharge for the Caloosahatchee River at S-79, 1974-81.

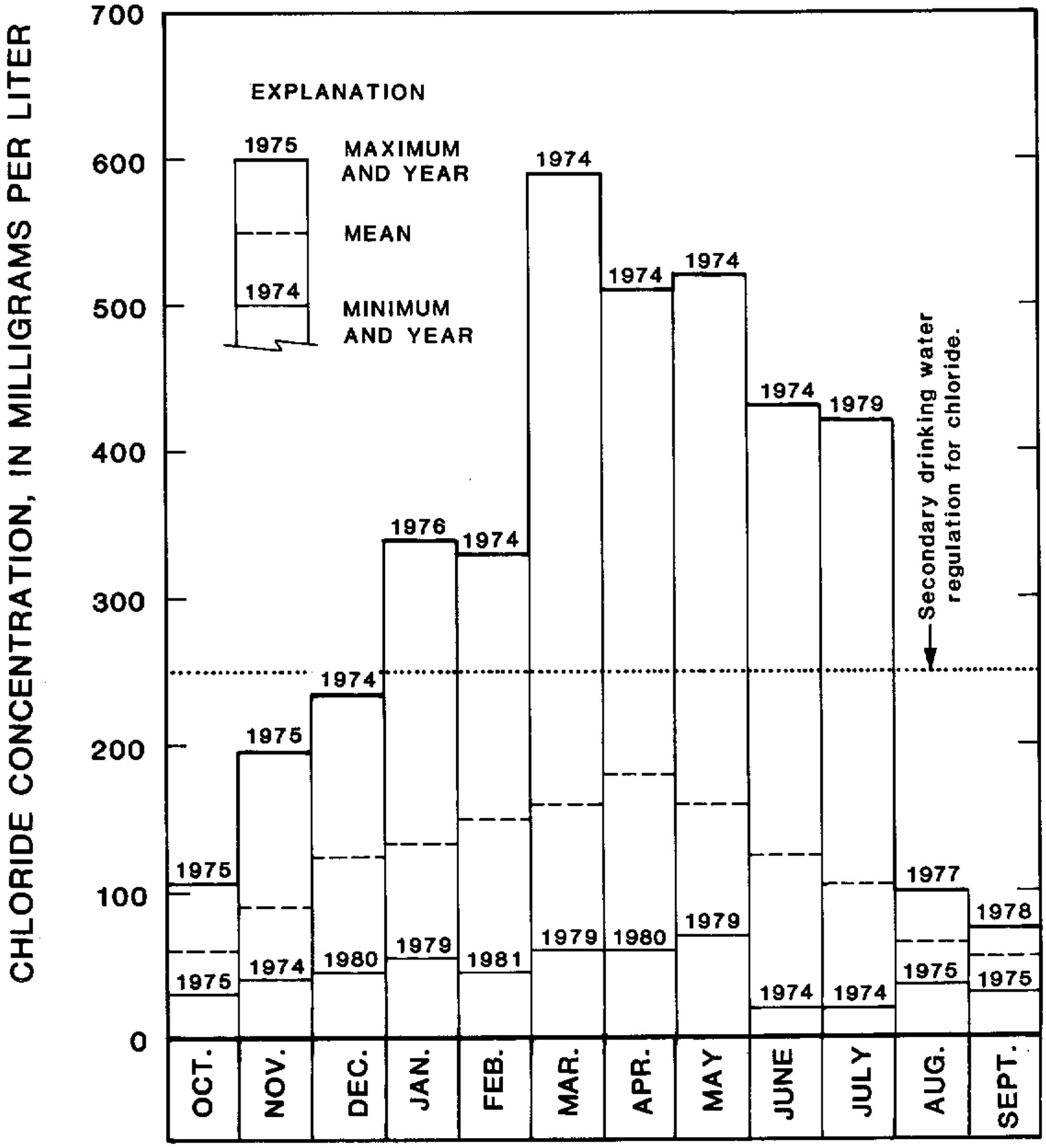

Figure 6.--Maximum, minimum, and mean monthly chloride concentrations for the Caloosahatchee River at S-79, 1974-81.

Table 5.--Water-quality data for the Caloosahatchee River at S-79, 1976-79

[Adapted from La Rose and McPherson, 1983; concentrations in milligrams per liter]

Constituent	No. of samples	Mean	Maximum	Minimum
Major dissolved inorganics				
Calcium (Ca)	41	72	272	40
Chloride (Cl)	43	96	270	46
Fluoride (F)	41	.3	.6	.1
Magnesium (Mg)	41	14	25	7.9
Potassium (K)	41	4.7	8.0	2.7
Silica (SiO_2)	41	7.1	10	3.7
Sodium (Na)	41	54	140	4.6
Sulfate (SO_4)	41	49	90	27
Bicarbonate (as HCO_3)	50	195	250	120
Dissolved solids (residue at 180°C).	41	457	806	313
Total trace elements				
Aluminum (Al)	6	.06	.10	.04
Arsenic (As)	6	.002	.005	.001
Boron (B)	6	.09	.13	.03
Copper (Cu)	6	.002	.004	.00
Iron (Fe)	6	.23	.37	.12
Lead (Pb)	2	.001	.001	.00
Manganese (Mn)	6	.02	.02	.01
Mercury (Hg)	6	.0005	.0005	.0005
Nickel (Ni)	6	.005	.011	.00
Strontium (Sr), dissolved	41	.89	2.10	.10
Zinc (Zn)	6	.02	.05	.00

INJECTION AND MONITORING PROCEDURES

A system was designed to inject treated or untreated river water at a minimum rate of 300 gal/min. Water was pumped from the county water-treatment plant's intake canal and injected into the well through a 10-inch galvanized "T" at the wellhead; recovery of the water was by artesian flow. One or two intake lines were used, depending on whether treated or untreated water was being injected. Hydrologic data collection included injection and discharge rates, changes in hydraulic head, and water quality.

Water-quality data were collected throughout the injection and recovery test periods. A continual recording, flow-through water-quality monitor was installed in the injection-discharge line. Temperature, specific conductance, pH, and dissolved oxygen were monitored hourly during the injection and recovery cycles. Manual measurements were also made periodically for calibration purposes. Water samples were collected less frequently for analyzing major ions, trace metals, nutrients, organics, and bacteria. Sampling frequency varied during each test and depended largely on the expected rate of change in concentration of the chemical constituents. Major ion, nutrient, organic, and bacteriological data were also collected from observation wells L-2530 and L-3224.

Three injection tests were conducted to examine the suitability of storing freshwater in the artesian limestone between 550 and 580 feet. Injection duration, injection rate, storage duration of injectant, and quality of water injected (treated or untreated) all varied during the test. A summary of information relating to the tests is given in table 6.

Temperature of the injected water changed during each test but most significantly in those tests of extended duration. For example, temperature during the second test varied between 20.5°C and 26.2°C over a 16-day period, and temperature during the third test varied between 31.2°C and 25.4°C over a 70-day period. Because the viscosity of water varies inversely with temperature and the hydraulic conductivity varies inversely with the viscosity of water, adjustments were made in the measured head buildup to account for these temperature differences. Head-buildup measurements during the three tests were adjusted to the equivalent at 26.6°C, the temperature of the native ground water. Adjustments were made using the kinematic viscosity of water (Clark, 1966, p. 916):

$$H\ (26.6^\circ C) = \frac{V\ (26.6^\circ C)}{V\ (X^\circ C)} \times H\ (X^\circ C)$$

where H is head buildup in the injection well;
V is kinematic viscosity;
X°C is water temperature corresponding to the observed head buildup.

Test 1

The objective of Test 1 was to determine the recoverability of the injected water immediately after injection stopped. The test called for the injection of untreated river water at 350 gal/min for 2 weeks followed

Table 6.--Summary of parameters for three injection tests

Test No.	Date	Type of water injected	Injection rate (gal/min)	Total amount injected (1,000 gallons)	Storage duration (days)	Recovery rate (gal/min)
1	10/14/80	Untreated	350-170	572	0	95-120
2	3/26/81	Untreated	300	6,832	47	165
3	8/18/81	Treated	300	8,548		
		Untreated	300	20,478	98	150

by immediate recovery. During the initial part of the injection period, a rapid buildup of pressure to the maximum output of the injection pump, about 100 lb/in^2, caused a decrease in injection rate to 170 gal/min. The test was discontinued after 40 hours at which time 572,000 gallons had been injected. The maximum head buildup of 193 feet occurred after 37 minutes of injection. Graphs of head buildup in injection well L-3225 and the decline in injection rate over time are illustrated in figure 7.

Except for pH and suspended solids, little variation of river-water quality was noted during the injection period. Higher variations in pH and suspended solids concentrations were observed during the injection period as a result of temporary operational problems at the water plant where high concentrations of residue, entrapped in the water plant's filter system, were being discharged to the intake canal on October 15, 1980 (table 7). The duration of these effects on the injection water quality was generally 1 to 2 hours. The intake water became highly alkaline, and the suspended solids increased from 7 to more than 40 mg/L.

The chloride concentration of the recovered water was 58 mg/L (table 7) initially and then increased to that of the native ground water, about 500 mg/L. About 221,000 gallons of the recovered water, or 38.7 percent of the total volume injected, had a chloride concentration of 250 mg/L or less. Analyses of water samples collected during recovery are given in table 8.

Test 2

Prior to Test 2, the injection well was acidized to improve the specific capacity (table 4). In Test 2, untreated river water was injected at 300 gal/min for 16 days. During the test, the injection was stopped 3 times, and the injection well was backflushed by artesian flow development at intervals of 1 1/2 to 2 1/2 hours. The net amount injected was about 6,800,000 gallons. Recovery at a rate of 165 gal/min began after a 47-day storage period. The head at the injection well rose from 35 to 80 feet after 16 days of injection. Reductions in the head were noted when backflushing occurred; however, the trend throughout the test was upward. A graph of head buildup over time and the effects of backflushing are illustrated in figure 8.

The quality of the untreated river water varied during the test. As shown in figure 9, chloride concentrations ranged from about 350 to 135 mg/L although during most of the injection period concentrations ranged from 150 to 175 mg/L. Other water-quality constituents are given in table 9.

Water-quality characteristics of the initially recovered water, compared to primary and secondary drinking water regulations where appropriate, are given in table 10. Only iron and dissolved solids concentrations exceeded drinking water standards.

The chloride concentration of 200 mg/L in the initially recovered water, relative to the chloride concentration at the end of injection (170 mg/L), suggests that the injected water had mixed with the resident ground water.

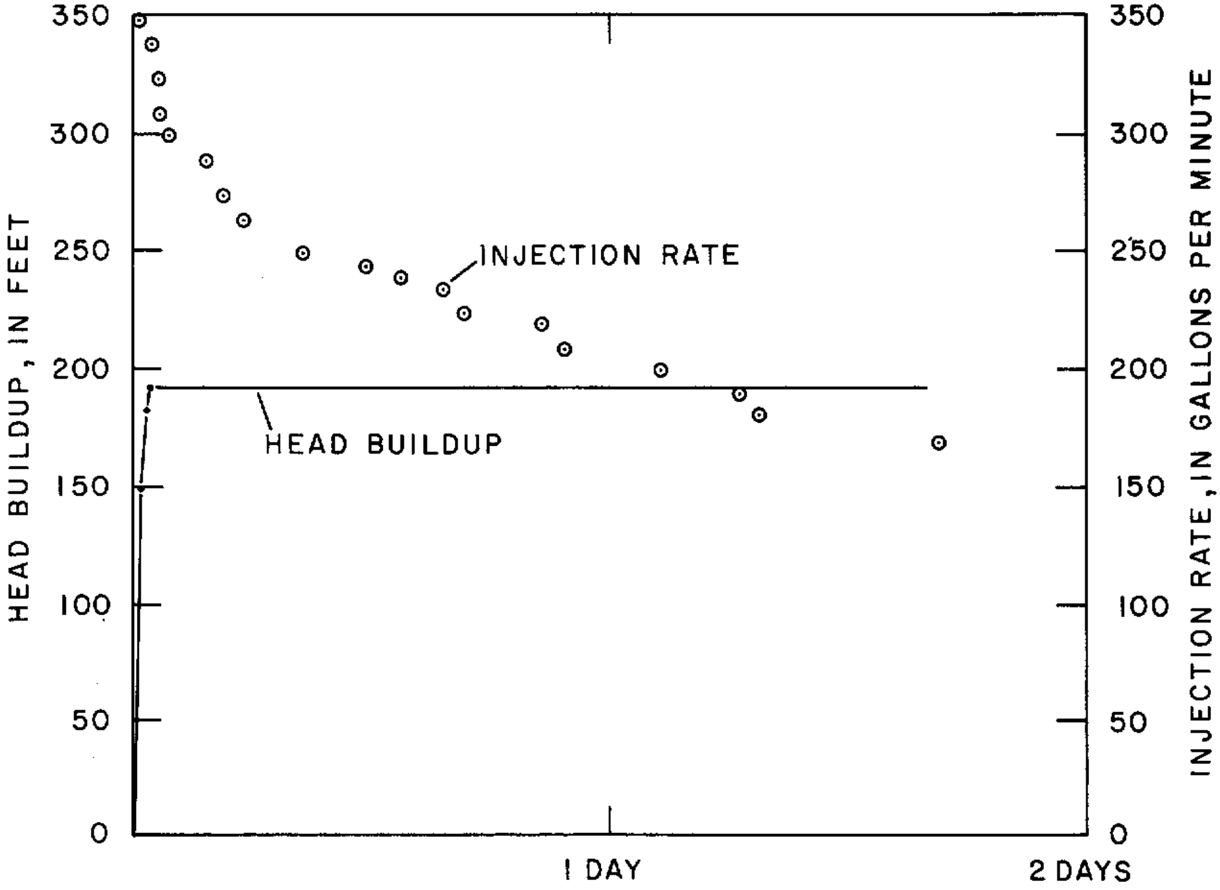

Figure 7.--Injection-head buildup and injection rate decline during Test 1.

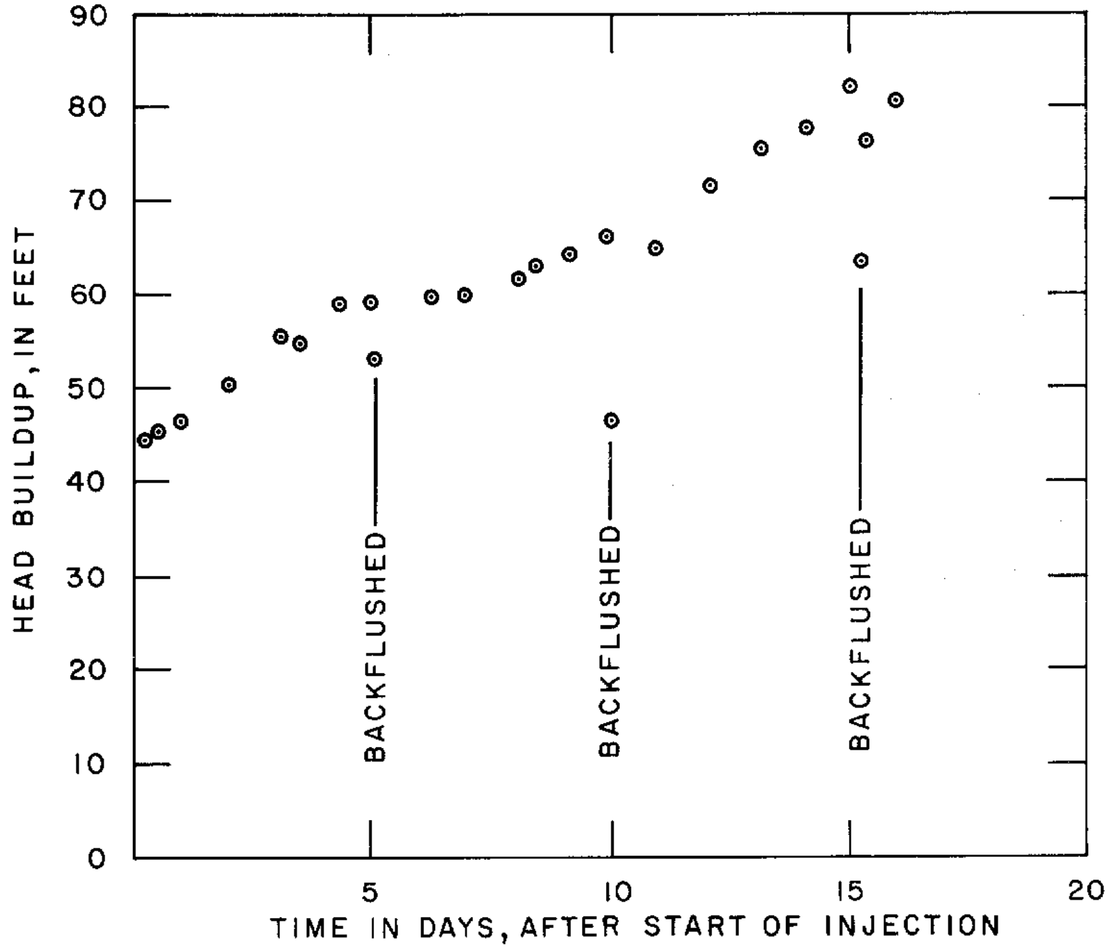

Figure 8.--Injection-head buildup over time during Test 2.

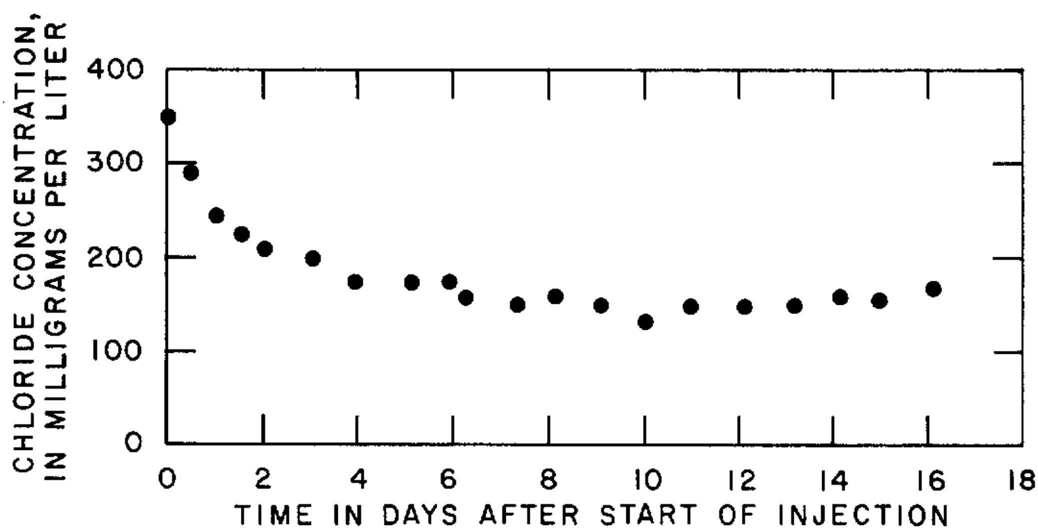

Figure 9.--Chloride concentrations of injected water over time during Test 2.

Table 7.--Water-quality data of untreated Caloosahatchee River water injected during Test 1

[Concentrations in milligrams per liter, except where noted]

Constituent	Date 10/14/80	Date 10/15/80
Time of collection	1745	2300
Major dissolved inorganics and related physical characteristics		
Alkalinity (as $CaCO_3$)	140	99
Calcium (Ca)	65	56
Chloride (Cl)	58	61
Fluoride (F)	.3	.2
Magnesium (Mg)	7.9	5.5
Potassium (K)	2.7	3.6
Silica (SiO_2)	9.9	8.5
Sodium (Na)	33	30
Sulfate (SO_4)	39	42
Noncarbonate hardness (as $CaCO_3$)	56	64
Total hardness (as $CaCO_3$)	280	160
Dissolved solids (residue at 180°C)	342	320
Suspended solids (110°C)	7	43
Temperature (°C)	28.0	26.0
pH (units)	7.6	8.6
Turbidity (NTU)	4	
Dissolved trace elements		
Iron (Fe)	.140	.01
Strontium (Sr)	.700	.56
Selected total nutrients and related characteristics		
Ammonia nitrogen	.04	
Organic nitrogen	2.9	
Nitrate nitrogen	.40	
Nitrite nitrogen	.01	
Phosphorus	.17	
Total orthophosphate phosphorus	.10	

Table 8.--Quality of recovered water during Test 1

[Concentrations in milligrams per liter, except where noted]

Constituent	Date 10/16/80	10/18/80	10/20/80
Time of collection	1200	0700	1145
Percent of injected water	5	39	86
Major dissolved inorganics and related physical characteristics			
Alkalinity (as $CaCO_3$)	150	140	140
Calcium (Ca)	61	59	61
Chloride (Cl)	56	250	360
Fluoride (F)	.3	1.2	1.4
Magnesium (Mg)	10	35	47
Potassium (K)	3.7	10	13
Silica (SiO_2)	9.9	11	12
Sodium (Na)	32	190	270
Sulfate (SO_4)	38	180	230
Noncarbonate hardness (as $CaCO_3$)	45	160	220
Total hardness (as $CaCO_3$)	190	300	360
Dissolved solids (residue at 180°C)	352	856	1,150
Suspended solids (110°C)	3	0	0
pH (units)	7.2	7.2	7.4
Temperature (°C)	26.0	26.5	26.5
Dissolved trace elements			
Iron (Fe)	.13	.06	.11
Strontium (Sr)	1.00	8.70	12.00
Selected total nutrients and related characteristics			
Ammonia nitrogen	.04	.15	.22
Organic nitrogen	.62	.07	.06
Nitrate nitrogen	.37	.00	.00
Nitrite nitrogen	.01	.00	.00
Phosphorus	.11	.02	.02
Total orthophosphate phosphorus	.08	.02	.01

Table 9.--Water-quality data of untreated Caloosahatchee River water injected during Test 2

[Concentrations in milligrams per liter, except where noted]

Constituent	No. of samples	Range	Average
Major dissolved inorganics and related physical characteristics			
Alkalinity (as $CaCO_3$)	3	150 - 170	163
Calcium (Ca)	4	69 - 91	84
Chloride (Cl)	3	180 - 270	223
Fluoride (F)	3	.3 - .4	.4
Magnesium (Mg)	4	21 - 31	25
Potassium (K)	4	7.5 - 11.0	8.9
Silica (SiO_2)	4	4.7 - 6.5	5.6
Sodium (Na)	4	83 - 220	153
Sulfate (SO_4)	3	66 - 91	80
Noncarbonate hardness (as $CaCO_3$)	3	130 - 180	153
Total hardness (as $CaCO_3$)	3	300 - 330	317
Dissolved solids (residue at 180°C)	3	576 - 768	675
pH (units)	4	8.0 - 8.4	
Temperature (°C)	2	20.5 - 25.5	23.0
Dissolved trace elements			
Iron (Fe)	4	.01 - .03	.02
Strontium (Sr)	4	1.20 - 1.50	1.40
Selected total nutrients and related characteristics			
Ammonia nitrogen	4	.04 - .08	.06
Nitrate nitrogen	4	.02 - .28	.17
Nitrite nitrogen	4	.00 - .02	.01
Organic nitrogen	4	.82 - 1.60	1.12
Dissolved organic carbon	3	16 - 18	17
Total organic carbon	4	16 - 21	18.5
Phosphorus	4	.06 - .10	.08
Total orthophosphate phosphorus	4	.04 - .08	.06

Table 10.—Quality of recovered water during Test 2

[Concentrations in milligrams per liter, except where noted]

Constituent	Maximum contaminant level[1/] Primary regulation	Secondary regulation	Date, 5/27/81
Time of collection			1300
Major dissolved inorganics and related physical characteristics			
Alkalinity (as $CaCO_3$)			160
Calcium (Ca)			68
Chloride (Cl)		250	200
Fluoride (F)	1.0		.9
Magnesium (Mg)			31
Potassium (K)			8.5
Silica (SiO_2)			8.7
Sodium (Na)			140
Sulfate (SO_4)		250	150
Noncarbonate hardness (as $CaCO_3$)			140
Total hardness (as $CaCO_3$)			300
Dissolved solids (residue at 180°C)		500	771
pH (units)		6.5 - 8.5	7.5
Total trace elements			
Arsenic (As)	.05		.008
Barium (Ba)	1.00		.1
Cadmium (Cd)	.010		.001
Chromium (Cr)	.05		.01
Copper (Cu)		1	.002
Iron (Fe)		.3	.44
Lead (Pb)	.05		.002
Manganese (Mn)		.05	.01
Mercury (Hg)	.002		.0002
Selenium (Se)	.01		.000
Silver (Ag)	.05		.000
Strontium (Sr), dissolved			4.70
Zinc (Zn)		5	.01
Selected total nutrients and related characteristics			
Ammonia nitrogen			.30
Organic nitrogen			.57
Nitrate nitrogen	10		.00
Nitrite nitrogen			.00
Chemical oxygen demand			45
Dissolved organic carbon			16
Suspended organic carbon			0
Phosphorus			.03
Total orthophosphate phosphorus			.02

1/ Florida Department of Environmental Regulation, 1982, Public drinking water systems: Chapter 17-22 *in* Florida Administrative Code.

Soon after recovery began, the chloride concentration increased steadily, approaching that of the resident ground water (fig. 10). About 663,000 gallons of the recovered water, or 9.7 percent of the total river water injected, had a chloride concentration of 250 mg/L or less.

Bacteriological data of the recovered water and of water from the observation wells were collected at the start of the recovery and are given in table 11. The data suggest that injection has resulted in marked bacterial growth in the vicinity of the observation well at 140 feet from the injection well, but minimal growth at the well 335 feet from the injection well.

Test 3

Test 3 followed a second acidizing of the injection well. This time treated water from the water plant and untreated river water were injected to observe the difference in pressure buildup due to clogging. Treated water was injected intermittently at the rate of 300 gal/min until 8,458,000 gallons were injected after 26 days. After a 2-day delay, untreated water was injected at 300 gal/min for 51 days, but injection was interrupted periodically to backflush the well by surging it with air. The interval between backflushings was reduced during the test from 7 days, initially, to 2 days near the end of the test. A total of 20,873,000 gallons was injected, and about 395,000 gallons were discharged during backflushings. The injectant was stored for 98 days after which recovery began at about 150 gal/min.

Chloride concentrations ranged from 84 to 134 mg/L for treated water and from 54 to 100 mg/L for untreated water. Dissolved solids concentrations ranged from 365 to 467 mg/L for treated water and 340 to 470 mg/L for untreated water. Constituents in the treated and untreated water are given in tables 12 and 13. Water-treatment processes at the plant caused chemical variations in the river water at the intake which included: (1) increased concentrations of chloride, sulfate, and sodium and a general increase in pH; (2) decreased alkalinity, turbidity, and concentrations of organic constituents, hardness, and most of the other major ions; and (3) absence of bacteria.

Turbidity and concentrations of suspended solids were measured more frequently than other constituents because they are important considerations in the potential for clogging of the injection well. Suspended solids concentrations and turbidity of the treated water during injection are illustrated in figures 11 and 12. Suspended solids concentrations and turbidity of the untreated water during injection are illustrated in figures 13 and 14. Concentrations of suspended solids were low during Test 3, ranging from 2 to 11 mg/L for both treated and untreated water. Turbidity showed fairly rapid changes ranging from less than 2 units to 75 units for untreated water. Large fluctuations can be expected because flows in the river are man regulated for boat lockages at S-79 and by releases of highly colored water from Lake Okeechobee for lake-level regulation.

Water quality in observation wells L-2530 and L-3224 was also monitored. Chloride concentrations in these wells along with those of the injected water are illustrated in figure 15. The chloride concentration in well L-2530

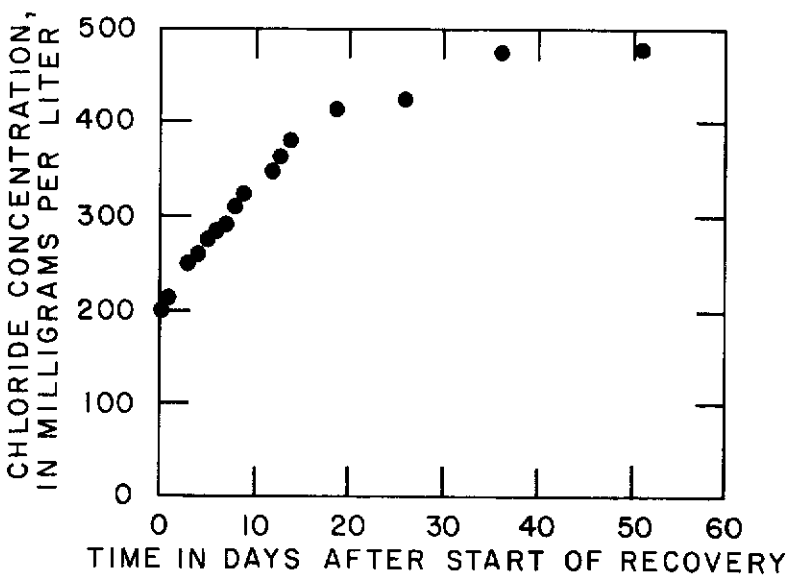

Figure 10.--Chloride concentrations of recovered water over time from injection well L-3225 during Test 2.

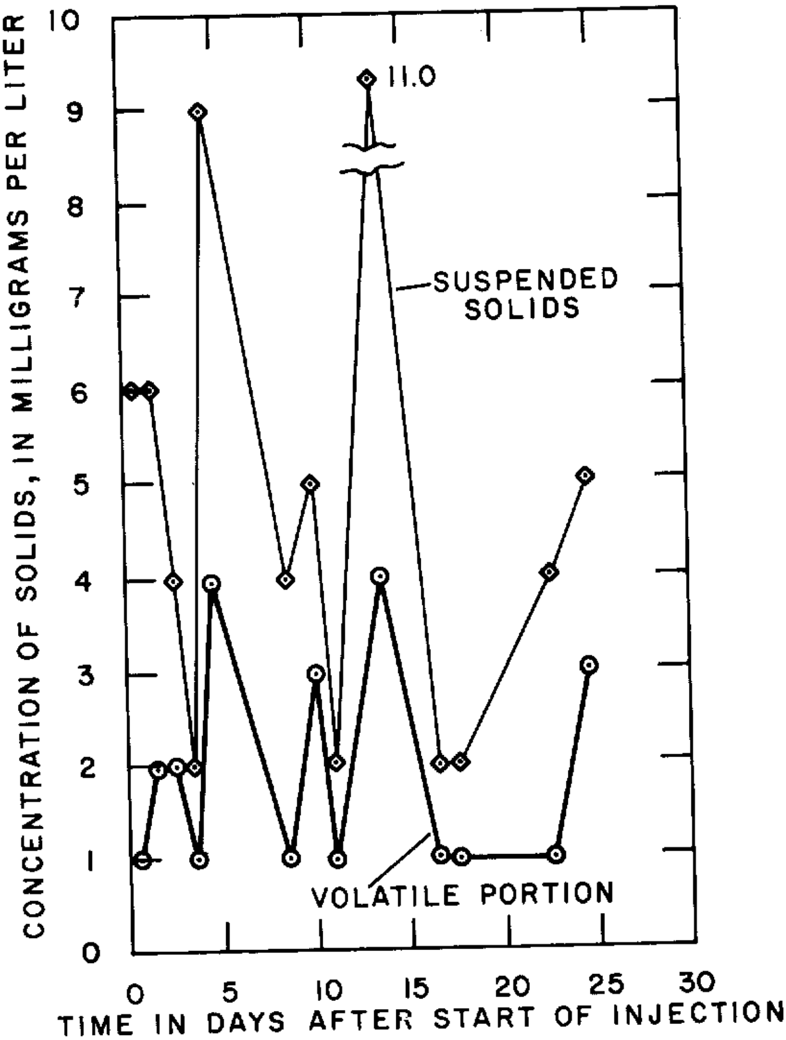

Figure 11.--Concentrations of suspended solids and the volatile part in treated injected water during Test 3.

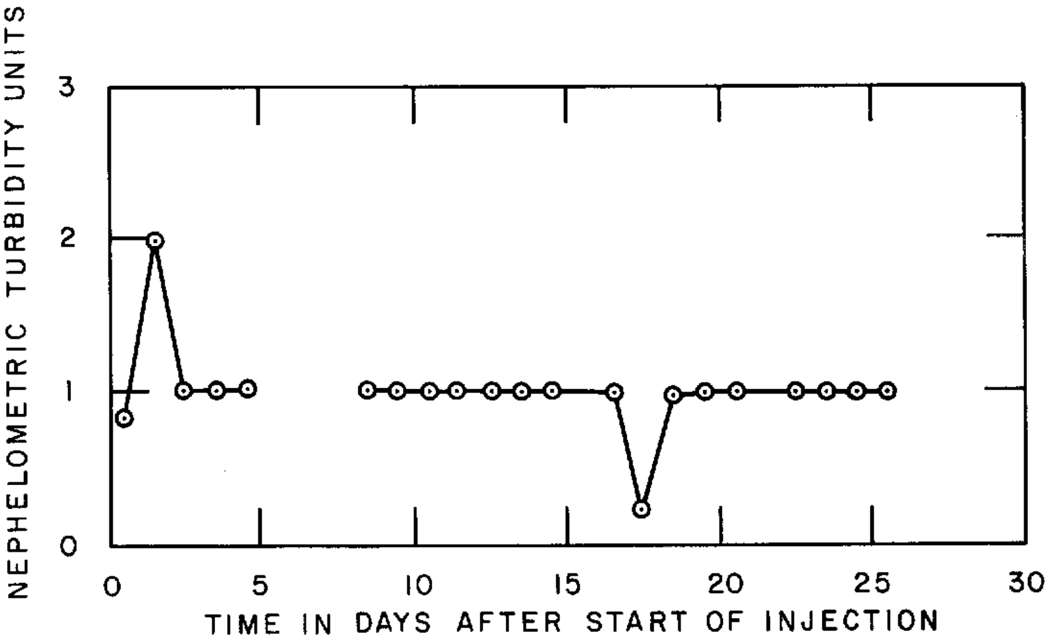

Figure 12.--Turbidity in treated injected water during Test 3.

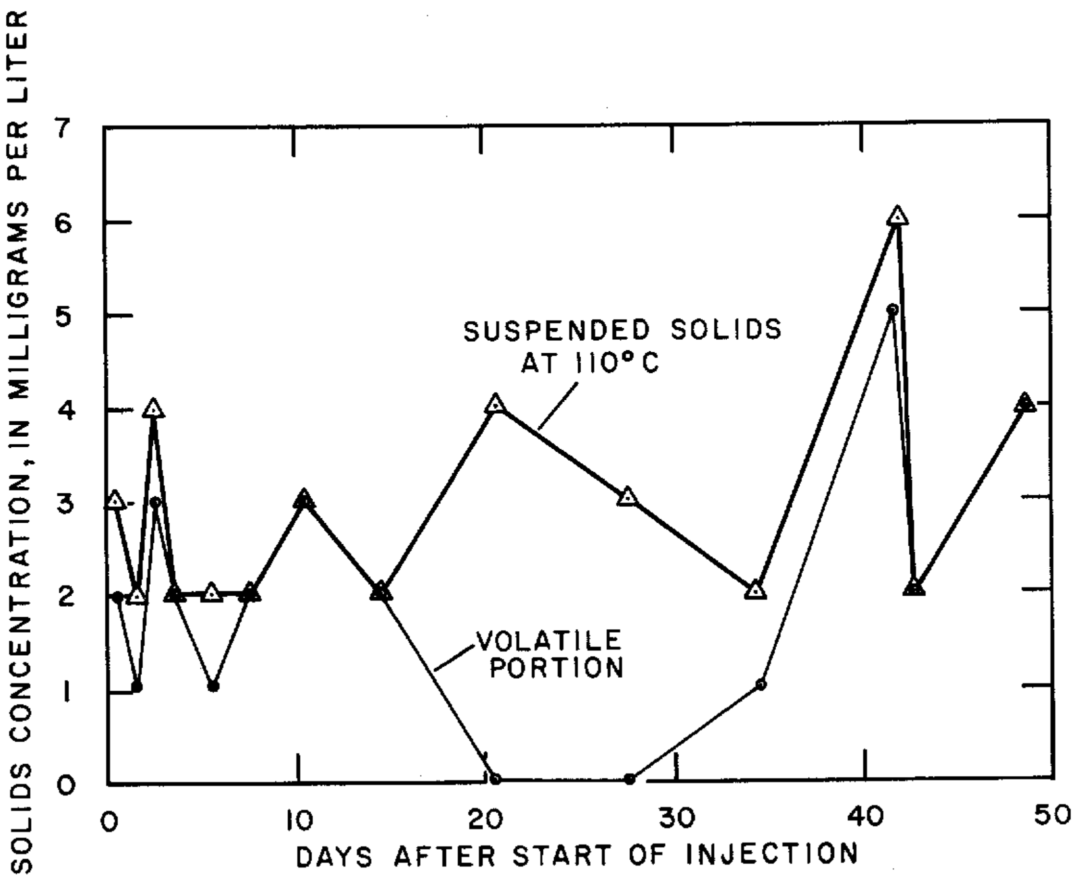

Figure 13.--Concentrations of suspended solids and the volatile part in untreated injected water during Test 3.

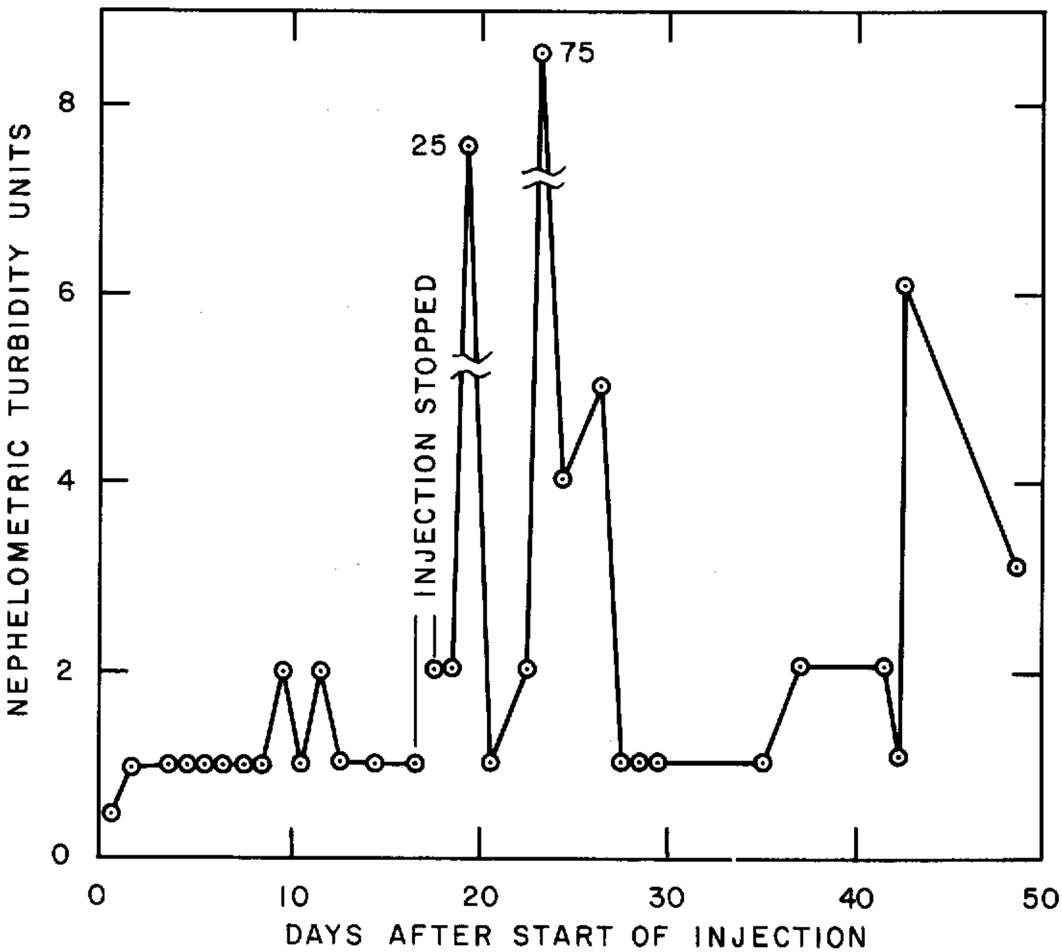

Figure 14.--Turbidity in untreated injected water during Test 3.

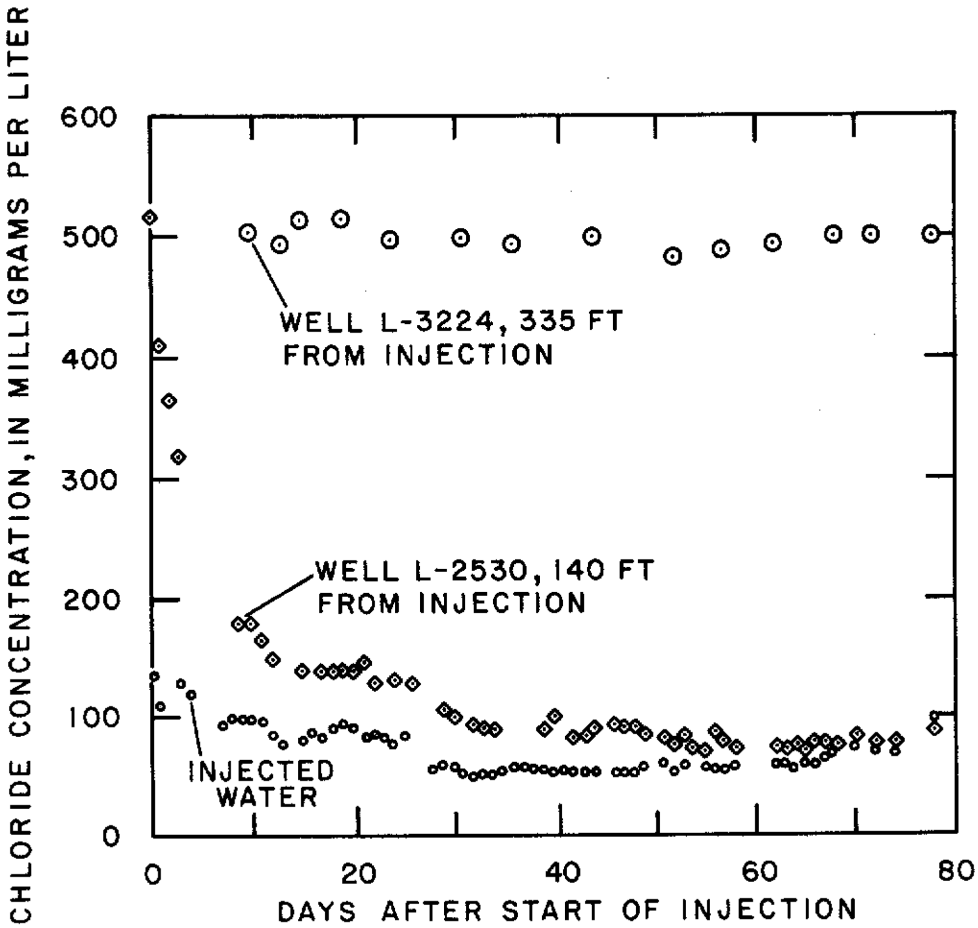

Figure 15.--Chloride concentrations of injected water and of water from observation wells L-2530 and L-3224 during Test 3.

Table 11.--Bacteriological data for injection well L-3225 and observation wells L-2530 and L-3224 during the recovery period of Test 2

[Analyses were conducted on May 27, 1981; analyses in parentheses indicate that a second analysis was conducted that same day]

	Well L-3225		Well L-2530	Well L-3224
Bacteria (colonies/100 mL)				
Fecal coliform	0	(0)	0	0
Fecal streptococci	0	(0)	0	0
Bacteria (organisms/100 mL)				
Total anaerobes	>2,400	(>2,400)	23	<3
Total aerobes	>2,400	(>2,400)	240	4
Denitrifiers	>2,400	(>2,400)	1,100	43
Sulfate reducers	10^6	(10^4)	10^2	10
Methanogyens producing	5×10^5	(5×10^4)	<1	<1

Table 12.--Water-quality data of treated Caloosahatchee River water injected during Test 3

[Concentrations in milligrams per liter, except where noted]

Constituent	No. of samples	Range	Average
Major dissolved inorganics and related physical characteristics			
Alkalinity (as $CaCO_3$)	5	17 - 53	39
Calcium (Ca)	4	40 - 58	48.8
Chloride (Cl)	5	84 - 134	107
Fluoride (F)	5	.1 - .3	.2
Magnesium (Mg)	4	4.2 - 12.0	8.0
Potassium (K)	4	4.1 - 6.7	5.6
Silica (SiO_2)	5	4.0 - 7.0	5.4
Sodium (Na)	4	34 - 66	52
Sulfate (SO_4)	5	54 - 86	68
Noncarbonate hardness (as $CaCO_3$)	4	110 - 130	120
Total hardness (as $CaCO_3$)	4	150 - 170	158
Dissolved solids (residue at 180°C)	5	365 - 467	407
pH (units)	5	6.6 - 9.7	
Temperature (°C)	3	29.5 - 30.5	30.0
Total trace elements			
Aluminum (Al)	1	.300	
Arsenic (As)	2	.001 - .002	
Barium (Ba)	2	<.050 - .100	
Cadmium (Cd)	2	.001	
Chromium (Cr)	2	.010 - .020	
Copper (Cu)	2	.008 - .020	
Iron (Fe)	5	.02 - .35	
Lead (Pb)	2	.002 - .009	
Manganese (Mn)	2	<.010	
Mercury (Hg)	2	.0001 - .0001	
Selenium (Se)	2	<.001	
Silver (Ag)	2	<.001	
Strontium (Sr), dissolved	4	.54 - .65	
Zinc (Zn)	2	.030 - .240	
Selected total nutrients and related characteristics			
Ammonia nitrogen	4	.01 - .03	.02
Organic nitrogen	4	.38 - .50	.44
Nitrate nitrogen	4	.34 - .73	.53
Nitrite nitrogen	4	.00	.00
Chemical oxygen demand	3	25 - 37	29
Dissolved organic carbon	4	7.6 - 12.0	9.9
Suspended organic carbon	4	.00 - .1	.075
Phosphorus	4	.33 - .56	.44
Total orthophosphate phosphorus	4	.02 - .09	.04

Table 13.--Water-quality data of untreated Caloosahatchee River water injected during Test 3

[Concentrations in milligrams per liter, except where noted]

Constituent	No. of samples	Range	Average
Major dissolved inorganics and related physical characteristics			
Alkalinity (as $CaCO_3$)	9	130 - 170	149
Calcium (Ca)	8	57 - 71	63
Chloride (Cl)	9	54 - 100	61
Fluoride (F)	9	.20 - .30	.26
Magnesium (Mg)	8	9.2 - 13.0	10.5
Potassium (K)	8	3.3 - 5.0	4.0
Silica (SiO_2)	9	8.4 - 11.0	9.4
Sodium (Na)	8	28 - 48	34
Sulfate (SO_4)	9	37 - 50	40
Noncarbonate hardness (as $CaCO_3$)	8	39 - 64	52
Total hardness (as $CaCO_3$)	8	180 - 230	201
Dissolved solids (residue at 180°C)	9	340 - 470	373
pH (units)	7	7.0 - 7.7	
Temperature (°C)	8	26.0 - 29.5	28.2
Total trace elements			
Aluminum (Al)	2	.08 - .10	
Arsenic (As)	2	.001 - .004	
Barium (Ba)	2	<.100 - .100	
Cadmium (Cd)	2	<.001	
Chromium (Cr)	2	.010 - .030	
Copper (Cu)	2	.006 - .031	
Iron (Fe)	8	.14 - .36	
Lead (Pb)	2	.003 - .004	
Manganese (Mn)	2	.010 - .023	
Mercury (Hg)	2	<.0001	
Selenium (Se)	2	<.001	
Silver (Ag)	2	<.001	
Strontium (Sr), dissolved	8	.63 - .83	
Zinc (Zn)	2	.020 - .080	
Selected total nutrients and related characteristics			
Ammonia nitrogen	6	.03 - .06	.04
Organic nitrogen	6	.85 - 1.10	.96
Nitrate nitrogen	6	.34 - .50	.42
Nitrite nitrogen	6	.01 - .03	.01
Chemical oxygen demand	6	25 - 65	44
Dissolved organic carbon	5	18 - 21	19.6
Suspended organic carbon	5	.01 - .3	.18
Phosphorus	6	.14 - .21	.17
Total orthophosphate phosphorus	6	.13 - .19	.15
Bacteria			
Fecal coliform (colonies per 100 mL)	5	8 - 98	35
Fecal streptococci (colonies per 100 mL)	4	17 - 200	102

began decreasing 1 day after injection started and continued until the end of the injection period when the concentration was nearly equal to that of the injected water (fig. 15). Conversely, little or no change was noted in well L-3224 as a result of the injection, suggesting anisotropic flow conditions in the aquifer. More complete water-quality data for observation wells L-2530 and L-3224 during Test 3 are given in table 14.

The rate of head buildup during the test was largely a function of the type of water injected. During the injection of treated water, the head increased 24 feet after 20 days, or a rate of 1.2 ft/d. During the injection of untreated water, the head increased 73 feet after 50 days, or 1.5 ft/d. The average rate of head buildup during the injection of the untreated water was also affected by the periodic backflushings of the injection well. A comparison of head buildup over time during the injection of the treated and untreated water is given in figure 16.

Recovery began after a retention period of 98 days. Selected chemical analyses of samples taken when recovery began and when the water approached a chloride concentration of 250 mg/L are given in table 15 with the appropriate drinking regulations. Only iron exceeded the drinking water regulations in the initial water recovered; in the March 16, 1982, sample, only the limits cited in regulations for iron and dissolved solids concentrations were exceeded.

The initial chloride concentration in the recovered water (120 mg/L, fig. 17) was slightly higher than the final concentration in the injected water (100 mg/L, fig. 15), indicating that as in Test 2, the injected water was mixing with the resident ground water. As in Test 2, the chloride concentration in the recovered water began to increase steadily throughout the recovery period. About 9 Mgal, or 30.4 percent of the total injected, contained a chloride concentration of 250 mg/L or less.

Bacteriological data from observation wells L-2530 and L-3224 and from the recovered water at the start of recovery and 33 days later are given in table 16. Unlike the data for recovery water in Test 2, the results of bacteria counts for Test 3 showed virtually no methanogenic bacteria nor denitrifiers. This may be due to the intermittent injections of treated rather than untreated water during the first 26 days of Test 3. Numbers of anaerobic bacteria in Test 3 reflect the pattern of occurrence in Test 2 wherein growth was heavy at the injection site but diminishing at the observation wells.

ANALYSIS OF TESTS

Water-Quality Effects of Injection and Storage

The injection of water into an aquifer with a substantially different water type than the injected water may result in geochemical interactions that lead to water-quality changes and affect aquifer properties. The injected water may react with the aquifer matrix and the native water and: (1) precipitate minerals, thus, reducing the transmissivity, or (2) dissolve

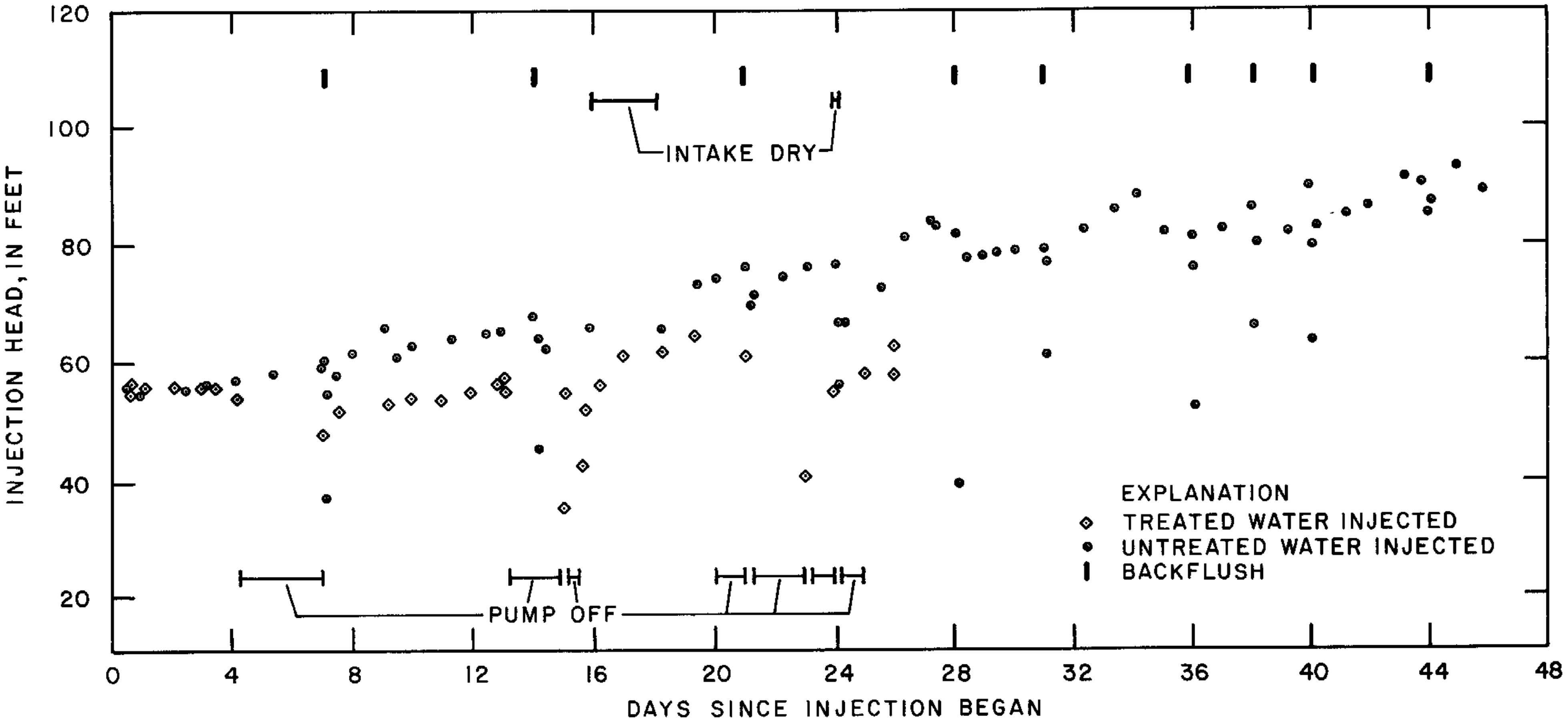

Figure 16.--Injection-head buildup over time for treated and untreated water during Test 3.

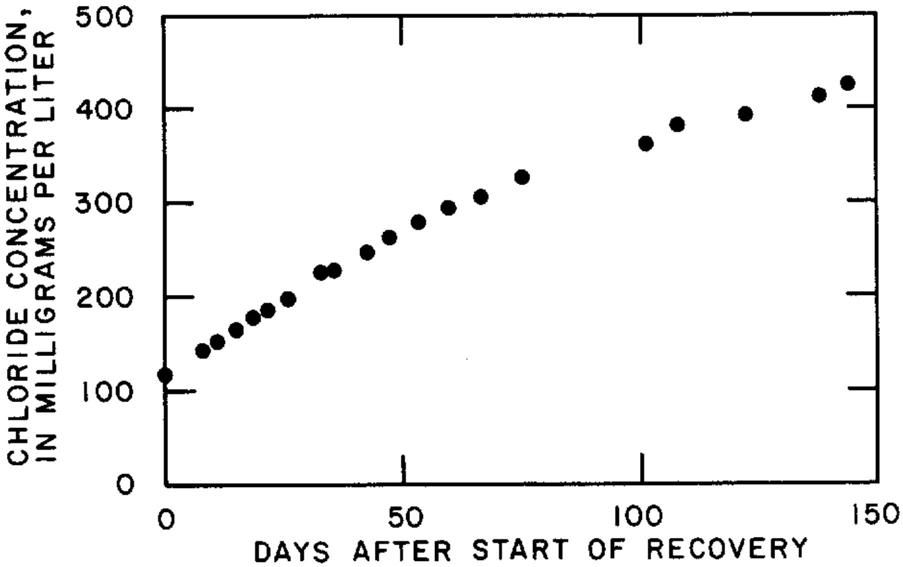

Figure 17.--Chloride concentrations of recovered water from injection well L-3225 during Test 3.

Table 14.--Water-quality data from observation wells L-2530 and L-3224 prior to injection (8/12/81) and during injection, Test 3

[Concentrations in milligrams per liter, except where noted]

Constituent	Well No.	Date 8/12/81	8/27/81	9/21/81	11/4/81
Alkalinity (as $CaCO_3$)	L-2530	150	64	120	140
	L-3224	150	140	150	150
Calcium (Ca)	L-2530	66	52	54	58
	L-3224	69	67	65	67
Chloride (Cl)	L-2530	530	178	86	88
	L-3224	525	--	--	500
Fluoride (F)	L-2530	1.6	1.3	1.2	1.2
	L-3224	1.7	1.6	1.6	1.6
Iron (Fe)	L-2530	.07	.03	.04	.01
	L-3224	.05	.04	.01	.02
Magnesium (Mg)	L-2530	65	24	19	20
	L-3224	70	73	70	68
Potassium (K)	L-2530	18	8.0	6.0	4.9
	L-3224	20	17	17	17
Silica (SiO_2)	L-2530	13	6.7	8.5	10
	L-3224	11	10	11	10
Sodium (Na)	L-2530	310	100	58	49
	L-3224	320	330	310	290
Strontium (Sr)	L-2530	13	6.6	6.7	6.9
	L-3224	14	13	14	13
Sulfate (SO_4)	L-2530	320	130	97	82
	L-3224	310	340	320	300
Noncarbonate hardness (as $CaCO_3$).	L-2530	300	170	100	95
	L-3224	330	340	320	310
Total hardness (as $CaCO_3$)	L-2530	450	240	220	240
	L-3224	480	480	470	460
Dissolved solids (residue at 180°C).	L-2530	1,490	641	452	446
	L-3224	1,570	1,580	1,510	1,500
pH (units)	L-2530	7.4	7.3	--	7.4
	L-3224	7.5	7.3	--	7.2
Temperature (°C)	L-2530	25.5	27.0	27.0	26.0
	L-3224	25.7	25.0	27.0	--

Table 15.--Quality of recovered water during Test 3

[Concentrations in milligrams per liter, except where noted]

Constituent	Maximum contaminant level[1/] Primary regulation	Maximum contaminant level[1/] Secondary regulation	Date 2/11/82	Date 3/16/82
Time of collection			1610	1130
Major dissolved inorganic and related physical characteristics				
Alkalinity (as $CaCO_3$)			150	140
Calcium (Ca)			64	61
Chloride (Cl)		250	120	225
Fluoride (F)	1.0		.5	.9
Magnesium (Mg)			21	35
Potassium (K)			5.1	8.7
Silica (SiO_2)			11	11
Sodium (Na)			65	160
Sulfate (SO_4)		250	81	150
Noncarbonate hardness (as $CaCO_3$)			99	160
Total hardness (as $CaCO_3$)			250	300
Dissolved solids (residue at 180°C)		500	496	2/767
pH (units)		6.5-8.5	7.4	7.5
Temperature (°C)			27.0	27.2
Total trace elements				
Aluminum (Al)				.08
Arsenic (As)	.05		.012	.007
Barium (Ba)	1.00		<.10	<.10
Cadmium (Cd)	.010		.001	.001
Chromium (Cr)	.05		.02	.02
Copper (Cu)		1	.006	.003
Iron (Fe)		.3	.72	.53
Lead (Pb)	.05		.004	.001
Manganese (Mn)		.05	.050	.005
Mercury (Hg)	.002		.0001	.0001
Selenium (Se)	.01		<.001	<.001
Strontium (Sr), dissolved			2.70	6.10
Silver (Ag)	.05		.001	<.001
Zinc (Zn)		5	.02	.01
Selected total nutrients and related characteristics				
Ammonia nitrogen			.43	.18
Organic nitrogen			.51	.29
Nitrate nitrogen	10		.00	.00
Nitrite nitrogen			.00	.00
Chemical oxygen demand			38	27
Dissolved organic carbon			11	3.0
Suspended organic carbon			.2	.10
Phosphorus			.14	.04
Total orthophosphate phosphorus			.11	.03

1/ Florida Department of Environmental Regulation, 1982, Public drinking water systems: Chapter 17-22 *in* Florida Administrative Code.

2/ Calculated from sum of constituents.

Table 16.--Bacteriological data for injection well L-3225 and observation wells L-2530 and L-3224 during the recovery period of Test 3

[Analyses were conducted on February 11, 1982 (twice) and March 16, 1982, for well L-3225 and on February 11, 1982, for wells L-2530 and L-3224]

	Well L-3225			Well L-2530	Well L-3224
	2/11/82		3/16/82		
Bacteria (colonies/100 mL)					
Fecal coliform	0	(0)	0	0	0
Fecal streptococci	0	(0)	0	0	0
Bacteria (organisms/100 mL)					
Total anaerobes	460,000	(9,000)	900	90	3
Total aerobes	ND	(ND)	--	ND	ND
Denitrifiers	<3	(<3)	--	<3	<3
Sulfate reducers	104	(104)	0	103	0
Methanogyens producing	0	(0)	0	10	10

ND indicates that total aerobes were found but unable to count.
-- indicates that data are lacking.

minerals, thus, increasing transmissivity. The injected water may also be in equilibrium with the aquifer minerals and native water, resulting in no reactions.

A determination of the stability of aquifer minerals in contact with the injected water can be made by a calculation of the saturation state of the injected water with respect to those minerals. The saturation state is usually defined in terms of the saturation index (SI):

$$SI = \log \frac{IAP}{K}$$

where IAP is ion activity product for the mineral-water reaction;

K is equilibrium constant (L. N. Plummer and others, U.S. Geological Survey, written commun., 1982).

If the saturation index for a given mineral is zero, the water is in equilibrium with that mineral. If the index is a negative value, the water is undersaturated, and the potential for the dissolution of aquifer material is present. If the saturation index is a positive value, the water is oversaturated, and the potential for precipitation of the mineral exists. The saturation indices for the resident ground water and for treated and untreated river water, with respect to minerals commonly found in the limestone, were calculated using the computer program WATEQF (Plummer and others, 1976) and are given in table 17. All the minerals listed do not necessarily occur beneath the Lee County water-treatment plant area.

The values in table 17 show that the native ground water is oversaturated with dolomite, nearly in equilibrium with calcite and magnesite, and undersaturated with respect to the remaining minerals. The treated river water is undersaturated with all minerals except for dolomite, calcite, and aragonite; therefore, some precipitation might occur when treated water is injected. The untreated river water is undersaturated with all of the minerals. Therefore, the untreated river water apparently could dissolve additional amounts of all these minerals including calcite and dolomite, the principal minerals that make up the carbonate aquifers. The saturation indices are not absolute and may vary in the aquifer environment as a result of: (1) uncertainties of the equilibrium constants; (2) uncertainties in the analytical and thermodynamic data (L. N. Plummer and others, U.S. Geological Survey, written commun., 1982); (3) seasonal variations in the water quality of the injected water; and (4) mixing of the injected water with the resident ground water.

Many of the water-quality changes in the injected water that occurred as a result of injection, other than simple mixing, involved either changes in bacterial concentration or bacterial reduction of certain organic and, possibly, inorganic compounds in the stored water. One change which occurred was in coliform concentration. Fecal coliform and fecal streptococcus bacteria, indicators of the presence of fecal material associated with warm-blooded animals, were monitored periodically in the untreated river water which was injected during the latter part of Test 3 (table 13). The data in table 13 indicate that bacteria were generally present in the injected water.

Table 17.--Saturation indices for minerals commonly found in limestone for representative water samples

Mineral	Chemical formula	Native ground water	Treated river water	Untreated river water
Anhydrite	$CaSO_4$	-1.293	-1.705	-2.043
Aragonite	$CaCO_3$	- .283	.646	- .655
Calcite	$CaCO_3$	- .024	.905	- .396
Celestite	$SrSO_4$	- .425	-2.077	-2.378
Dolomite	$CaMg(CO_3)_2$	.226	.995	-1.204
Fluorite	CaF_2	- .461	-2.783	-1.814
Gypsum	$CaSO_4 \cdot 2H_2O$	-1.098	-1.543	-1.876
Magnesite	$MgCO_3$	- .053	- .206	-1.104
Strontianite	$SrCO_3$	- .305	- .638	-1.899

No coliforms or fecal streptococcus were found in the recovered water or in observation wells L-2530 and L-3224 (table 16) at the start of the recovery period following a 98-day storage in Test 3. The results were the same after a 47-day storage in Test 2 (table 11). The absence of coliform and fecal streptococcus in the recovered water is expected since coliforms are generally short lived, particularly in the low oxygen ground-water environment.

The recovered water in Tests 2 and 3 was also analyzed for aerobic and anaerobic bacteria species (tables 11 and 16). The presence and growth of anaerobic bacteria in the aquifer are expected due to the organic-rich nature of the untreated water, because ground water provides a suitable condition for anaerobic ecosystems (Godsey and Ehrlich, 1978). Types of anaerobic bacteria found were denitrifiers, sulfate reducers, and methanogyens. The presence of aerobic bacteria in the analyses is not inconsistent with an anaerobic environment since aerobic bacteria have been known to exist in a dormant state in an anaerobic environment; or the aerobic bacteria found may be facultative anaerobes, bacteria that can survive in both anaerobic and aerobic environments. Denitrifiers are such an example.

Differences in bacteria concentration were noted between Tests 2 and 3. These differences may have been due to sampling and analytical uncertainties, normal ranges in the anaerobic environment, or an effect from the injection of chlorinated water during the first part of the third injection period.

The effect of the bacteria in the aquifer on the injected water quality includes taste and odor problems and changes as a result of bacterial reduction of some chemical constituents. Changes known to occur in anaerobic environments include reduction of nitrate to nitrogen gas, organic nitrogen to ammonia, and fermentation of organic compounds to carbon dioxide and methane gases. Several other reductions can also occur in anaerobic ecosystems. Reduction of hydrated ferric oxides and manganic oxide is sometimes observed (Godsey and Ehrlich, 1978).

Other than simple mixing of the injected water with the resident ground water, some water-quality changes were evident in the stored water. These changes were examined by comparing the quality of the injected untreated river water with the quality of the recovered water during Test 3. The injected water quality was adjusted to account for the mixing with the native ground water by normalizing the chemical constituents on the chloride concentration as described in Reeder and others (1976, p. 46-47).

A comparison of calculated values of selected chemical constituents with observed values from the initial water recovered is made in table 18. The calculated values were based upon analyses representing the range in concentration which occurred in the untreated water. A significant difference between the calculated and observed values in the recovered water would indicate the occurrence of chemical reactions in the water or between the water and the aquifer.

Significant differences are indicated in most of the organic constituents. Decreases are apparent in concentrations of dissolved and suspended organic carbon and organic nitrogen; an increase in ammonia nitrogen is evident. Other changes in table 18 include increases in the iron and manganese concentrations. The changes in the organics, iron, and manganese concentrations are probably a result of bacterial reduction and are indicative of anaerobic conditions in the aquifer (E. M. Godsey, U.S. Geological Survey, oral commun., 1982). Ammonia, iron, and manganese are considered byproducts of the reduction of the organic and inorganic compounds. Carbon dioxide, methane, nitrogen, and hydrogen sulfide gases would be other expected byproducts, although they were not analyzed.

Arsenic concentrations in the recovered water during Tests 2 and 3 (tables 10 and 15) were below maximum contaminant levels for primary regulation. However, concentrations were higher than those found in both the resident ground water and in the injected river water.

Freshwater Recoverability

An important factor in determining the suitability of the limestone between 550 and 580 feet at the injection site for the storage of freshwater is the quantity that can be recovered relative to the quantity injected, or freshwater recoverability. As used in this report, freshwater recoverability is that amount recovered which contains a chloride concentration of 250 mg/L or less, relative to the amount injected which contains a chloride concentration of 250 mg/L or less. This measure does not necessarily reflect the amount (or percentage) of the actual water injected because the recovered water was virtually a mixture, to varying degrees, of the injected water with the resident ground water. However, this measure does indicate the public supply potential of the stored water since chloride concentration was found to be the limiting factor with regard to maximum contaminant levels for drinking water. As shown in tables 10 and 15, when the chloride concentration was near the maximum contaminant level of 250 mg/L, the only other constituents which approached or exceeded the maximum contaminant level were dissolved solids and iron.

Data in table 6 from the three tests indicate that freshwater recoverability ranged from 9.7 to 38.7 percent. Variations in injected water quality and in storage duration were two major factors causing the wide range in recoverability. In general, recovery rates decrease with increased storage durations and increased chloride concentration of the injected water.

The most important factor was the quality of the water injected as indicated by the chloride concentration. For example, In Test 3 where chloride concentrations generally ranged from 50 to 80 mg/L (fig. 17), the recoverability was 30.4 percent. During Test 2 where chloride concentrations generally ranged from 150 to 175 mg/L (fig. 10), the recoverability was 9.7 percent. The recoverability in Test 3 was more than three times greater than that in Test 2 even though the storage during Test 3 was longer than that in Test 2 (table 6).

The major reason for the difference in recoverability between Test 1 (38.7 percent) and Test 3 (30.4 pecent) is less certain. The chloride concentration of water injected during these tests was nearly comparable

Table 18.--Observed quality of recovered water compared with values calculated for untreated water normalized on chloride concentration

[Concentrations in milligrams per liter]

Constituent	Calculated 9/15/81	Calculated 11/4/81	Observed 2/11/82
Major dissolved inorganics			
Calcium (Ca)	61	71	64
Chloride (Cl)	120	120	120
Fluoride (F)	.5	.4	.5
Magnesium (Mg)	17	15	21
Potassium (K)	6.6	4.5	5.1
Silica (SiO_2)	9.0	10	11
Sodium (Na)	65	60	65
Sulfate (SO_4)	72	52	81
Noncarbonate hardness (as $CaCO_3$)	84	73	99
Total hardness (as $CaCO_3$)	223	241	250
Dissolved solids (residue at 180°C)	502	520	496
Total trace elements			
Arsenic (As)	.004	.001	.012
Barium (Ba)	.094	<.100	.100
Cadmium (Cd)	<.001	<.001	.001
Chromium (Cr)	.011	.023	.020
Copper (Cu)	.006	.030	.006
Iron (Fe)	.34	.25	.75
Lead (Pb)	.004	.003	.004
Manganese (Mn)	<.010	<.022	.050
Mercury (Hg)	.0003	<.0001	.0001
Selenium (Se)	<.001	<.001	.001
Silver (Ag)	<.002	<.001	.001
Strontium (Sr), dissolved	2.20	1.30	2.70
Zinc (Zn)	.021	.078	.02
Selected total nutrients and related characteristics			
Ammonia nitrogen	.10	.06	.43
Organic nitrogen	.97	.86	.51
Nitrate nitrogen	.36	.48	.01
Nitrite nitrogen	.03	.01	.00
Dissolved organic carbon	18	17	11
Suspended organic carbon	.3	.3	.2
Phosphorus	.19	.16	.14
Total orthophosphate phosphorus	.17	.14	.11

although the chloride concentration of water injected during part of Test 3 exceeded that in water injected during Test 1. However, there was no retention period preceding recovery in Test 1, but there was a 98-day retention period preceding recovery in Test 3. This difference in retention probably had a greater effect on recoverability than did the difference in water quality.

Freshwater recoverability data, as determined in this investigation, probably do not totally reflect recoverability that might be obtained in an operational system. Computer models simulating injection, storage, and recovery in south Florida (Merritt, 1983) demonstrate several management variables, other than those already mentioned, that can affect freshwater recoverability. These studies, which assumed varying aquifer conditions, indicated that the factors affecting recoverability also included:

1. Quantities injected; under certain conditions, recovery increased with increasing volumes injected;

2. Well clogging; in some cases, recovery efficiency is reduced by well clogging; and

3. Successive cycles of injection and recovery; in all cases, recovery efficiency is improved with repeated cycles.

Successive cyclic injection has the greatest effect on recoverability. When successive injection-recovery cycles are made, water is withdrawn until the chloride concentration reaches 250 mg/L. Water then remaining in the aquifer adjacent to the injection well is of better quality with respect to chloride than the resident ground water. In the next injection cycle, this residual blend of freshwater and resident ground water mixes with the fresh injected water, resulting in a blend fresher than that in the previous cycle. Following each cycle, the areal extent of the mixing zone increases as does the recovery efficiency.

In simulating successive injection cycles and using various dispersivity coefficients, Merritt (1983) noted that recoverability varied from less than 20 percent to 75 percent after 1 injection cycle to at least 70 percent and greater than 90 percent after 7 cycles. The rate of increase generally declined after each cycle.

For comparison, all of the data on recovery for this investigation would be considered to be after one cycle since resident water-quality conditions existed at the injection well prior to each test. Although the modeling results obtained by Merritt (1983) may not directly relate to the area of these tests, the recoverability would certainly be expected to increase upon successive cycles of injection.

Injection-Head Variations

Buildup in injection head occurred throughout the tests. Head buildup during each of the three tests and drawdown during an aquifer test are illustrated in figure 18. The data in this figure were derived by dividing

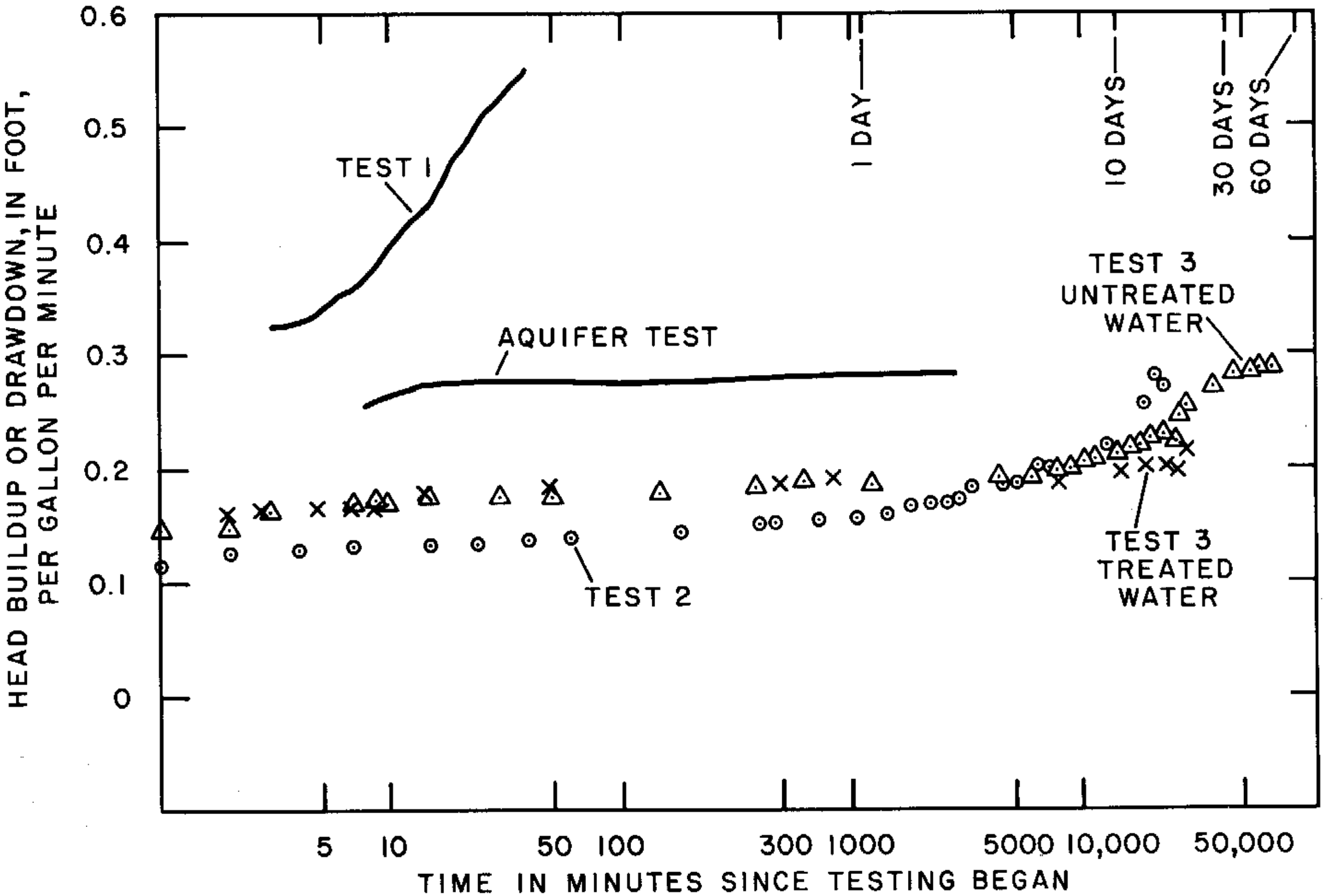

Figure 18.--Head buildup and drawdown during injection and aquifer tests.

head buildup or drawdown by flow rate for comparison. As shown, head buildup increased throughout each test whereas a near steady-state condition was reached during the aquifer test. Theoretically, head buildup during injection should equal drawdown during withdrawal, all other things being equal; any additional head buildup can probably be attributed to well clogging.

Difference in head buildup, particularly Test 1 compared to Tests 2 and 3, is apparent in figure 18. The major reason for these differences was the first well acidizing before the injection of Test 2 and its effect on the well's capacity to receive the injected water. As shown in table 4, the specific capacity of the injection well was increased from 5.39 (gal/min)/ft of drawdown prior to the first injection test to 7.89 (gal/min)/ft following the first well acidizing. However, the acidizing had a much more pronounced effect on head buildup as shown in figure 18. Some increase in the specific capacity (table 4) and decrease in the injection head (fig. 18) followed the second well acidizing (third injection test) although these changes were considerably less than the decrease after the first acidizing.

Head buildup during injection was also affected by the quality of the water injected as noted during Test 3 (fig. 18). The rate of head buildup diminished during the injection of the treated river water.

Well Clogging

A common and severe problem involved with artificial recharge is clogging of the injection well. Causes of clogging, as reported by Sniegocki (1963), include:

1. Suspended particles in the injected water;

2. Bacterial contamination of the injected water and subsequent clogging of the aquifer by bacterial growths;

3. Chemical reactions between the resident ground water and injected water, causing precipitation of insoluble products;

4. Mechanical plugging of the aquifer caused by particle rearrangement when the direction of water movement in the aquifer is reversed;

5. Swelling of clay colloids in the aquifer;

6. Ion-exchange reactions that result in clay-particle dispersal;

7. Precipitation of iron contained in the injected water as a result of aeration;

8. Biochemical changes in the injected water involving bacteria; and

9. Gas binding or air entrainment in the aquifer.

Many or all of these factors may have contributed to clogging in the limestone during the injection periods of the three tests.

Major causes of clogging can best be determined from Test 3 in which a high head buildup resulted when untreated river water was injected. Some clogging occurred during injection of the treated river water (fig. 16) which was probably a result of the suspended matter in that water (fig. 11).

A comparison of total suspended solids data for both treated and untreated water (figs. 11 and 13) shows no significant difference. A difference was apparent in the solids composition as evident from the generally higher volatile or organic part in the untreated river water (figs. 11 and 13). High turbidity was generally characteristic of the untreated river water. Also, since the treated river water was withdrawn from the bottom of the finished-water storage tank at the water-treatment plant, much of the visible suspended matter consisted of sand particles and gravel-size charcoal bits (presumably from filters), which had settled to the tank bottom. Conversely, suspended solids in the untreated river water was fine organic material consisting of algae and clay and silt-size particles. The difference in composition of the residue in the two waters probably accounts for differences in the turbidity.

Head buildup was caused by the suspended material collecting in the limestone pore spaces at the wellbore interface. This was evident by the increased concentration of suspended solids in the backflush water when the well was flushed periodically during Test 3. The concentration was many times greater than that found in the injected water. The differences in head buildup from clogging may also have been due to settling out in the well of the larger particles in the treated water as opposed to their lodging in small pore spaces in the aquifer. Use of treated water with less suspended solids could produce still better results.

A major water-quality difference between the treated and untreated river water is the higher potential for biological growth in the untreated water. The organic-rich untreated river water in the limestone provided a suitable substrate for bacterial growth. Since most of the organics probably collect at the wellbore-aquifer interface, high bacterial growth there would be expected, posing potential clogging problems. Biological clogging has been documented by Ehrlich and others (1979). Clogging due to biological growth during injection of the treated river water would be minimal because of less organic concentration and the chlorine-treated water.

To minimize the effects of well clogging on head buildup, the injection well was backflushed by permitting the well to discharge by artesian flow or by surging with air. Figures 8 and 16 show that the total head buildup was reduced after each backflushing by the removal of suspended material that had accumulated on the wellbore-limestone interface; however, the specific capacity of the well was never restored to preinjection condition nor was the increase in head buildup controlled. Backflushing did reduce total head buildup during Test 3. The residual effect of the clogging on the specific capacity of the injection well is shown in table 4.

SUMMARY

The purpose of this investigation was to examine the suitability of using a 30-foot limestone section of the Floridan aquifer system in southwest Florida for injecting, storing, and recovering freshwater from the adjacent Caloosahatchee River. The limestone is 550 to 580 feet below land surface, is under artesian pressure, and is overlain and underlain by materials of low permeability. The transmissivity of the limestone section is 700 to 800 ft^2/d, storage is 1×10^{-4}, and leakance is 0.01 per day. The contained ground water ranged in chloride concentration from 500 to 550 mg/L.

An injection well and two observations wells were constructed at the site of the Lee County water-treatment plant in order to use freshwater from the Caloosahatchee River for injection and recovery tests. Specific capacity of the injection well varied throughout the investigation as a result of well acidizing and residual effects of well clogging.

Three tests were conducted by injecting and storing untreated and treated river water for different periods. During Test 1, rapid head buildup and decreasing injection rates resulted in a shortened test. Recovery began immediately after injection, and a freshwater recoverability of about 40 percent resulted.

After the well was acidized to increase well specific capacity, Test 2 was conducted with untreated river water as in Test 1. Head buildup during this test was reduced. Because the salinity of the injected water was higher than that of Test 1, freshwater recovery was less than 10 percent.

After a second acidizing of the injection well, Test 3 was conducted using treated river water followed by untreated river water; head buildup was less during the treated river injection. Freshwater recoverability was about 30 percent.

The potential for both the precipitation and dissolution of certain minerals in the limestone is associated with the injection of river water. Growth of anaerobic bacteria within the limestone occurs with untreated injectant. The effect of these bacteria can be the chemical reduction of certain organic and inorganic compounds and taste and odor problems in the recovered water. Observed changes of the chemical composition of the recovered water included decreases in organic carbon, organic nitrogen, nitrite nitrogen, and nitrate nitrogen concentrations. Increases in concentrations of ammonia, iron, and manganese were also observed. These changes are consistent with the existence of an anaerobic ecosystem.

Well clogging and accompanying head buildup were major problems which occurred during the three injection tests. Differences in clogging were noted between the injection of treated and untreated water. Major causes of the clogging were probably suspended material, which collected at or near the wellbore-aquifer interface, and bacteriological growth at the wellbore interface. Periodic backflushing of the injection well during Test 3 resulted in a reduction in total head buildup, but it did not control the continual head buildup.

The amount of freshwater recovered is important in determining the suitability of injection as an alternate source of water supply. In this study, the quality of the injected water was a main factor controlling recoverability. Variation in the storage durations was also a factor. Recoverability achieved during the injection tests did not accurately reflect what would be attained in an operational system of repeated cycles. Recoverability would be expected to increase with successive cycles of injection, storage, and recovery.

REFERENCES

Brown, D. L., and Silvey, W. D., 1977, Artificial recharge to a freshwater-sensitive brackish-water sand aquifer, Norfolk, Virginia: U.S. Geological Survey Professional Paper 939, 53 p.

Clark, S. P., Jr., ed., 1966, Handbook of physical constants, Revised Edition: Geological Society of America Memoir 97.

Ehrlich, G. G., Ku, H. F. H., Vecchioli, John, and Ehlke, T. A., 1979, Microbiological effects of recharging the Magothy aquifer, Bay Park, New York, with tertiary-treated sewage: U.S. Geological Survey Professional Paper 751-E.

Florida Department of Environmental Regulation, 1982, Public drinking water systems: Chapter 17-22 in Florida Administrative Code.

Godsey, E. M., and Ehrlich, G. G., 1978, Reconnaissance for microbial activity in the Magothy aquifer, Bay Park, New York, four years after artificial recharge: U.S. Geological Survey Journal of Research, v. 6, no. 6, p. 829-836.

La Rose, H. R., and McPherson, B. F., 1980, Hydrologic and land-cover features of the Caloosahatchee River basin, Lake Okeechobee to Franklin Lock, Florida: U.S. Geological Survey Water-Resources Investigations Open-File Report 80-732, 1 sheet.

----- 1983, Chemical and hydrologic assessment of the Caloosahatchee River basin, Lake Okeechobee to Franklin Lock, Florida: U.S. Geological Survey Water-Resources Investigations Report 83-4126.

Lohman, S. W., 1979, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

McPherson, B. F., and La Rose, H. R., 1981, Algal conditions in the Caloosahatchee River (1975-79), Lake Okeechobee to Franklin Lock, Florida: U.S. Geological Survey Water-Resources Investigations 81-81, 28 p.

Merritt, M. L., 1983, Subsurface storage of freshwater in south Florida: A digital model analysis of recoverability: U.S. Geological Survey Open-File Report 83-536, 73 p.

Plummer, L. N., Jones, B. F., and Truesdell, A. H., 1976, WATEQF - a FORTRAN IV version of WATEQ, a computer program for calculating chemical equilibrium of natural waters: U.S. Geological Survey Water-Resources Investigations 76-13, 63 p.

Reeder, H. O., Wood, W. W., Ehrlich, G. G., and Sun, R. J., 1976, Artificial recharge through a well in fissured carbonate rock, West St. Paul, Minnesota: U.S. Geological Survey Water-Supply Paper 2004, 80 p.

Sniegocki, R. T., 1963, Problems in artifical recharge through wells in the Grand Prairie Region Arkansas: U.S. Geological Survey Water-Supply Paper 1615-F, 25 p.

Vecchioli, John, and Ku, H. F. H., 1972, Preliminary results of injecting highly treated sewage plant effluent into a deep sand aquifer at Bay Park, New York: U.S. Geological Survey Professional Paper 751-A, 14 p.

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