EFFECTS ON GROUND WATER OF SPRAY IRRIGATION USING TREATED MUNICIPAL SEWAGE SOUTHWEST OF TALLAHASSEE, FLORIDA

By Michael C. Yurewicz and Jack C. Rosenau

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 86-4109

Prepared in cooperation with the

CITY OF TALLAHASSEE

Tallahassee, Florida

1986

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONTENTS

ILLUSTRATIONS

Page

TABLES

Page

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ABSTRACT

Increases in the concentrations of chloride and nitrate nitrogen in ground water have resulted from land application of secondary-treated municipal sewage southwest of Tallahassee, Florida. The increases occurred predominantly during periods of above normal application rates. This result is based upon a data-collection program which began in 1972, 6 years after the initial application of treated sewage. The data collection period for this report is 1972 through June 1981.

Although an estimated minimum volume of 4,220 million gallons of treated sewage was spray irrigated from July 1966 through June 1981, distortion of the local ground-water flow pattern did not occur because of the high, natural recharge and high permeability of the limestone aquifer. Direct recharge from the land surface to the Floridan aquifer system occurs by rapid infiltration through the sand overburden and a discontinuous clay layer above the limestone formation. Soluble constituents move laterally and vertically with the ground-water flow pattern. Use of chloride as a tracer of water movement indicates that treated sewage occurs at depths greater than 200 feet below land surface below the spray sites. The direction and rate of ground-water movement is southwesterly toward the Gulf of Mexico, at a rate of approximately 5 feet per day, with significant downward movement also occurring.

The most significant effect on ground-water quality has been high nitrate nitrogen concentrations which were detected between 1972 and 1976 when high volumes of treated sewage were applied for experimental purposes. During this period, nitrate nitrogen concentrations in the upper limestones of the Floridan aquifer system exceeded the maximum contaminant level of 10 milligrams per liter established for potable water supplies. Computations indicate that if the monthly load of nitrogen does not exceed 130 to 180 pounds per acre, the concentration of nitrate nitrogen in the upper part of the aquifer will not exceed 10 milligrams per liter.

Other water-quality characteristics were not significantly affected by the application of treated sewage. Concentrations of trace metals including arsenic, cadmium, chromium, copper, iron, lead, manganese, mercury, selenium, and zinc in ground water remained at background levels. Organochlorine insecticides and chlorinated phenoxy acid herbicides were analyzed, but not detected in 18 ground-water samples collected in 1974 and 1978. Concentrations of major inorganic ions in the ground water likely are controlled by equilibrium conditions between the water and the aquifer matrix.

INTRODUCTION

The City of Tallahassee has been spray irrigating pine forest, grasses, and forage crops with secondary-treated municipal sewage southwest of Tallahassee, Fla., since July 1966 (fig. 1). Although the first several years of spray irrigation next to the Thomas P. Smith Wastewater Treatment Facility were experimental, this method of treated-sewage disposal has since become routine, partly in the effort to eliminate the discharge of treated sewage to nearby Munson Slough and Lake Munson (fig. 2). The amount of treated sewage disposed of in this manner has increased as techniques of application developed and land became available. In 1980, spray irrigation began on another field 8 miles southeast of Tallahassee and by 1984 all treated sewage from Tallahassee was irrigated at this field (W. G. Leseman, City of Tallahassee, written commun., 1986).

Land application of the municipal sewage has the beneficial effects of treating the sewage, eliminating direct discharge of sewage to surface water, applying nutrients to cultivated land, and recharging the underlying Floridan (limestone) aquifer system. It also has the potential, however, to adversely affect the water quality of that aquifer, which is the source of drinking water in the area.

To assess the effects on ground water caused by spray irrigation of secondary-treated sewage, the U.S. Geological Survey, in cooperation with the City of Tallahassee and in close coordination with officials of the Thomas P. Smith Wastewater Treatment Facility, began a hydrologic investigation in 1972. This report presents results based upon data collected at the southwest spray field through June 1981 (Yurewicz, 1983).

The findings of the investigation are being applied to a similar investigation which began in 1979 at the southeast spray field (Elder and others, 1985). The decision to construct the southeast spray field was based upon the Tallahassee-Leon County Florida 201 Facilities Plan and the Tallahassee-Leon County 208 Areawide Waste Treatment Management Plan (William M. Bishop Consulting Engineers, Inc., 1976; Tallahassee-Leon County Planning Department, 1978). Routine spray irrigation with treated municipal sewage began at the southeast spray field in November 1980 on 1,086 acres and irrigation of an additional 750 acres began in early 1982. Secondary treated sewage from the Thomas P. Smith Wastewater Treatment Facility is pumped through an underground pipe to the southeast field where various grasses and forage crops are irrigated. Treated-sewage application rates depend upon crop needs but average 3 inches per week. The "southeast spray field" investigation is also being done in cooperation with the City of Tallahassee. The southeast spray field investigation has the advantage of: (1) considerable baseline hydrologic data available from the southwest field investigation, (2) a comprehensive monitoring well network established prior to treated-sewage application, (3) collection of ground-water quality samples from both the limestone aquifer and the overlying surficial sand, and (4) collection of accurate data regarding the amount and quality of the treated sewage applied on various crops.

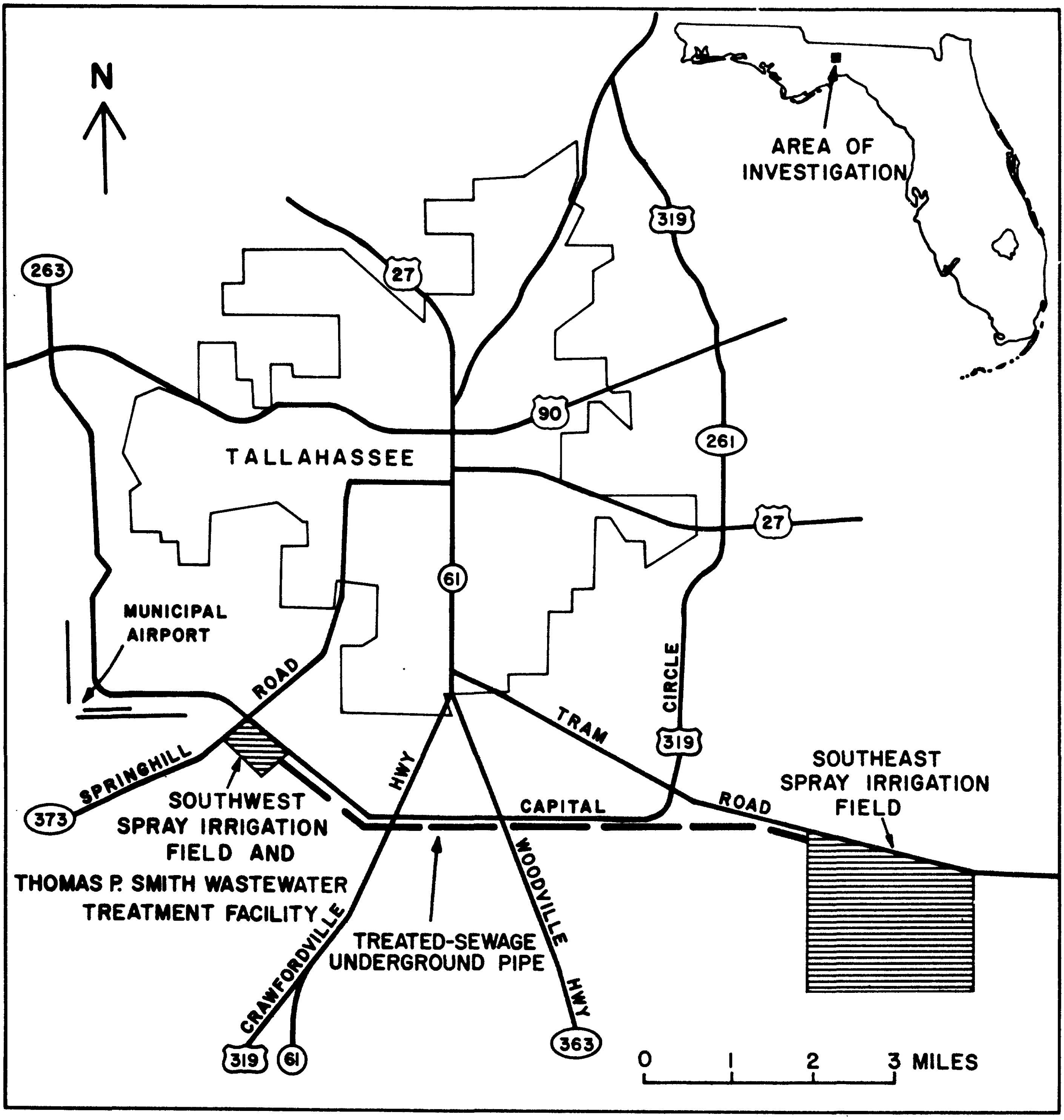

Figure 1.--Area of investigation in Florida and locations of the southwest and southeast spray fields.

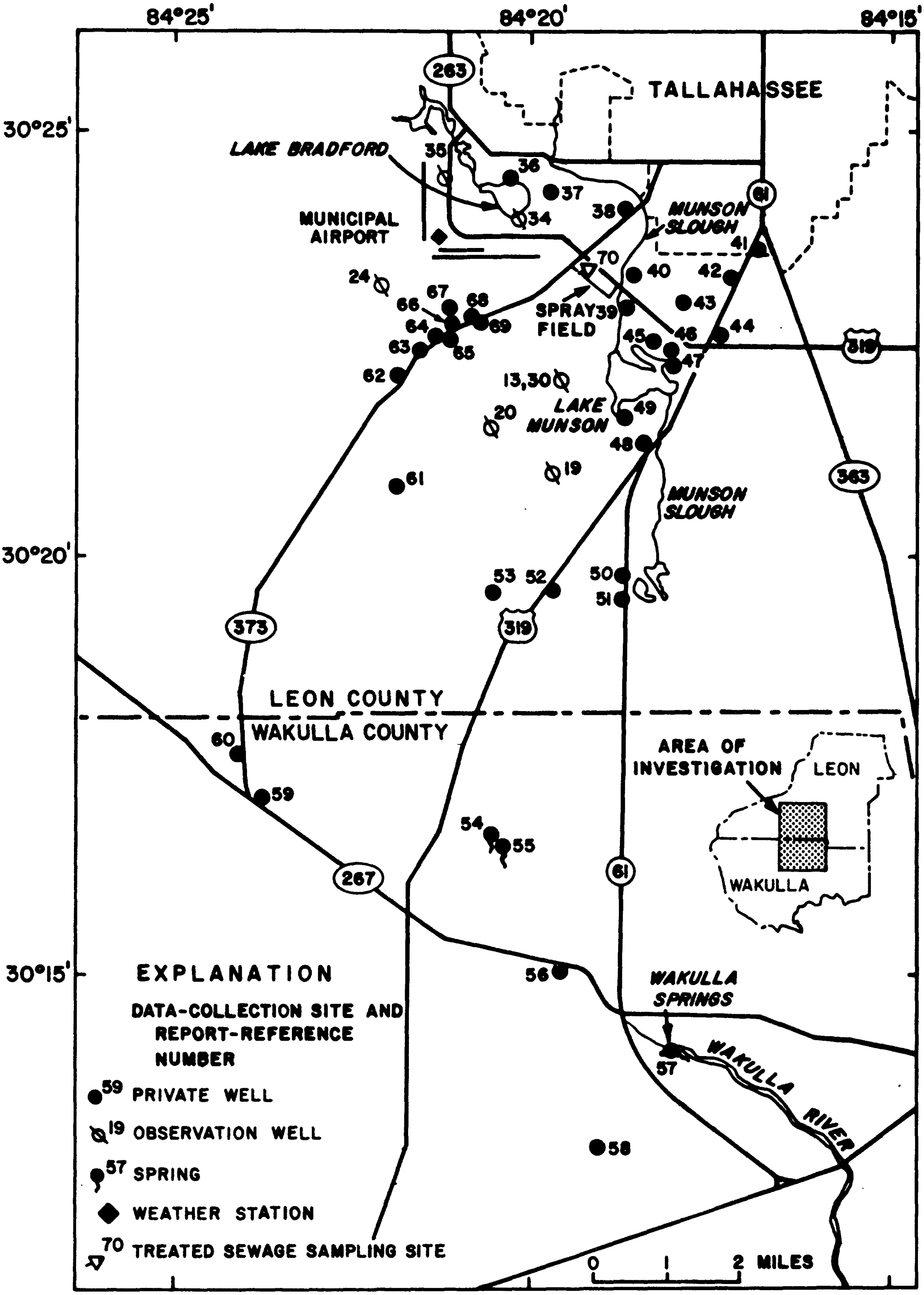

Figure 2.--Area of investigation as related to Leon and Wakulla Counties and locations of selected sampling sites outside of the southwest spray field for hydrologic data.

Purpose and Scope

The purpose of this report is to describe and assess the hydrologic effects on the Floridan aquifer system due to spray irrigation with treated municipal sewage. This report is based upon a data-collection program maintained from 1972 through June 1981, and includes analyzing samples to determine changes in water-quality characteristics. The high nitrate nitrogen concentrations are explained and supporting data are presented. The effects of treated-sewage application on other water-quality characteristics and on trace metals are also addressed. This report also examines the effects of the treated sewage on ground-water levels of the Floridan aquifer system.

The information presented will assist future management decisions concerning the long-term environmental impacts resulting from spray application of treated sewage as contrasted to potential impacts using other methods of land or surface-water disposal, for example, rapid infiltration or discharge. In addition, recent mandates by the U.S. Environmental Protection Agency require that wastewater management alternatives such as land application be considered by local planners.

The investigation began 6 years after spray irrigation began; therefore, limited baseline data exist. Hydrologic data were obtained from an area of approximately 83 square miles; they include rainfall information, ground-water level measurements, and analyses of water-quality samples of springs, wells, and treated sewage. Sampling sites are shown in figures 2 and 3. Geological information is based on drillers and field observation notes, lithologic samples, and geophysical logs. Several assumptions were necessary to interpret selected aspects of the hydrologic data; these will be discussed later. The report is based on data collected through June 1981, as reported by Slack (1975) and Yurewicz (1983). A limited monitoring program, which will include ground-water sampling and ground-water level measurements, will be continued at the southwest spray field area to permit assessment of the effects of decreased land application of treated sewage by spray irrigation.

Acknowledgments

The assistance of numerous people during the investigation is appreciated, especially Thomas P. Smith, Director of Underground Utilities, and William G. Leseman, Superintendent of the City of Tallahassee Water-Quality Laboratory. Mr. Leseman, and other laboratory personnel, cooperated fully in the analysis of water-quality samples. Keith Turner, Chief Operator of the Thomas P. Smith Wastewater Treatment Facility, provided monthly spray-irrigation volume information. Thomas Pratt and Thomas Kwader of the Northwest Florida Water Management District obtained geophysical logs; the National Oceanic and Atmospheric Administration at the Tallahassee Municipal Airport provided rainfall data; and many individuals allowed access to their land to collect ground-water samples and measure water levels.

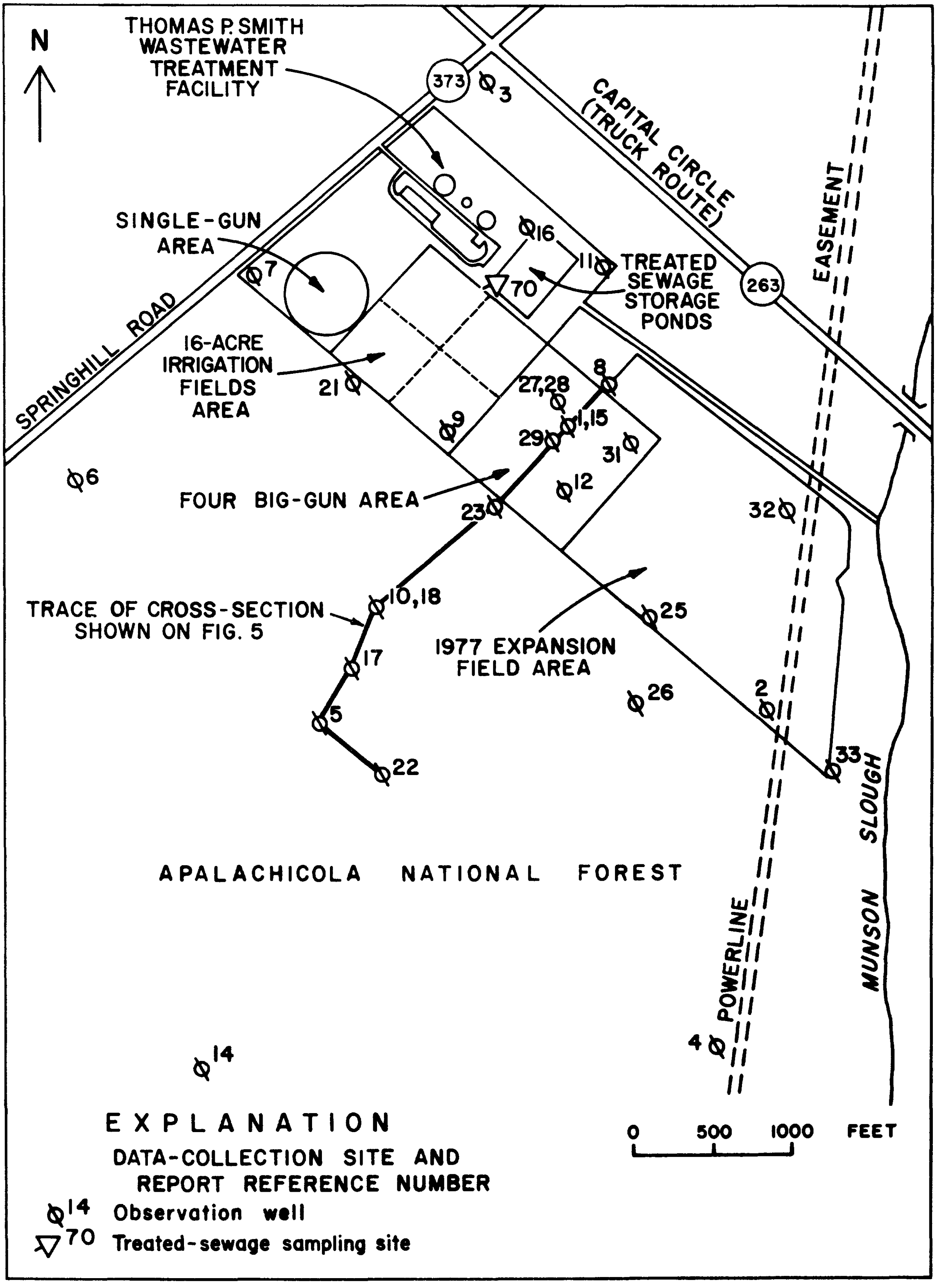

Figure 3.--Southwest spray field and locations of selected sampling sites.

Previous Investigations

Previous investigations of the area include: the geology as reported by Hendry and Sproul (1966); an investigation of the soil and geology of the southwest spray field area by Ardaman and Associates, Inc., (1976); and the hydrologic effects of spray irrigation for the period July 1972 to June 1974 as reported by Slack (1975). The latter report discusses the hydrogeology of the area, the changes in quality of the treated sewage in the subsurface, the variations of ground-water quality with time and depth, and the areal extent of ground water affected by spray irrigation. Overman (1979) discussed the effects of spray irrigation with treated municipal sewage in relation to crop uptake, changes in soil characteristics, and shallow ground-water quality. Because Overman examined the effects of the treated sewage on the soil and shallow sand formation, the present investigation was limited to the study of the effects of spray irrigation on the Floridan aquifer system. Elder and others (1985) discussed the effects of treated sewage application by spray irrigation on ground-water quality and quantity at the southeast field.

Methods of Investigation

The methods used in the initial period of investigation were reported by Slack (1975). The overall approaches for the data-collection program have been: installing observation wells and obtaining lithologic samples and geophysical logs, collecting and analyzing ground-water quality samples, and measuring ground-water levels. The City of Tallahassee provided information concerning monthly treated-sewage application volumes and treated-sewage water quality.

Whenever applicable, standard methods were used for data collection and analysis. Such methods are described in a series of manuals published by the U.S. Geological Survey entitled "Techniques of Water-Resources Investigations of the U.S. Geological Survey." They include: Goerlitz and Brown (1972), Greeson and others (1977), and Skougstad and others (1979).

Locations and descriptions of the sampling sites shown in figures 2 and 3 are given in table 1. Subsurface samples were collected during drilling operations and examined to provide lithologic descriptions. Due to drilling problems, cuttings from well 23 were considered unreliable at depths greater than 60 feet (Slack, 1975). Wells were completed by surging and pumping with either compressed air or a submersible pump. Geophysical logs were obtained for many of the wells by personnel of the Northwest Florida Water Management District. Rainfall data were obtained from the National Oceanic and Atmospheric Administration at the Tallahassee Municipal Airport, 2 miles northwest of the southwest spray field.

Ground-water level measurements were made using either a steel measuring tape delineated to the nearest hundreth of a foot, or a battery operated water-level measurement meter. Ground-water-level measurements were made when water-quality samples were collected, and during selected periods of high or low ground-water level to develop contour maps of the potentiometric surface of the area. Analog or analog-to-digital recorders were used to obtain continuous ground-water levels at wells 1, 34, and 35. Water levels were recorded once an hour on 16 channel paper tape for analog-to-digital recorders.

Table 1.--Locations and descriptions of sampling sites

Map site No.	U.S. Geological Survey site-ID	Latitude	Longitude	Local identifier	Well: Total depth (feet)	Well: Casing depth (feet)	Well: Casing diameter (inches)	Altitude (feet): Land surface	Altitude (feet): Water level[1/]
3	302335084191901	30°23'35"	084°19'19"	USGS LS 3	104	93	4	69	[2/]
4	302235084190301	30°22'35"	084°19'03"	USGS LS 4	53	38	4	45	20
5	302233084194101	30°22'56"	084°19'30"	USGS LS 5	51	33	4	50	20
6	302308084195301	30°23'08"	084°19'53"	USGS LS 6	45	35	4	41	20
7	302322084193601	30°23'23"	084°19'36"	USGS LS 7	35	27	2	37	20
8	302316084191101	30°23'16"	084°19'11"	USGS LS 8	49	47	2	57	19
9	302313084192201	30°23'13"	084°19'22"	USGS LS 9	42	40	2	48	21
10	302301084192901	30°23'01"	084°19'29"	USGS LS 10	43	41	2	58	19
11	302323084191201	30°23'23"	084°19'12"	USGS LS 11	40	38	2	52	22
12	302309084191101	30°23'09"	084°19'11"	USGS LS 12	50	48	2	58	19
13	302206084194001	30°22'06"	084°19'40"	USGS LS 13	37	35	2	42	17
14	302234084193901	30°22'34"	084°19'39"	USGS LS 14	55	53	2	45	18
15	302313084191302	30°23'13"	084°19'13"	USGS LS 15	47	45	2	56	21
16	302325084191601	30°23'25"	084°19'16"	USGS LS 16	67	65	2	59	22
17	302258084193001	30°22'58"	084°19'30"	USGS LS 17	152	152	4	49	20
18	302301084192902	30°23'01"	084°19'29"	USGS LS 18	160	54	4	58	20
19	302122084194001	30°21'22"	084°19'40"	USGS LS 19	80	53	4	39	14
20	302135084202001	30°21'35"	084°20'20"	USGS LS 20	145	145	4	29	14
21	302315084192801	30°23'15"	084°19'28"	USGS LS 21	248	247	4	58	20
22	302252084192901	30°22'52"	084°19'25"	USGS LS 22	268	267	4	49	19
23	302310084191901	30°23'10"	084°19'19"	USGS LS 23	270	240	4	53	21
24	302319084220601	30°23'19"	084°22'06"	USGS LS 24	260	244	4	106	18
25	302303084190901	30°23'03"	084°19'09"	USGS LS 25	69	54	4	61	20

See footnotes at end of table.

Table 1.--Locations and descriptions of sampling sites--Continued

Map site No.	U.S. Geological Survey site-ID	Latitude	Longitude	Local identifier	Well: Total depth (feet)	Well: Casing depth (feet)	Well: Casing diameter (inches)	Altitude (feet): Land surface	Altitude (feet): Water level[1]
26	302257084191101	30°22'57"	084°19'11"	USGS LS 26	200	194	4	53	12
27	302314084191501	30°23'14"	084°19'15"	USGS LS 27	150	[3]	4	54	19
28	302314084191502	30°23'14"	084°19'15"	USGS LS 28	158	145	4	54	24
29	302312084191301	30°23'12"	084°19'16"	USGS LS 29	250	153	4	54	22
30	302206084194002	30°22'06"	084°19'40"	USGS LS 30	150	148	2	42	--
31	302314084190902	30°23'14"	084°19'09"	BOG 4-2	70	60	4	55	22
32	302309084185701	30°23'09"	084°18'57"	BOG 6-5	80	58	6	64	19
33	302251084185301	30°22'51"	084°18'53"	BL-3	33	23	4	41	23
34	302410084200001	30°24'07"	084°20'10"	USGS 150 (Lk Bradford)	57	57	4	38	30[4]
35	302424084311301	30°24'27"	084°21'14"	Municipal Airport	194	190	6	67	21
36	302433084201901	30°24'33"	084°20'19"	L. D. Singleton	100	70	4	37	21
37	302418084195501	30°24'18"	084°19'55"	Wilson	--	--	4	48	28
38	302409084183801	30°24'09"	084°18'38"	Cleve Jones	--	--	4	64	--
39	302306084184901	30°23'06"	084°18'49"	Animal Shelter	125	80	4	41	20
40	302326084184001	30°23'26"	084°18'40"	Robert Postell	--	--	4	45	21
41	302341084165701	30°23'41"	084°16'57"	Foursquare Church	--	--	--	80	--
42	302321084171601	30°23'21"	084°17'16"	Johnson	--	--	4	50	13
43	302324084175701	30°23'24"	084°17'57"	William Jones	262	256	4	74	20
44	302241084172801	30°22'41"	084°17'28"	Cox Gas Station	--	--	--	50	--
45	302235084181601	30°22'35"	084°18'16"	Baxley	--	--	--	45	19
46	302234084180301	30°22'34"	084°18'03"	Mike Gill	--	--	--	45	--
47	302219084180101	30°22'19"	084°18'01"	Morris Singletary	--	--	4	25	17
48	302125084182301	30°21'25"	084°18'23"	Carmen G. Hiers	100	--	4	27	14
49	302137084184701	30°21'37"	084°18'47"	Neil Gray	--	--	4	40	--
50	301953084184301	30°19'53"	084°18'43"	Glover	--	--	4	20	5

See footnotes at end of table.

Table 1.--Locations and descriptions of sampling sites--Continued

Map site No.	U.S. Geological Survey site-ID	Latitude	Longitude	Local identifier	Well: Total depth (feet)	Well: Casing depth (feet)	Well: Casing diameter (inches)	Altitude (feet): Land surface	Altitude (feet): Water level [1]
51	301930084184201	30°19'30"	084°18'42"	St. Peters Church	--	--	4	20	6
52	301935084194701	30°19'35"	084°19'47"	Messer	--	--	--	25	16
53	301935084203501	30°19'35"	084°20'35"	Wallace	--	--	--	25	9
54	301643084203400	30°16'43"	084°20'34"	Kini Spring	--	--	--	10	--
55	301636084202800 [5]	30°16'36"	084°20'28"	River Sink Spring	--	--	--	10	--
56	301507084192801	30°15'07"	084°19'28"	Bethel Church	--	--	4	15	--
57	301407084181000 [6]	30°14'05"	084°18'10"	Wakulla Springs	--	--	--	5	--
58	301301084190201	30°13'01"	084°19'02"	Hugh McCallister	--	--	4	15	--
59	301707084234301	30°17'07"	084°23'43"	Glen Miller	--	--	4	50	--
60	301741084240301	30°17'41"	084°24'03"	Hudson	--	--	4	65	--
61	302056084214901	30°20'56"	084°21'49"	Henry Bratcher	80	--	4	46	6
62	302212084214901	30°22'12"	084°21'49"	Minnick	--	--	4	25	13
63	302228084213401	30°22'28"	084°21'34"	James R. Mims	--	--	2	35	14
64	302233084212501	30°22'33"	084°21'25"	Tom Greene	--	--	4	40	--
65	302337084211301	30°22'37"	084°21'13"	Betty Kelly	160	--	4	33	15
66	302250084210501	30°22'50"	084°21'05"	John D. Gray	--	--	--	50	--
67	302257084210901	30°22'57"	084°21'09"	Marvin C. Gray	--	33	4	60	15
68	302252084204901	30°22'52"	084°20'49"	Joe Messenger	--	--	4	45	15
69	302251084204201	30°22'51"	084°20'42"	Tom Golden, Sr.	--	--	--	45	--
70	302322084192000	30°23'22"	084°19'20"	Sewage sampling site	--	--	--	--	--

1/ Measurements spanned September 1972 through March 1981.
2/ Dry hole.
3/ Casing removed 11/05/75.
4/ Measured 05/19/60.
5/ River Sink Spring also has water-quality data filed under 02326997.
6/ Wakulla Springs also has water-quality data filed under 02327000.

Ground-water samples were collected from wells after evacuating at least two times the volume of water in the well. For wells 4 inches or more in diameter, a submersible pump was used to collect the samples; 2-inch diameter wells were pumped using a stainless-steel air-squeeze pump. Selected unstable water-quality constituents and properties were analyzed in the field; these included temperature, specific conductance, pH, carbonate, and bicarbonate. Filtration of samples for dissolved constituents and properties was performed at the time of sample collection. Samples for dissolved inorganic constituents were filtered through 0.45-micrometer pore-size membrane filters. Samples for dissolved organic carbon were filtered through 0.45-micrometer pore-size silver membrane filters in a stainless steel pressure-filtration cylinder.

Immediately following collection, water-quality samples were chilled on ice and, with proper preservation, most were sent to one of three laboratories for analysis: the Geological Survey Atlanta Central Laboratory in Doraville, Ga.; the Survey's Quality of Water Service Unit in Ocala, Fla.; or the City of Tallahassee Water-Quality Laboratory. Quality assurance of analytical results among the laboratories was assessed by means of an ongoing program of split reference field samples.

DESCRIPTION OF AREA OF INVESTIGATION

The environmental characteristics of each spray irrigation system must be considered when evaluating potential effects upon the environment. The following tabulation indicates what factors might be important for operation of a spray irrigation system (U.S. Environmental Protection Agency, 1975).

- Climate
  - Seasonal distribution of rainfall
  - Seasonal variation of air temperature
  - Evapotranspiration
  - Wind velocities and direction
- Topography
  - Ground slope
  - Erosion potential
  - Flood potential
- Soil characteristics
  - Type and description
  - Infiltration rates
- Geology
  - Type and description
  - Depth to formations
- Ground water
  - Depth to ground water
  - Ground-water flow
  - Native ground-water quality
  - Use of ground water

It is not the purpose of this report to evaluate and discuss all of the factors given above; selected aspects are presented to familiarize the reader with the southwest spray field area.

Climate

Climatological data for air temperature and rainfall representative of the southwest spray field are given for the weather station at the Tallahassee Municipal Airport, approximately 2 miles northwest of the southwest spray field. The weather station is maintained by the National Oceanic and Atmospheric Administration; climatological data given in this report are taken from monthly and annual climatological summary reports prepared by that Federal agency. As calculated for the reference period 1941-70, the average air temperature is 68°F. The lowest monthly average air temperature of 53°F occurs in January, and the highest average monthly temperature of 81°F occurs in July and August. Based upon the same reference period, the mean annual rainfall is 62 inches. The average annual rainfall during the period of treated-sewage application (1966 through 1980) was 69 inches; the lowest average monthly rainfall of 2.8 inches occurred in November and the highest average monthly rainfall of 8.9 inches occurred in July.

One method of depicting trends in rainfall is a cumulative departure curve. Cumulative departures from the monthly average rainfall are plotted for January 1960 through June 1981 in figure 4 (reference period 1941-70). Four general trends are shown in the graph; two decreasing trends (1961 to 1963 and 1967 to 1969) and two increasing trends (1964 to 1967 and 1969 to 1981). Thus, a general trend of above-normal rainfall occurred in the area during most of the spray irrigation operation at the southwest spray field.

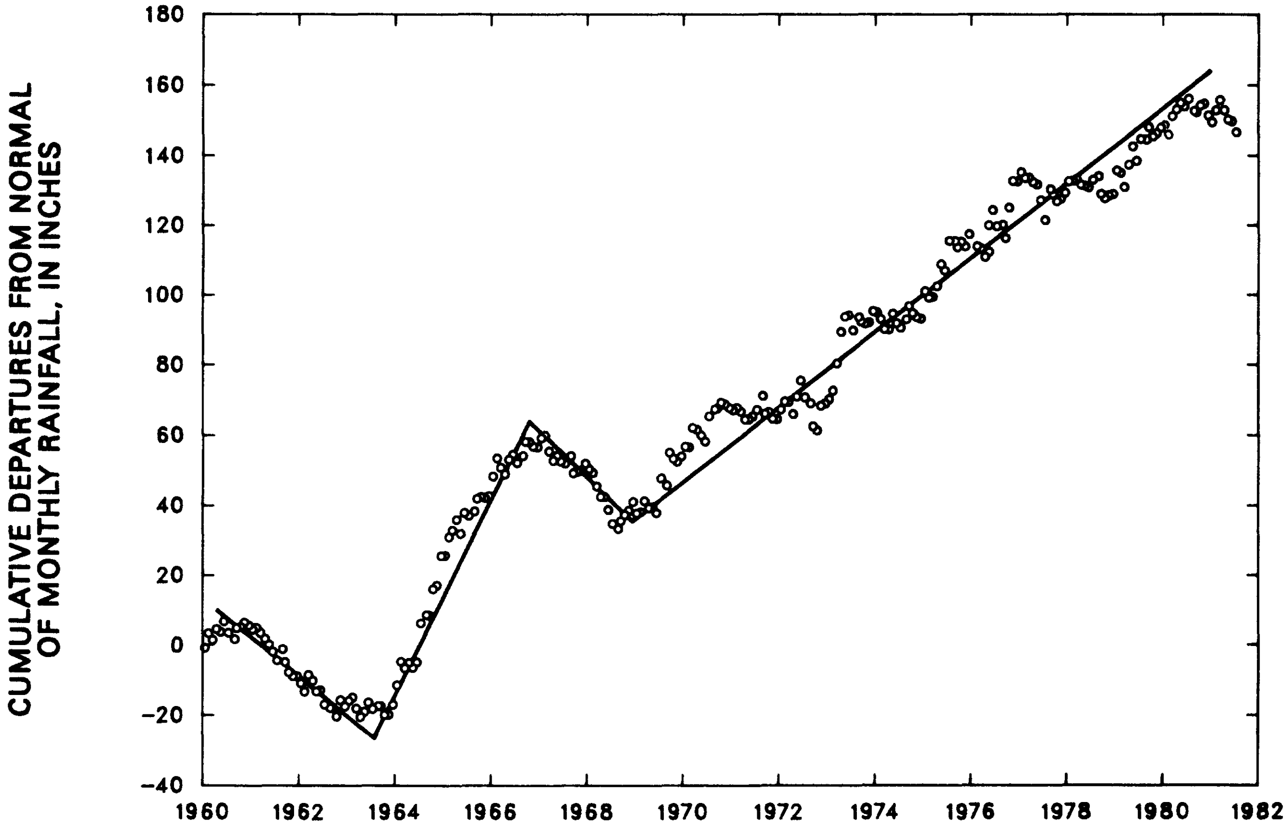

Figure 4.--Cumulative departures from 1941-70 normal of monthly rainfall for Tallahassee Municipal Airport from January 1960 through June 1981.

The average annual rainfall of 69 inches exceeds the average annual potential evapotranspiration value of 46 as reported by Visher and Hughes (1975). Considering that actual evapotranspiration is less than potential and that there is virtually no direct surface runoff from the area of the spray field, these values indicate that more than 23 inches of rainfall per year recharges the Floridan aquifer system.

Hydrogeology

The southwest spray field and surrounding area lie within the Lake Munson Hills of the Woodville Karst Plain (Hendry and Sproul, 1966). This physiographic subdivision is characterized by quartz sands which veneer a limestone substratum. The soil at the spray field is Lakeland fine sand which consists of approximately 95 percent sand, 3 percent clay, and 2 percent silt. The cation exchange capacity of the soil is low, and the natural pH of a 1:1 soil-water mixture is approximately 5.5 (Overman, 1979). Clay is intermittently interbedded with the sand. Land altitudes are 20 to 60 feet above sea level, with a sinkhole-sand dune topography. Where the surficial material has subsided or collapsed into solution cavities in the limestone, closed depressions, or sinkholes, have formed at the land surface south of the spray field. The sands readily allow percolation of rainfall to the underlying stratum, thus resulting in little stream development.

The limestone substratum comprises a sequence of limestones and dolomites that act as a hydrologic unit referred to as the Floridan aquifer system in Florida. This aquifer extends from southern Alabama and Georgia beneath all of Florida. In the area of investigation and in neighboring counties, the aquifer is recharged by local rainfall.

Slack (1975, p. 16) used lithologic and geophysical logs to prepare a hydrogeologic section of the subsurface at the southwest spray field (fig. 5) through wells 8 to 22 (fig. 3). Figure 5 indicates that approximately 15 to 40 feet of sand at the surface overlies a discontinuous clay layer with another sand layer between the clay and the top of the limestone.

The applied treated sewage percolates through the sand; and if it encounters a clay layer, it moves horizontally until reaching a break in the clay before again moving vertically to the water table or to the limestone. Horizontal and vertical movement, therefore, depends on physical conditions encountered prior to reaching the limestone aquifer.

Upon encountering the limestone aquifer and mixing with native ground water, the treated sewage is diluted. Because of solution cavities and channels, and the megaporosity of the limestone aquifer, ground-water flow is about 2,400 ft/yr (Slack, 1975). The presence of solution cavities in the limestone beneath the southwest spray field is verified by nearby sinks and by drillers notes that reported cavities at well site 17 (73 to 75 and 101 to 102 feet below land surface) and at well site 29 (63 to 65 feet below land surface).

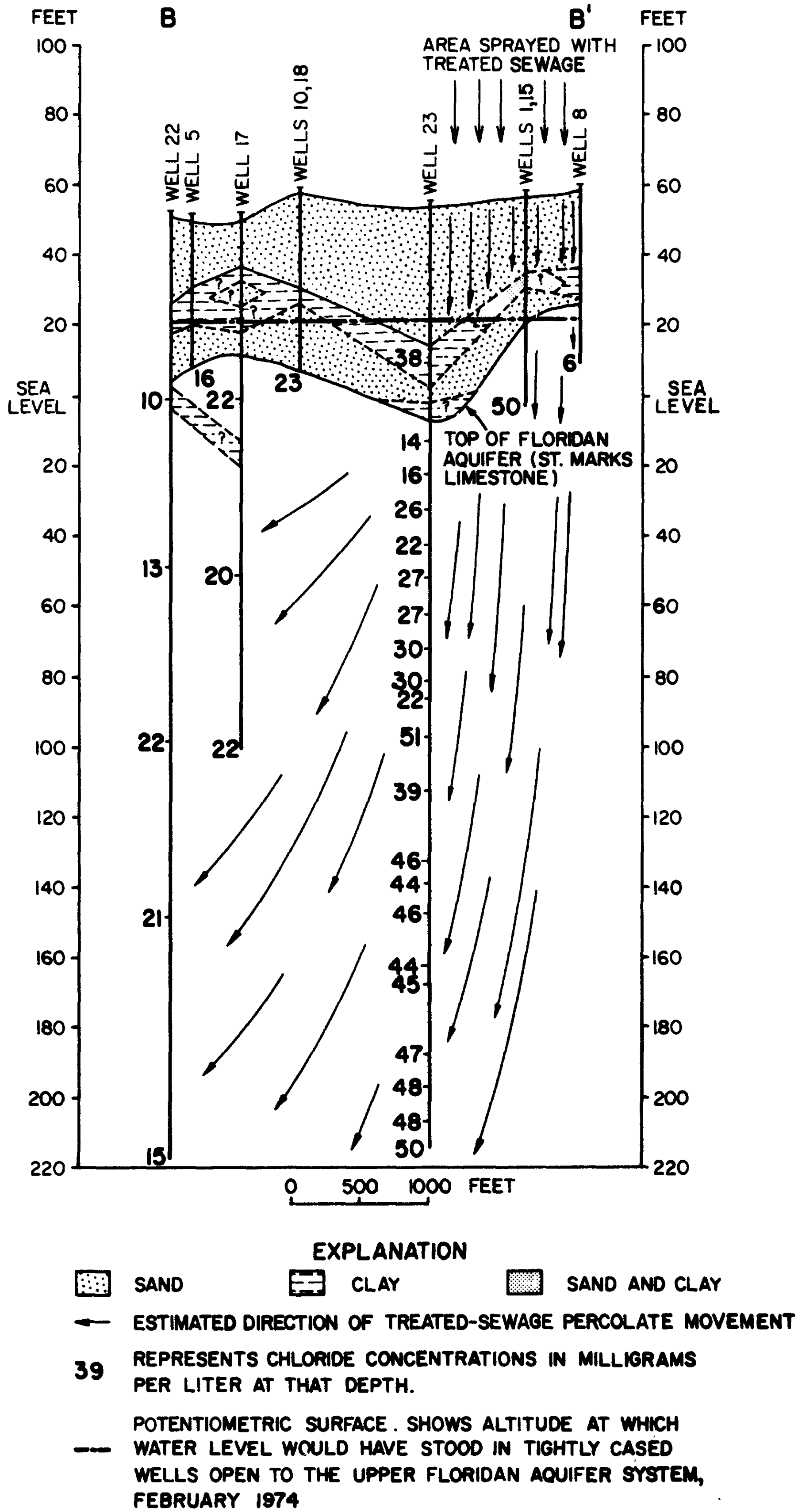

Figure 5.--Hydrogeologic section from site 8 to site 22 (Modified from Slack, 1975, p. 16).

Native Ground-Water Quality

Native ground water in the Floridan aquifer system in the area of the spray field can be characterized as typical of a carbonate system. Water from the upper part of the aquifer (less than 100 feet below land surface) is low in dissolved solids and nutrients and has a pH of approximately 8. Table 2 gives a statistical summary of selected water-quality variables for sites 4, 14, 19, 20, and 24. These wells are unaffected by sprayed treated sewage and thus represent native ground-water quality. The average specific conductance and chloride among the sites ranged from 66 μS/cm (microsiemens per centimeter) and 1.8 mg/L (milligrams per liter), respectively, at site 4 to 240 μS/cm and 7.0 mg/L at site 24.

Figure 6 is a plot of mean specific conductance and dissolved chloride concentrations versus the depths at which sites 4, 14, 19, 20, and 24 are open to the Floridan aquifer system. The plot indicates increasing specific conductance and chloride concentrations with depth, because of longer exposure of ground water to the limestone formation, and thus greater opportunity for the water to establish chemical equilibrium with the aquifer. Analyses of ground-water quality samples collected from private wells in the area of investigation indicated a similar distribution of dissolved solids. Exceptions generally occurred at sites near lakes (sites 36, 47, and 49), and where effects from private septic tanks are possible (Yurewicz, 1983, table 6, site 53).

Table 2.--Statistical summary of selected water-quality variables for selected background sites

[Concentrations are expressed as mg/L unless otherwise stated]

Water-quality variable	No. of samples	Minimum	Maximum	Mean
	Site 4			
Specific conductance, μS/cm	35	55	84	66
pH, units	26	6.7	8.6	7.8
Phosphorus, total	31	.00	.20	.2
NO_2+NO_3, total, as N	24	.00	.10	.03
Organic carbon, total	17	.0	9.0	2.3
Hardness, as $CaCO_3$	19	26	42	30
BOD, 5 day, mg/L O_2	15	.0	.4	.1
Calcium, dissolved	19	10	16	11
Magnesium, dissolved	19	.20	1.1	.40
Sodium, dissolved	30	.10	2.4	1.1
Potassium, dissolved	18	.00	.70	.26
Bicarbonate, as HCO_3	16	26	38	34
Carbonate, as CO_3	18	0	0	0
Chloride, dissolved	38	.50	3.3	1.8
Fluoride, dissolved	11	.10	.20	.11
Sulfate, dissolved	12	.40	2.40	.94
Dissolved solids	10	28	47	37

Table 2.--Statistical summary of selected water-quality variables for selected background sites--Continued

Water-quality variable	No. of samples	Minimum	Maximum	Mean
	Site 14			
Specific conductance, μS/cm	33	70	110	85
pH, units	18	7.0	8.6	8.0
Phosphorus, total	26	.00	.10	.04
NO_2+NO_3, total, as N	28	.02	.33	.07
Organic carbon, total	10	0	11	3.2
Hardness, as $CaCO_3$	13	33	75	44
BOD, 5 day, mg/L O_2	11	.4	3.7	1.2
Calcium, dissolved	13	12	28	16
Magnesium, dissolved	13	.7	1.2	.9
Sodium, dissolved	25	.7	2.2	1.4
Potassium, dissolved	13	.3	.7	.5
Bicarbonate, as HCO_3	10	38	88	60
Carbonate, as CO_3	11	0	0	0
Chloride, dissolved	43	1.0	4.0	2.0
Fluoride, dissolved	6	.1	.2	.1
Sulfate, dissolved	6	.2	5.8	2.0
Dissolved solids	6	36	89	56
	Site 19			
Specific conductance, μS/cm	21	125	176	155
pH, units	15	7.6	8.2	7.8
Phosphorus, total	18	.01	.04	.02
NO_2+NO_3, total, as N	21	.03	.15	.08
Organic carbon, total	6	.0	3.0	.5
Hardness, as $CaCO_3$	7	70	80	76
BOD, 5 day, mg/L O_2	5	.1	.4	.2
Calcium, dissolved	7	26	30	28
Magnesium, dissolved	7	1.1	1.7	1.3
Sodium, dissolved	18	.9	2.0	1.5
Potassium, dissolved	7	.2	.6	.3
Bicarbonate, as HCO_3	8	75	100	89
Carbonate, as CO_3	8	0	0	0
Chloride, dissolved	22	1.8	3.0	2.5
Fluoride, dissolved	6	.0	.2	.1
Sulfate, dissolved	6	.4	1.0	.7
Dissolved solids	5	80	102	88

Table 2.--Statistical summary of selected water-quality variables for selected background sites--Continued

Water-quality variable	No. of samples	Minimum	Maximum	Mean
	Site 20			
Specific conductance, µS/cm	21	210	243	229
pH, units	13	7.4	8.2	7.8
Phosphorus, total	18	.01	.10	.02
NO_2+NO_3, total, as N	21	.03	.78	.32
Organic carbon, total	4	0	2	.5
Hardness, as $CaCO_3$	6	110	120	115
BOD, 5 day, mg/L O_2	3	.1	.6	.4
Calcium, dissolved	6	34	40	37
Magnesium, dissolved	6	4.6	5.8	5.3
Sodium, dissolved	15	2.0	3.1	2.6
Potassium, dissolved	6	.2	.4	.3
Bicarbonate, as HCO_3	6	129	150	140
Carbonate, as CO_3	6	0	0	0
Chloride, dissolved	21	2.8	5.4	4.6
Fluoride, dissolved	6	.1	.1	.1
Sulfate, dissolved	6	.1	2.4	1.4
Dissolved solids	5	124	138	130
	Site 24			
Specific conductance, µS/cm	18	240	310	263
pH, units	12	7.6	8.1	7.9
Phosphorus, total	19	.00	.20	.03
NO_2+NO_3, total, as N	19	.00	.10	.06
Organic carbon, total	6	0	2	.7
Hardness, as $CaCO_3$	9	120	140	126
BOD, 5 day, mg/L O_2	4	.0	.5	.2
Calcium, dissolved	9	30	37	32
Magnesium, dissolved	9	9.9	12	11
Sodium, dissolved	14	3.7	4.8	4.5
Potassium, dissolved	9	.4	.7	.5
Bicarbonate, as HCO_3	6	130	140	133
Carbonate, as CO_3	5	0	0	0
Chloride, dissolved	20	6.0	9.0	7.0
Fluoride, dissolved	9	.1	.3	.2
Sulfate, dissolved	8	13	19	17
Dissolved solids	8	141	164	154

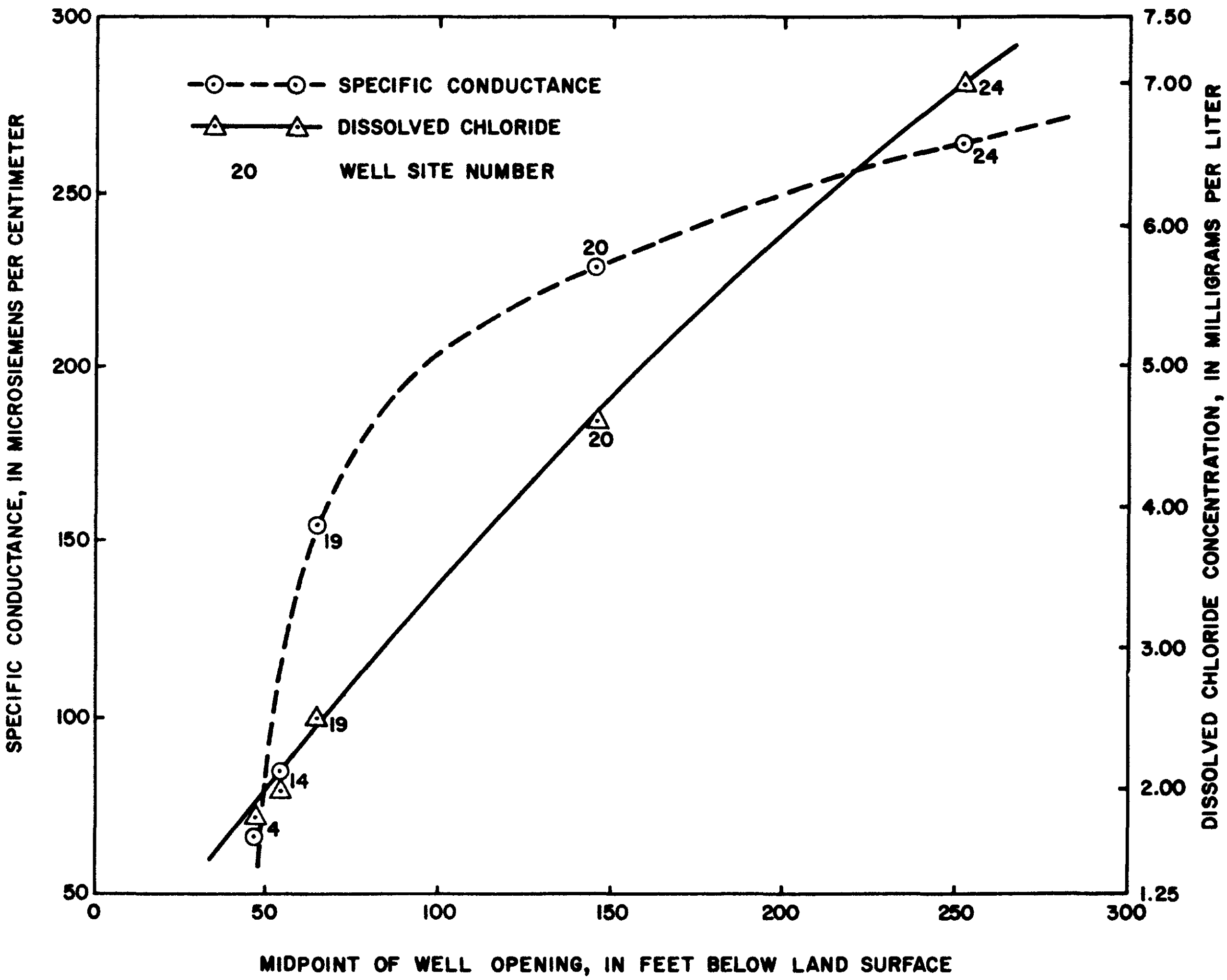

Figure 6.--Relation of depth versus mean values for specific conductance and dissolved chloride concentration for sites outside the spray area (see tables 1 and 2).

IRRIGATION WITH TREATED SEWAGE

The concept of spray irrigation with treated sewage was locally introduced by Thomas P. Smith, formerly City Sanitary Engineer. Mr. Smith initiated treated-sewage irrigation of various forage crops on an experimental basis in 1966 as a means of reducing treated-sewage discharge to Munson Slough and Lake Munson. Beginning with an application rate of about 0.5 Mgal/d, treated sewage was applied to the Thomas P. Smith Wastewater Treatment Facility (Slack, 1975).

The sprayed sewage is chlorinated, secondary-treated wastewater. After treatment, the sewage flows into a holding pond from which it is pumped to nearby fields through an underground distribution system to sprinklers of the fixed 360-degree rotating type.

Application Volumes

The spray irrigation operation has undergone four major expansions since its planning phase (fig. 3). In 1966, irrigation was initiated in the 4.5 acre single gun area and the 16-acre irrigation fields area; in 1972, the 18 acre four big-gun area was added; in 1977, the 80-acre expansion area was added; and in 1980, the 1,800 acre southeast spray field was opened 8 miles east of the southwest spray field. Monthly and annual treated-sewage irrigation volumes are summarized by Yurewicz (1983, tables 3 and 4) based upon records provided by the City of Tallahassee. The irrigation volumes for the respective general areas shown in figure 3 are graphically represented in figures 7 and 8. The total monthly volumes for the entire southwest spray field are shown in figure 9.

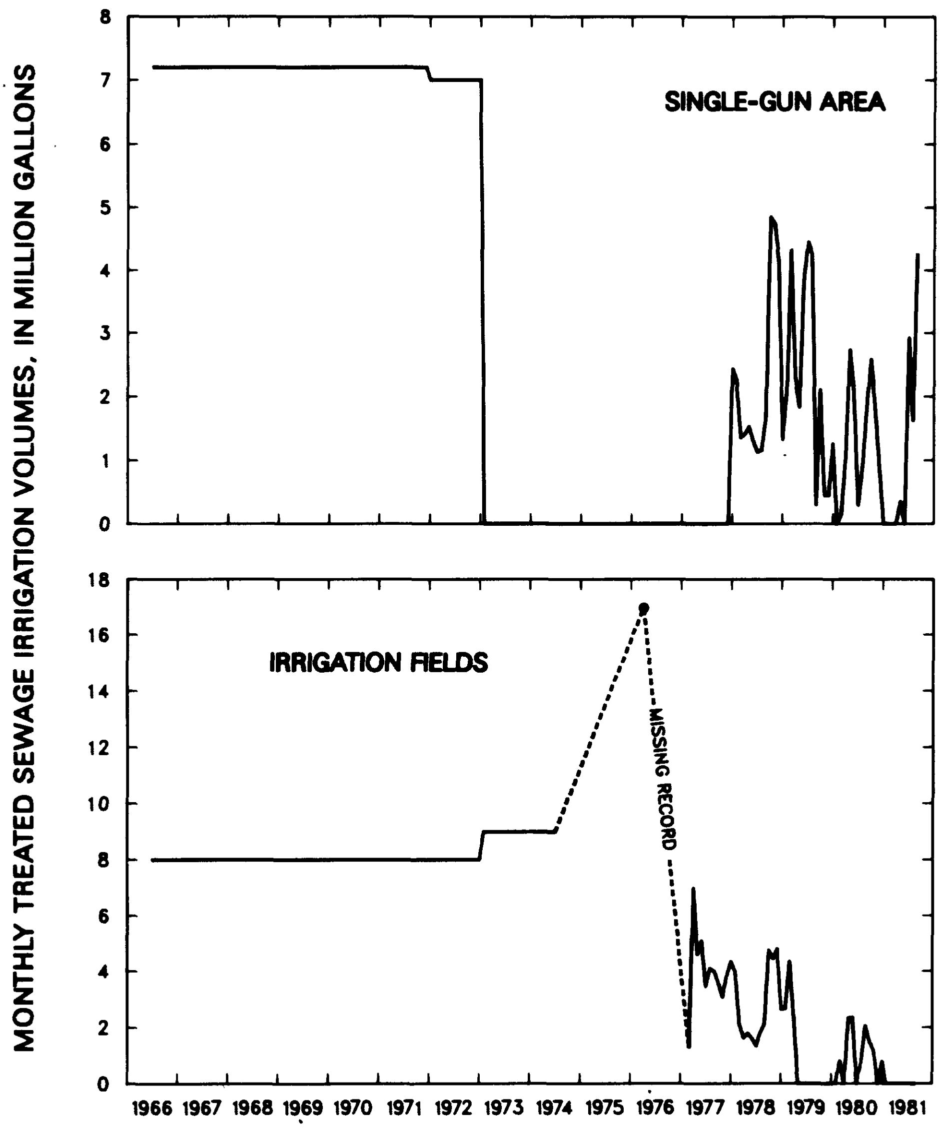

Figure 7.--Monthly treated-sewage application volumes for the single-gun area and the irrigation fields area for 1966 through June 1981. Data provided by the City of Tallahassee; missing data points represent periods of no records.

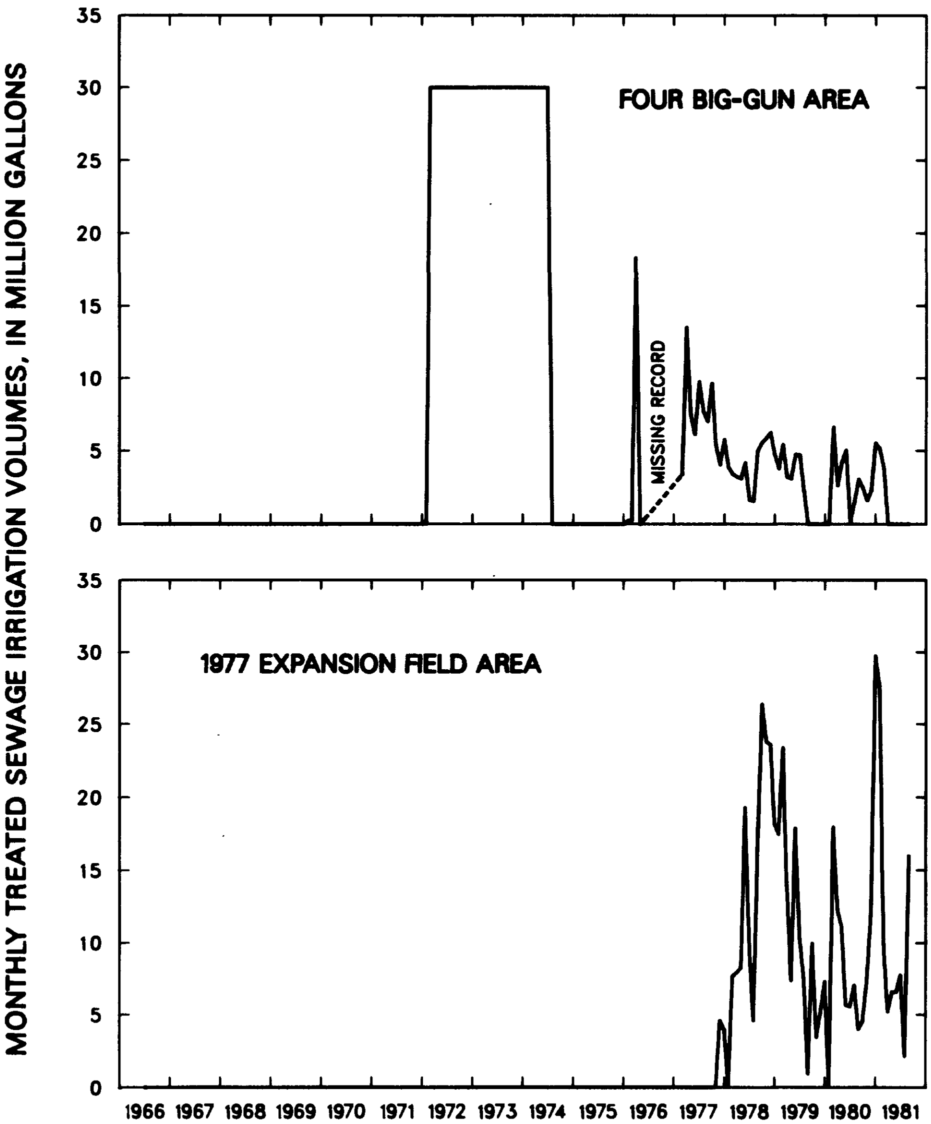

Figure 8.--Monthly treated-sewage application volumes for the four big-gun area and the 1977 expansion field area for 1966 through June 1981. Data provided by the City of Tallahassee; missing data points represent periods of no record.

The size of the four areas varied slightly throughout the spray irrigation operation. The outline of the four areas presented in figure 3 thus represents the general location, configuration, and size of each of the areas. Monthly irrigation volumes varied greatly from no application to a high of 14 inches per week from March 1972 through July 1974 in the four big-gun area. A complete description of irrigation practices for each of the four spray areas follows.

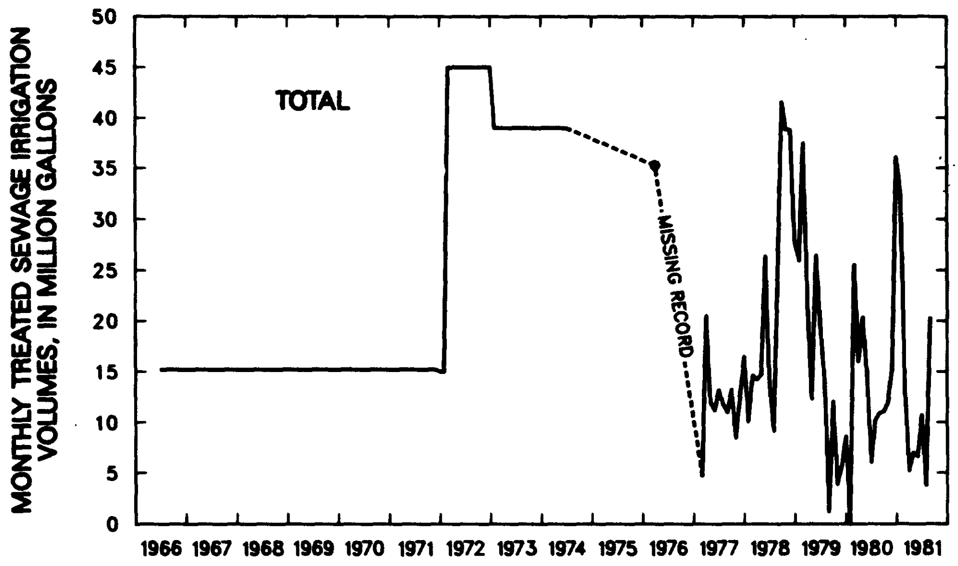

Figure 9.--Monthly treated-sewage application volumes for the southwest spray field for 1966 through June 1981. Data provided by the City of Tallahassee; missing data points represent periods of no record.

Single-Gun Area

The single gun area consisted of 4.5 acres that was sprayed as much as 24 hours a day, 2 days a week, yielding an irrigation rate of up to 16 inches per week from the beginning of the irrigation experiment in July 1966 until February 1973 (Slack, 1975). In January 1978, irrigation began again but with numerous small sprinklers. The area sprayed increased to 7.54 acres, with a small percentage of treated sewage applied on an additional 5.5 acres along the fenceline parallel to Springhill Road (fig. 3). The monthly irrigation volumes for the single gun area were variable from 1978 through 1981 as illustrated in figure 7.

Irrigation Fields Area

Irrigation of the 16-acre irrigation fields area began in 1966 with establishment of four 4-acre plots. Each plot had 16 sprinklers. The monthly irrigation volumes for this area are illustrated in figure 7 and given by Yurewicz (1983, tables 3 and 4). From February 1973 to July 1974, approximately 5 inches per week (9.0 Mgal/mo) of treated sewage were applied on the 16 acres. In April 1976, a total of 9.2 inches per week (17.1 Mgal/mo) of treated sewage were applied for experimental purposes to one section of the field; this was the greatest monthly volume recorded. In 1980, the size of the irrigation fields area was reduced from 16 to 10 acres and the sprinklers were replaced with those of larger capacity. The reduction was to permit construction to increase the treatment plant capacity.

Four Big-Gun Area

In March 1972, the four irrigation sprinklers rated at 1,000 gal/min were installed in an 18-acre area east of the 16-acre irrigation fields area. The sprinklers were set on 400-foot centers and were designed to reach an area of about 500 feet in diameter. The monthly irrigation volumes for this area are shown in figure 8 and given by Yurewicz (1983, tables 3 and 4).

The four big-gun area received up to 14 inches per week (30 Mgal/mo) until July 1974. This heavy application rate was for the purpose of gathering needed design information. From July 1974 until February 1976, varying amounts of a mixture of one-third sludge and two-thirds treated sewage were applied by three of the four big guns until June 1976.

The irrigation volumes for 1977 are given for a total area of 26 acres, which includes the addition of an area between the four big-gun area and the irrigation fields area. Construction of holding ponds and sludge pits in 1980-81 reduced the irrigated area from 26 acres to approximately 9 acres.

1977 Expansion Field Area

Irrigation in the expansion field area (fig. 8) began in December 1977, when 68 acres located east of the four big-gun area were incorporated into the system. As much as 4 inches per week was sprayed but irrigation rates varied, depending on which sprinklers were used and on the needs for crop growth. The size of this area remains 68 acres as of September 1981.

Quality of Treated Sewage

The treated sewage sprayed at the southwest spray field can be characterized as typical secondary-treated municipal sewage. A general summary of the analytical results of the treated sewage is given in table 3. Results of analyses of nitrogen species (table 4) are sorted by selected time periods because the efficiency of nitrogen stabilization during treatment varied through the period of sample collection. That is, the treated sewage from 1966-74 was from a high rate trickling filter plant; after the 1974 addition of a parallel activated sludge plant the treated sewage was more nitrified and contained less total nitrogen (W. G. Leseman, City of Tallahassee, written commun., 1986).

On the average, analyses of samples collected indicated that the mean total nitrogen concentration decreased with time. In 1980, the mean concentration was slightly more than one-half of the mean concentration for samples collected before 1974.

Water-Quality Constituent Loading

Estimated loads of the various constituents for July 1966 through June 1981 are given in table 5. The calculations, other than for nitrogen, are based on the simple assumptions of a mean value for each constituent and the total volume of treated sewage applied to the southwest spray field for the period. No allowance is made for variations in constituents and volume with time and with areas of application. The loads portrayed, with limitations, thus are gross and provide an insight to the loading of the spray field.

Table 3.--Statistical summary of selected water-quality variables for treated-sewage samples, 1972-81

[Concentrations are expressed as mg/L unless otherwise stated]

Water-quality variable	No. of samples	Minimum	Maximum	Mean
Specific conductance, μS/cm	12	541	718	649
pH, units	12	6.9	8.2	7.5
Phosphorus, total	13	5.9	12.0	9.1
Organic carbon, total	12	8.0	101	38
Hardness, as $CaCO_3$	12	120	180	140
Biochemical oxygen demand, 5-day	12	7.1	62	26
Calcium, dissolved	12	33	42	38
Magnesium, dissolved	12	8.8	20	12
Sodium, dissolved	12	40	56	48
Potassium, dissolved	12	3.0	16	9.3
Bicarbonate, as HCO_3	10	72	280	210
Carbonate, as CO_3	11	0	0	0
Chloride, dissolved	47	40	100	54
Fluoride, dissolved	7	.7	29	1.6
Sulfate, dissolved	8	18	34	25
Dissolved solids	8	270	390	321
Arsenic, μg/L	10	0	20	6
Cadmium, μg/L	12	--	--	[1] 1
Chromium, μg/L	7	--	--	[1] 20
Copper, μg/L	10	4	60	28
Iron, μg/L	10	30	630	400
Lead, μg/L	10	0	24	12
Manganese, μg/L	10	18	67	34
Mercury, μg/L	8	--	--	[1] .2
Zinc, μg/L	10	30	220	90

[1] Estimated values.

The percentage contribution to the total load for the southwest field was computed for the four areas based upon the total recorded volume of treated sewage applied and the respective mean concentration for each constituent. The calculations indicate the relative contributions of the four areas to the total load of water-quality constituents which may adversely affect the underlying soil and ground water (table 6). The area with the largest percentage contribution is the four big-gun area because of the large volume of treated sewage applied in 1972 through 1974. The smallest percentage contribution is the 1977 expansion field area because of the relatively late start of spray irrigation for that area.

Table 4.--Statistical summary of nitrogen species for treated-sewage samples

[Samples collected and analyzed by the City of Tallahassee. All concentrations are in mg/L as nitrogen and are for unfiltered samples]

Nitrogen species	No. of samples	Minimum	Maximum	Mean
Samples collected from September 1972 through August 1974				
Ammonia nitrogen (NH_4 as N)	13	11	25	20
Organic nitrogen	13	.85	14	5.0
Nitrite nitrogen (NO_2 as N)	13	.01	.55	.12
Nitrate nitrogen (NO_3 as N)	13	.00	2.6	.32
Ammonia plus organic nitrogen	13	14	34	25
Nitrite plus nitrate nitrogen	13	.01	2.9	.44
Total nitrogen	13	15	34	26
Samples collected after October 1974 but before 1980				
Ammonia nitrogen	--	--	--	--
Organic nitrogen	--	--	--	--
Nitrite nitrogen	--	--	--	--
Nitrate nitrogen[1/]	39	3.3	20.5	10.0
Ammonia plus organic nitrogen	39	3.1	16.2	6.6
Nitrite plus nitrate nitrogen	--	--	--	--
Total nitrogen[2/]	39	9.5	25.1	16.6
Samples collected in 1980				
Ammonia nitrogen	--	--	--	--
Organic nitrogen	--	--	--	--
Nitrite nitrogen	--	--	--	--
Nitrate nitrogen[1/]	4	1.1	2.8	2.2
Ammonia plus organic nitrogen	4	9.3	12.6	11.1
Nitrite plus nitrate nitrogen	--	--	--	--
Total nitrogen[2/]	4	12.1	15.3	13.3

[1/] Nitrate nitrogen analyses by specific ion electrode.
[2/] Nitrite nitrogen concentration assumed insignificant for calculation of total nitrogen concentration.

Because of the different concentrations computed for the nitrogen species as given in table 4, a different percentage loading for the four areas was calculated for the nitrogen species ammonia plus organic nitrogen, nitrite plus nitrate nitrogen, and total nitrogen. Also, because the concentrations are given for three periods of time, the total loads and percentage contributions are based upon the respective application volumes. The percentage contributions of the nitrogen species are given in table 6. The percentage contributions for ammonia plus organic nitrogen, and total nitrogen contributions of the four areas were generally similar to those computed for other constituents. However, nitrate plus nitrite nitrogen was distributed in a very different pattern, with the largest percentage contribution being for the 1977 expansion field area.

Table 5.--Estimated loads of selected water-quality constituents at the southwest spray field, July 1966 through June 1981

Water-quality constituent	Total estimated load (pounds)	Water-quality constituent	Total estimated load (pounds)
Ammonia plus organic nitrogen	510,000	Fluoride	42,000
Nitrite plus nitrate nitrogen	65,000	Sulfate	650,000
Total nitrogen	600,000	Dissolved solids	8,300,000
Phosphorus	240,000	Arsenic	160
Organic carbon	990,000	Cadmium	26
Calcium	990,000	Chromium	520
Magnesium	310,000	Copper	730
Sodium	1,200,000	Iron	10,000
Potassium	240,000	Manganese	880
Bicarbonate	5,500,000	Mercury	5.2
Chloride	1,400,000	Zinc	2,300

Table 6.--Percent contribution of nitrogen species and other water-quality constituents to total load for the four areas at the southwest spray field, July 1966 through June 1981

Water-quality constituent	Percent contribution to total load			
	Single-gun area	Irrigation fields area	Four big-gun area	1977 expansion field area
Ammonia plus organic nitrogen	24	35	38	3
Nitrite plus nitrate nitrogen	11	18	29	42
Total nitrogen	23	33	37	7
Other constituents	21	29	35	15

EFFECTS OF IRRIGATION ON GROUND-WATER LEVELS

Measurements of ground-water levels during the investigation indicate that spray irrigation did not noticeably affect ground-water levels in the Floridan aquifer system. Slack (1975, p. 19; figs. 8 and 9) prepared potentiometric maps for periods of high and low ground-water levels which indicated that treated-sewage application had not generated a mound nor otherwise distorted the regional ground-water flow pattern. Both potentiometric maps indicate that the direction of ground-water movement in the upper Floridan aquifer system is southwesterly, toward the Gulf of Mexico (fig. 10). The quantity of water being applied at the site is thus insignificant compared to the natural recharge and the quantity of water moving through the aquifer. Although permeability of the Floridan aquifer system near the southwest field was not quantified, the presence of solution cavities in and downgradient of the field, as discussed earlier, indicates that permeability and ground-water movement are high.

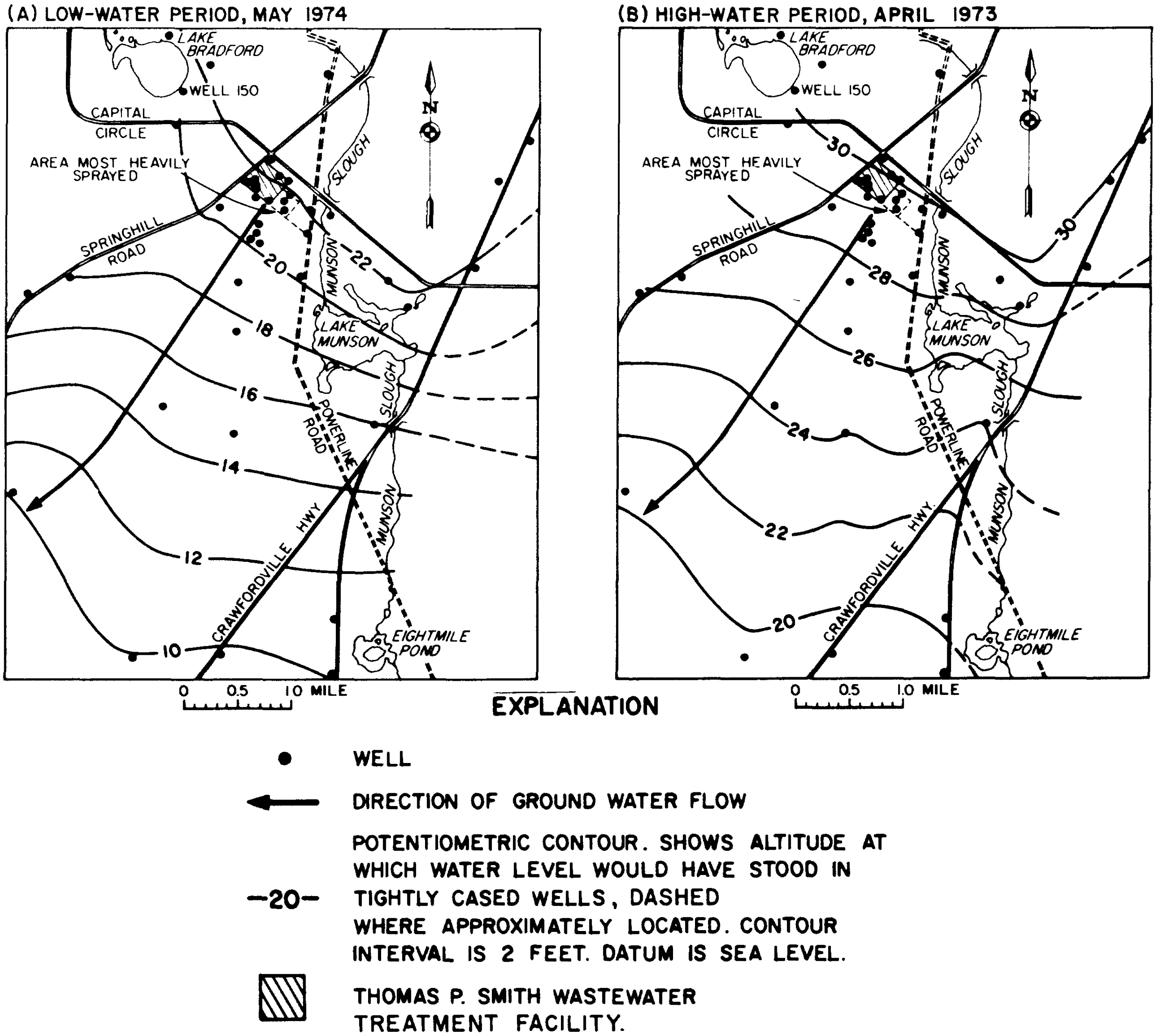

Figure 10.--Potentiometric surface of the upper part of the Floridan aquifer during low and high water periods, at, and southwest of, the southwest spray field, Tallahassee.

Another method of examining ground-water level trends is by use of the double mass curve. The relation of ground-water levels at sites 1 and 34 is meaningful in detecting water-level changes due to treated-sewage spray application. Site 1 (fig. 3) is in the spray field and site 34 (fig. 2), which represents background water levels, is approximately a mile northwest from site 1. Cumulative monthly mean ground-water levels for site 1 are plotted against cumulative monthly mean ground-water levels for site 34 from October 1972 to September 1979 (fig. 11). As shown, there is no change or break in the plot of cumulative mean water levels, thus indicating a constant relation in ground-water levels between the spray field and background conditions, and verifying the implications drawn from potentiometric mapping. Monthly spray irrigation volumes, however, dropped significantly during 1974 (fig. 9), and this is illustrated by the plot of chloride concentrations for site 1 (fig. 11). Thus, although the quantity of treated sewage applied has not been enough to affect aquifer water levels, there has been a significant change in chloride concentrations in the ground water at site 1. The chloride concentration at background site 35 during the same period remained constant at 2.7 mg/L (Yurewicz, 1983, table 6).

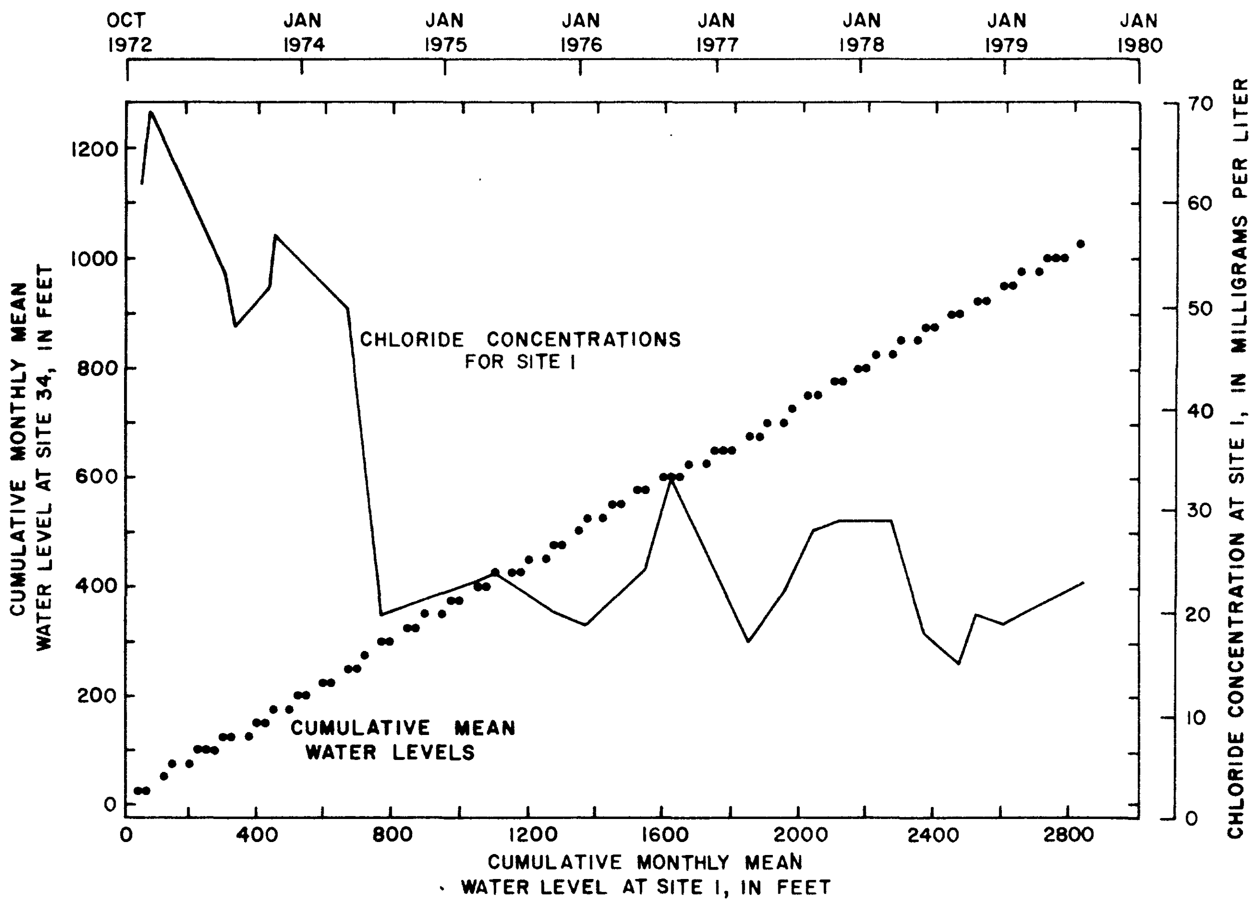

Figure 11.--Cumulative monthly mean ground-water levels for site 1 versus site 34, and chloride concentration for site 1 versus time.

Water-level data for site 1 indicate that ground-water levels ranged from 32.37 to 38.85 feet below land surface between October 1972 and May 1981. A plot of the daily mean ground-water altitudes for sites 1, 34, and 35 for October 1977 to September 1978 (fig. 12), shows that typical seasonal variations in water levels are affected primarily by rainfall and antecedent conditions. A similar conclusion was reached by Elder and others (1985) in the investigation of the southeast field. Pearson's correlation coefficient for ground-water data plotted in figure 12 for sites 1 and 34, as well as between sites 1 and 35, are high (0.994 and 0.993, respectively). This verifies the hydrologic similarities between site 1, located in the spray area, and background sites 34 and 35, located well outside the spray area.

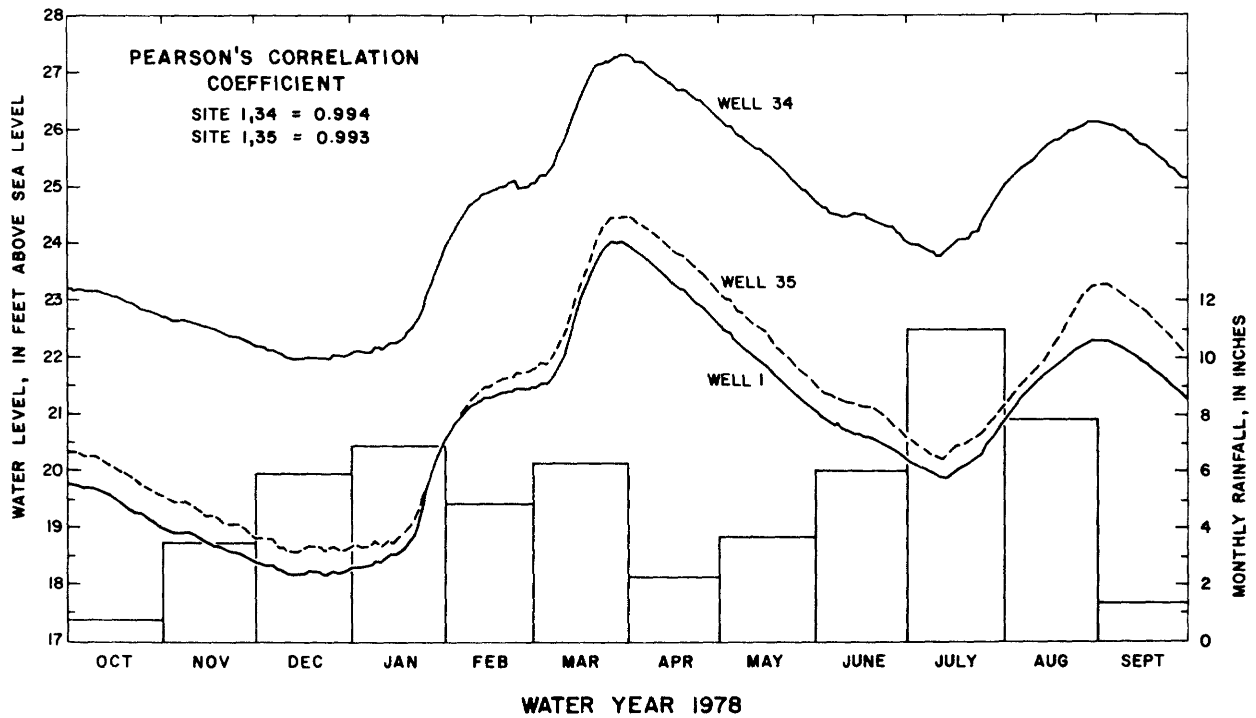

Figure 12.--Monthly rainfall at Tallahassee and daily mean ground-water levels for sites 1, 34, and 35 for October 1, 1977, through September 30, 1978.

EFFECTS OF IRRIGATION ON GROUND-WATER QUALITY

In addition to simple dilution (mixing), numerous interrelated biological, physical, and chemical processes may affect the water-quality of the sprayed sewage as it percolates through the unsaturated zone and commingles with the local ground water. However, only simple dilution was addressed within the scope of this investigation.

Estimates of Dilution

To assess the general effects of treated municipal sewage on ground water, the dilution or mixing of the treated sewage and ground water must be estimated from simple mixing ratios. Estimates of dilution require the use of a conservative constituent (tracer)--that is, a constituent that is not usually altered by chemical, physical, or biological processes other than mixing. Ideally, it should also be absent or at low concentrations in the natural system, have a low analytical cost, and the analytical determination should be sensitive. Chloride is generally considered conservative in most aqueous systems, and was selected as one of the tracers to estimate the percent dilution for this investigation.

A dilution model using chloride concentrations, for example, can be established to estimate the percentage treated sewage in the ground water. The following mass balance dilution model was used to estimate the percentage treated sewage in the ground water;

$$\text{Percentage treated sewage} = \frac{C_S - C_N}{C_E - C_N} \times 100 \qquad (1)$$

where

C_S = (chloride) concentration of ground-water sample,
C_N = (chloride) concentration of native ground water, and
C_E = (chloride) concentration of treated sewage.

A representative value for native chloride concentration (C_N) must be chosen for application in the dilution model. As illustrated by figure 6, chloride concentrations in background wells increase with depth. The value for C_N for each background site was based upon the mean chloride concentration of all samples collected from that particular site. For sites without background samples, C_N values were based upon the chloride trend line given in figure 6.

Slack (1975) used a uniform C_N value of 2 mg/L, based on the mean chloride concentration of samples from site 14 and, therefore, obtained percentage treated-sewage values that are generally smaller than those given in this report using C_N of 1.4 to 1.7 (see p. 30).

The chloride concentration of treated sewage (C_E) is based on the mean concentration of all treated-sewage samples analyzed; C_E equals 54 mg/L (table 3), which is 9 mg/L less than that used by Slack (1975).

Cation concentration changes in Floridan aquifer system water were examined using the dilution model. If the major inorganic cations calcium, magnesium, sodium, and potassium behaved conservatively (were not affected by cation exchange or other processes), they would exhibit the same degree of dilution in ground water as chloride. Thus the same dilution equation used for chloride, namely:

$$\text{Percentage treated sewage} = \frac{C_S - C_N}{C_E - C_N} \times 100 \qquad (1)$$

would apply to cations. Ground-water quality samples from sites 1, 5, 25, 31, and 32 were analyzed for calcium, magnesium, sodium, potassium, bicarbonate, and chloride, and used to study changes in cation concentrations. For each sample the percent treated sewage was calculated based upon the dilution model. The expected concentrations of the major cations and bicarbonate were then calculated, based upon the same dilution equation, but rearranged as follows:

$$C_S = \frac{\text{percentage treated sewage } (C_E - C_N) + C_N}{100} \qquad (2)$$

where

percentage treated sewage = the value calculated from the dilution equation using the chloride concentration associated with the cations and bicarbonate;

C_S = the cation or bicarbonate concentration (if it were a conservative constituent);

C_E = the mean cation or bicarbonate concentration for the treated sewage, based upon data given in table 3; and

C_N = the background cation or bicarbonate concentration for each site, based upon the mean concentration of all background samples.

Value of C_N in mg/L were calculated as:

	Site 15	Site 32
Calcium	8.5	10
Magnesium	.4	.8
Sodium	1.1	1.0
Potassium	.2	.2
Chloride	1.7	1.4
Bicarbonate	29	29

Values for C_N for sites 1, 5, and 31 are assumed to be the same concentrations as those given for site 32 because the sites are open to the Floridan aquifer system in approximately the same depths.

The mean differences between the actual concentrations in meq/L (milliequivalents per liter) and the expected concentrations in meq/L were then calculated. The results are given in table 7. A positive difference indicates that overall the actual concentrations are greater than the expected concentrations based upon the dilution equation. A negative value indicates that overall the actual concentrations are less than the calculated expected concentrations. Table 7 also gives the mean ratio of actual to expected concentrations, and the associated rank of the deviation of the mean ratio from 1.0. The rank of the mean ratio deviation from 1.0 provides an indication of the relative degree to which each constituent at each site behaves conservatively. That is, a rank of 4 indicates the most conservative constituent at each site.

Table 7.--Mean differences, mean ratios, and ranks of mean ratios of actual versus expected major cation and bicarbonate concentrations for selected sites

Ion	Mean difference for actual-expected concentrations for selected samples (meq/L)	Mean ratio of actual/expected concentrations	Rank of mean ratio deviation from 1.0
	Site 1		
Calcium	+0.13	2.17	1
Magnesium	+ .13	1.26	3
Sodium	.0	1.00	4
Potassium	- .05	.54	2
Bicarbonate	+ .42	1.37	--
	Site 5		
Calcium	+ .80	2.00	1
Magnesium	+ .16	1.59	3
Sodium	- .17	.69	4
Potassium	- .05	.22	2
Bicarbonate	+ .46	1.39	--
	Site 25		
Calcium	- .05	.94	4
Magnesium	- .30	.36	2
Sodium	- .38	.70	3
Potassium	- .07	.19	1
Bicarbonate	- .71	.37	--
	Site 31		
Calcium	+ .77	1.76	1
Magnesium	+ .07	1.16	4
Sodium	- .14	.83	3
Potassium	- .07	.27	2
Bicarbonate	- .04	.98	--
	Site 32		
Calcium	- .17	.79	4
Magnesium	- .14	.35	3
Sodium	- .29	.28	2
Potassium	- .04	.15	1
Bicarbonate	- .78	.31	--

Sites 1, 5, and 31 can be grouped for the purpose of discussing table 7. Both sites 1 and 31 have been affected by spray irrigation since first sampled in October 1972; they are located in the four big-gun area where spray irrigation began in March 1972. Site 5, which is 1,800 feet downgradient of the southwest field, has been affected by spray irrigation since February 1973. Sites 25 and 32 are both located in the 1977 expansion field area where spray irrigation began in November 1977.

Data for sites 1, 5, and 31 (Yurewicz, 1983; table 6) show that calcium and magnesium are present in concentrations greater than expected. The greatest deviation of the mean ratio values from 1.0 for sites 1, 5, and 31 are for calcium. The least rank of mean ratio deviation from 1.0 for sites 25 and 32 is for calcium. Calcium and magnesium concentrations for sites 25 and 32 are also less than expected. It is possible, therefore, that Floridan aquifer system water affected by spray irrigation may initially have calcium and magnesium concentrations less than expected, but after an indeterminate length of time or treated-sewage loading, these concentrations become greater than expected. Sodium and potassium concentrations are less than expected for all sites, except for sodium at site 1.

Ground-water samples collected and analyzed for major cation and bicarbonate concentrations thus indicate that although all major cation concentrations may initially be less than expected, as indicated for sites 25 and 32, a reversal for magnesium and particularly calcium occurs, as indicated for sites 1, 5, and 31. Bicarbonate concentrations also indicate that the actual concentrations are initially less than expected but show a similar reversal so that the actual concentrations tend to become greater than expected. Because calcium, bicarbonate, and magnesium are primary components of the rocks of the limestone aquifer, the cause of the reversals for these three constituents can be explained by the likely process of precipitation of these constituents as they reach the limestone aquifer. Initial studies of the degree of saturation of calcite and dolomite in the Floridan aquifer system at the southeast spray field, utilizing the geochemical model WATEQF, indicate that calcite and dolomite are undersaturated (Plummer and others, 1976; and U.S. Geological Survey, 1981; selected southeast spray field sites). This is expected because of the high rate of recharge in the area.

Dissolved calcium, magnesium, and bicarbonate thus evidently precipitate and establish new equilibrium conditions for solids phases such as calcite and dolomite. The chemical reaction equations which can be written to explain the reversals in concentrations of bicarbonate, calcium, and magnesium include:

$$CaCO_3 \text{ solid} + H_2CO_3 \rightleftharpoons Ca^{+2} + 2HCO_3^{-1}$$

(calcite)

$$CaMg(CO_3)_2 \text{ solid} + 2H_2CO_3 \rightleftharpoons Ca^{+2} + Mg^{+2} + 4HCO_3^{-}$$

(dolomite)

After a sufficient amount of calcium, magnesium, and bicarbonate reach the limestone and establish thermodynamic saturation (or perhaps supersaturation) conditions by precipitating as calcite and dolomite, the three concentrations then become greater than expected because they are no longer precipitating out of solution. Cation exchange may thus release calcium and magnesium from the clay materials, in exchange for sodium and potassium, but the actual concentrations of calcium and magnesium do not become greater than the expected concentrations (as would be expected from cation exchange), until the new equilibrium conditions exist in the limestone aquifer. Ground-water quality samples are being collected at the southeast spray field to aid in the further study of this process.

Nutrients

Irrigation with treated sewage increased the nutrient concentrations in the Floridan aquifer system. However, only during periods of nitrogen loadings, at rates greater than approximately 130 to 180 pounds per acre per month, did nitrate nitrogen concentrations exceed the established drinking water limit of 10 mg/L. Mean ground-water concentrations of organic carbon remained near background levels and phosphorus concentrations remained at background levels.

Organic Carbon

Interpretation of effects of treated-sewage application on organic carbon concentrations in Floridan aquifer system water is limited by the analytical accuracy for that constituent. For example, note the following statistical summary for three background sites and site 1 (concentrations are in mg/L).

	Site No.			
	4	14	24	1
Number of samples	19	12	7	13
Mean concentration	1.3	3.7	0.6	2.1
Standard deviation of concentration	2.3	3.9	0.8	2.4
Median concentration	<1	2	<1	1
Minimum concentration	<1	<1	<1	<1
Maximum concentration	9	11	2.0	7

The range in background concentrations of organic carbon is considerable, and the standard deviations exceed the means. The actual background concentration of organic carbon in the Floridan aquifer system is generally expected to be less than 1 mg/L (Leenheer and others, 1974). The median concentrations are lower than the means and much closer to the expected concentrations. This is characteristic of a skewed distribution in which relatively few values are much greater than the mean.

The concentrations of organic carbon at sites 1 and 9 show the effect of treated-sewage spraying. An estimated 35 percent or 346,000 of the 990,000 pounds of organic carbon applied to the southwest field was sprayed in the four big-gun area. The median concentration of organic carbon for samples collected from 1972 through 1981 from site 1 was 1 mg/L. The dilution ratio of the conservative constituent, chloride, suggests that the treated-sewage spraying could produce as much as a sixteenfold increase in organic carbon concentration. Ten ground-water samples were collected from site 9 during 1973 and 1974 when 14 inches per week of treated sewage were being sprayed in the four big-gun area. This mean chloride concentration was 55 mg/L, virtually the same concentration as the applied treated sewage, indicating that the samples collected were almost 100 percent treated sewage. The expected mean organic carbon concentration is 39 mg/L and the actual is 3 mg/L. Thus, only during periods of high application volumes did the organic carbon concentration become greater than background levels. In most cases, as shown for site 1, organic carbon concentrations in the upper part of the Floridan aquifer system remained near background levels.

Phosphorus

Phosphorus concentrations remained at or near background levels for all sites. The average phosphorus concentration in the treated sewage was approximately 9 mg/L, and the minimum estimated phosphorus load to the southwest field through June 1981 was 240,000 pounds. The four big-gun area received an estimated 84,000 pounds of phosphorus from treated-sewage irrigation at the southwest field, the greatest amount of the four irrigation areas. Sites 1 and 31 are in the four big-gun area and both wells are open-hole to the upper part of the limestone aquifer (45-61 and 60-70 feet below land surface, respectively). Total phosphorus concentrations at representative sites were as follows:

Site	Period	No. of samples	Mean concentration (mg/L)
1	1972-81	40	0.04
31	1980-81	14	0.03
4	1972-81	19	0.02

Slack (1975) reported that the Lakeland fine sand at the southwest field has a high capacity to fix phosphorus, particularly as the phosphorus concentration in the soil and subsurface increases, due to continuous breakdown of the clay materials and resultant release of aluminum and iron from the clays.

Nitrogen

Nitrification is the process whereby ammonia nitrogen is oxidized first to nitrite nitrogen and then to nitrate nitrogen. The group of bacteria known as *Nitrosomonas* oxidize ammonia to nitrite under aerobic conditions. Nitrite is then readily oxidized to nitrate by the bacteria group *Nitrobacter*, also under aerobic conditions. Temperature, oxygen, and pH are important for the nitrification process. Rates of nitrification should be lower during winter than summer months because of low soil temperatures.

Although nitrogen losses occurred because of processes such as denitrification and plant uptake, nitrogen was a significant water-quality characteristic because concentrations of nitrate nitrogen in the Floridan aquifer system exceeded the maximum contaminant level established for drinking water (10 mg/L as nitrogen). Nitrification resulted in practically complete oxidation of ammonia and organic nitrogen to nitrate nitrogen. Overman (1979) concluded that nitrification reached completion in the upper 4 feet of soil in his investigation of effects of spray irrigation on the shallow subsurface. Analyses of soil samples for the southwest field indicate that the number of nitrifying and denitrifying bacteria there are much greater than at nonspray sites (Yurewicz, 1983, table 5).

Background concentrations of nitrogen species in ground water may be represented by samples collected from site 4 (Yurewicz, 1983, table 6). The mean concentrations for all samples analyzed, given as nitrogen, are: ammonia 0.02 mg/L, organic nitrogen 0.03 mg/L, nitrite 0.01 mg/L, nitrate 0.02 mg/L, and total 0.09 mg/L. Data presented for treated sewage (table 4), indicate that ammonia plus organic nitrogen concentrations exceeded nitrite plus nitrate concentrations.

Mean concentrations of nitrogen species in ground water for sites 9 in the irrigation fields area and for 31 in four big-gun area show the degree of nitrification completion (Yurewicz, 1983, table 6). Samples collected during 1980-81 at site 31 indicate that nitrification was occurring. The mean concentrations of nitrogen species during that period were: ammonia 0.04 mg/L, organic nitrogen 0.06 mg/L, nitrite 0.00 mg/L, and nitrate 5.5 mg/L. During 1973-74, greater amounts of ammonia and organic nitrogen were reaching the upper part of the Floridan aquifer system at site 9; mean concentrations for the nitrogen species were: ammonia 0.38 mg/L, organic nitrogen 0.22 mg/L, nitrite 0.05 mg/L, and nitrate 18 mg/L. The corresponding mean chloride concentration for samples collected at site 9 is 56 mg/L, indicating that ground water entering through the well screen at 40-42 feet below land surface was 100 percent treated sewage. Treated sewage sprayed in the four big-gun area evidently was moving downgradient to the zone of the well screen at site 9, which was located near the southwest perimeter of the four big-gun area.

Concentrations of total nitrogen in ground water in the Floridan aquifer were less than the expected concentrations calculated from the chloride dilution model. Denitrification and the resultant loss of N_2 to the atmosphere in the upper soil zone, and uptake by crops are likely to cause reductions in nitrogen concentrations. Analyses of soil samples for denitrifier bacteria were presented by Slack (1975, table 7) and Yurewicz (1983, table 5). The bacteria counts were performed using the multiple tube technique, and many of the results were reported as less than or greater than a value; statistical tests of differences were therefore not possible. The results indicated, however, that denitrifier bacteria counts were greater in the spray field than in background sites.

Nutrient uptake by crops, as well as crop yields, increases with the treated-sewage application rate (Overman, 1979). Relative nutrient recovery, however, decreases at high application rates. Maximum nitrogen recovery (greater than 50 percent) occurs at irrigation rates from 1 to 2 inches per week.

Slack (1975) reported that nitrogen concentrations in ground water at sites 5 and 21 were less than expected (did not behave as a conservative constituent), based upon the chloride dilution model. Site 5 is 1,800 feet downgradient of the four big-gun area and site 21 is at the southwest boundary of the irrigation fields area. Ground water at both sites was 25 percent treated sewage from January 1974 to June 1974. The total nitrogen concentrations at sites 5 and 21 were expected to be 6.2 mg/L, if nitrogen were a conservative constituent (using the same computing procedures as in the major ions section). The actual nitrogen concentrations were 5.0 mg/L and 3.3 mg/L, respectively. Thus, approximately 5 mg/L at site 5 and 12 mg/L of total nitrogen at site 21 were removed from the treated sewage (Slack, 1975, p. 32).

Ground-water samples collected from site 32 during 1980-81 also indicate that the actual total nitrogen concentration is less than expected, based upon the chloride dilution model. Site 32 is in the 1977 expansion field area and is open-hole in the limestone from 58 to 80 feet below land surface. Conditions at this site are considered representative of conditions which result from typical low treated-sewage application rates at the expansion field area. The mean irrigation rate for November 1977 through June 1981 was 1.5 inches per week. Chloride concentrations of ground-water samples (Yurewicz, 1983) from site 32 consisted of 23 percent treated sewage during 1980-81 and the mean total nitrogen concentration was 2.0 mg/L. The minimum and maximum total nitrogen concentrations for the same period were 1.3 and 2.7 mg/L, respectively. The mean expected total nitrogen concentration, based upon the chloride dilution model, is 3.0 mg/L. Thus, the mean reduction of total nitrogen concentration was 30 percent or 1.0 mg/L.

Numerous factors affect changes in the nitrate concentrations in the Floridan aquifer system. They include: the application rate and character of treated sewage; the hydraulic connection from land surface to the aquifer; the rate of denitrification and nitrification; the seasonal effects of crop growth and resultant crop uptake of nitrogen; the hydraulic properties of the aquifer, such as dissolution channels and variation of permeability with depth; the crops grown; addition of nitrogen fertilizer; the depth below land surface; and the depth below the top of the aquifer.

The application and nitrogen loading rates are of particular interest in determining the amount of denitrification and nitrogen in the ground water beneath the spray fields. The relation of loading and nitrogen in ground water for the periods of records for the irrigation fields, the four big-gun, and 1977 expansion field areas are given in the following table. The values are based upon the mean monthly volume of treated sewage applied (figs. 7 and 8) and the mean monthly nitrogen concentration of treated sewage during the period.

	1973-74	Oct 1972- May 1974	Nov 1977- June 1981
Spray area	Irrigation field	Four big-gun area	1977 expansion field
Site	9	1	32
N content of sewage (mg/L)	26	26	13
Application rate of sewage:			
Mgal/mo	39	30	11
in/wk	10	14	1.5
N loading of area (lbs/acre/mo)	250	360	18
N content of ground water (mg/L)	18	19	1.9

Nitrate nitrogen concentrations in the ground water exceeded the drinking water standard of 10 mg/L during periods of high nitrogen loading of the irrigation fields area and four big-gun area during 1973-74. The mean monthly load of nitrogen per acre for the 1977 expansion field area for November 1977 through June 1981 was significantly lower than the 1973-74 loading of the areas at sites 1 and 9, and the nitrate concentration in the aquifer, consequently, was lower.

The data indicate that the mean nitrate concentration in the upper part of the Floridan aquifer at the southwest spray field is related to the mean monthly nitrogen load per acre during periods of relatively constant nitrogen loading. Because initial spray irrigation with treated municipal sewage was experimental, monthly nitrogen loading was highly variable, and monthly irrigation volumes sometimes were unavailable, the time periods which can be used to verify this relation are limited.

As an approximation, the nitrogen loads (in pounds of nitrogen per acre per month) for sites 1, 9, and 32 are plotted (fig. 13) with the associated mean nitrate concentrations in ground water for the periods discussed earlier. The mean nitrate concentrations represent the nitrate concentrations in the upper part of the Floridan aquifer during periods of relatively constant nitrogen loading due to treated-sewage application. The graph is presented as a means of estimating the nitrogen load from treated-sewage application without exceeding the drinking water standard for nitrate nitrogen in the aquifer. The data points for sites 1 and 9 represent areas with high nitrogen loading and the data point for site 32 represents an area with a low level of nitrogen loading. The graph suggests that the maximum nitrogen loading permissible without exceeding 10 mg/L is approximately 130 to 180 pounds of nitrogen per acre per month; however, it is not known if these relations are necessarily linear.

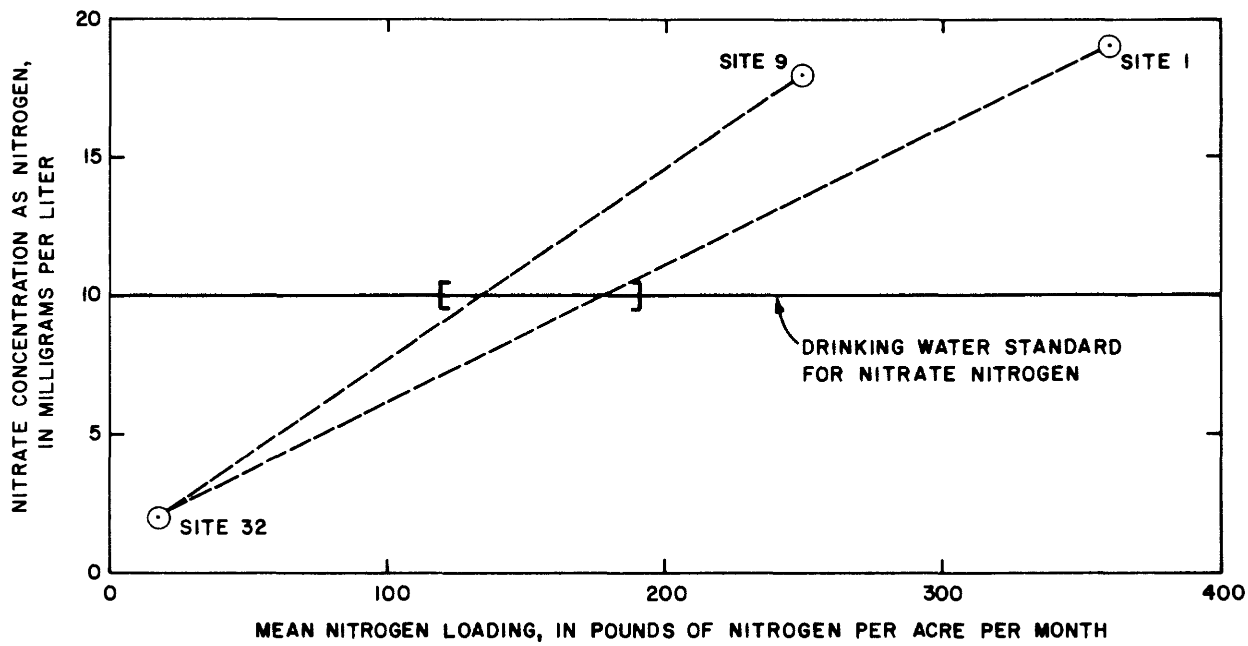

Figure 13.--Relation between the mean nitrate concentration in the Floridan aquifer system for sites 1, 9, and 32, and the mean nitrogen loading.

The depth below the top of the limestone is one of the factors that affects nitrate concentrations in the Floridan aquifer system in relation to nitrogen loading as shown in figure 13. The nitrate concentration for site 9 is 5 mg/L greater than the estimated value corresponding to 250 pounds of nitrogen per acre per month for the sites 1-32 line. This may be caused by the difference in depths below the top of limestone for which sites 1 and 9 are open to the Floridan aquifer system and hence, the greater dilution associated with the aquifer for site 1. The 2-foot well screen for site 9 lies 5 to 7 feet below the top of the limestone. The 11-foot open-hole section for site 1 lies 2 to 13 feet below the top of the limestone. If the screened part of site 9 was at a greater depth below the top of the limestone, a greater degree of dilution would likely occur, and the nitrate concentration would be less. This would place the data point for site 9 closer to the line between sites 1 and 32.

Other Effects on Ground-Water Quality

Concentrations of trace metals for which maximum contaminant levels have been established for drinking water did not increase above background levels in the Floridan aquifer system (table 8). Ground-water samples collected from 1973 to 1981 from site 1 exhibit trace metal concentrations similar to site 4 which is unaffected by spray irrigation. No increasing trend of trace metal concentrations exists for site 1, even though 35 percent (or 1,090 Mgal of the total estimated minimum 3,100 Mgal total volume sprayed) was applied to the four big-gun area. Other sites sampled and analyzed for trace metals also had concentrations of trace metals at background levels (Yurewicz, 1983). Probable causes for the absence of trace metal enrichment in the Floridan aquifer system are associated with the unsaturated zone of the sand formation and soil, and include: precipitation, complexation, ion exchange, and plant uptake.

Table 8.--Amount of selected trace metals applied in the four big-gun area, corresponding concentrations in ground water from sites 1 and 4, and maximum contaminant levels established for drinking water

Metal	Total estimated amount applied in four big-gun area[1/]		Site 4, June 6,	Concentration for sample collected from site 1[2/]		Maximum contaminant levels established
	1966 to May 1973 (pounds)	1966 to April 1981 (pounds)	1973 (µg/L)	June 7, 1973 (µg/L)	April 30, 1981 (µg/L)	for drinking water[3/] (µg/L)
Arsenic	23	55	<1	1	3	50
Cadmium	3.8	9.2	ND	2	0	10
Chromium	75	180	ND	ND	6	50
Copper	110	260	ND	ND	0	1,000
Iron	1,500	3,600	--	--	13	300
Lead	45	110	5	2	0	50
Manganese	130	310	--	10	1	50
Mercury	.75	1.8	<.5	.5	.0	2
Zinc	340	830	ND	20	0	5,000

[1/]Based upon irrigation volumes and mean trace metal concentrations given in table 3.

[2/]Values given are for either total or total recoverable.

[3/]Florida Department of State (1977; 1981).

Fecal coliform concentrations in the ground water of the Floridan aquifer system remained at or near zero throughout the sampling program. A few samples were believed to have been contaminated during sampling. No fecal coliform organisms were detected in the initial sampling program, although concentrations in the treated sewage ranged from 4,000 to 80,000 organisms per 100 mL (milliliter) (Slack, 1975). Water samples collected from site 31 during 1980-81 indicated the aquifer water was 39 percent treated sewage and coliform free (Yurewicz, 1983). Coliform organisms, pertinent to drinking-water quality, were thus removed or died before reaching the aquifer.

The concentrations of all pesticide residues were below the detection limits of either 0.1 or 0.01 mg/L and thus were not detectable in the Floridan aquifer system beneath the spray field. Six sites (4, 5, 6, 17, 18, and 22) were sampled for organochlorine insecticides in 1974: aldrin, chlordane, DDD, DDE, DDT, dieldrin, endrin, heptachlor, heptachlor expoxide, lindane, and toxaphene. Sites 1, 4, 5, 6, 17, 18, 19, 22, and 29 were sampled in 1974 for the following chlorinated phenoxy acid herbicides: 2,4,D; 2,4,5-T; and silvex. The same nine sites were sampled in 1978 for those insecticides itemized above plus endosulfan, methoxychlor, and mirex (Yurewicz, 1983).

Pesticides would not be expected to be a problem in spray irrigation of treated sewage because no pesticides are applied to the forest or forage crops and pesticide residue concentrations in the Tallahassee municipal treated sewage should normally be low because the municipal system does not include stormwater drainage.

AREAL, VERTICAL, AND TEMPORAL DISTRIBUTION OF AFFECTED GROUND WATER

Areal Distribution

The approximate areal extent of ground water affected by spray irrigation is illustrated by figures 14 through 17 and all show the same south to southwest flow. Figure 14 shows the chloride concentrations in ground water in December 1972 and figure 15 the concentrations in June 1974. The main difference between figures 14 and 15 is the southwesterly increase in areal extent of the affected area. The chloride concentration of a ground-water sample from site 5 was 1.5 mg/L in November 1972 and 17 mg/L by June 1974. Chloride concentrations in samples from sites 2, 6, 7, 14, and 26 remained at or near background levels throughout the investigation.

Figure 16, based on ground-water samples collected during February 1981 (samples from site 5 were collected in March and from sites 4 and 14 in April), shows that the areal extent of ground water affected by treated-sewage application shifted southeast and decreased in concentration between the 1974 and 1981 sampling. This shift was due to the initiation of treated-sewage application on the 1977 expansion field area and sharp decreased treated-sewage application on the other areas (Yurewicz, 1983, tables 3 and 4). Chloride concentrations in 1981 at sites 4, 6, 7, 14, 26, and 33 were at or near background levels; other sites showed chloride concentrations lower than in 1974. This decrease is noteworthy in that it reflects the changed treated-sewage application and the importance of a mobile treated-sewage distribution system.

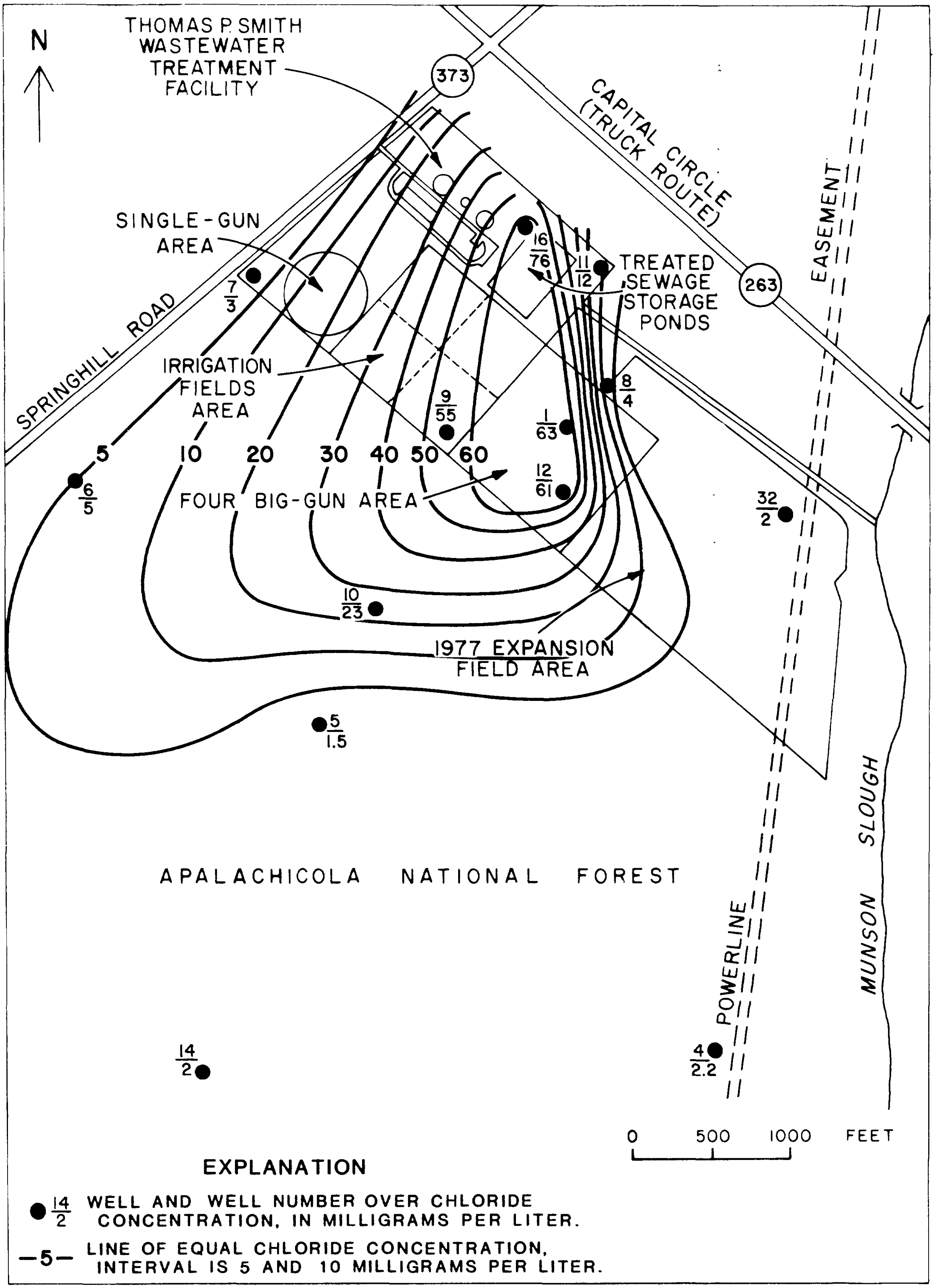

Figure 14.--Approximate areal extent of ground water affected by treated-sewage application, based on chloride concentrations in ground water at the southwest spray field, December 1972.

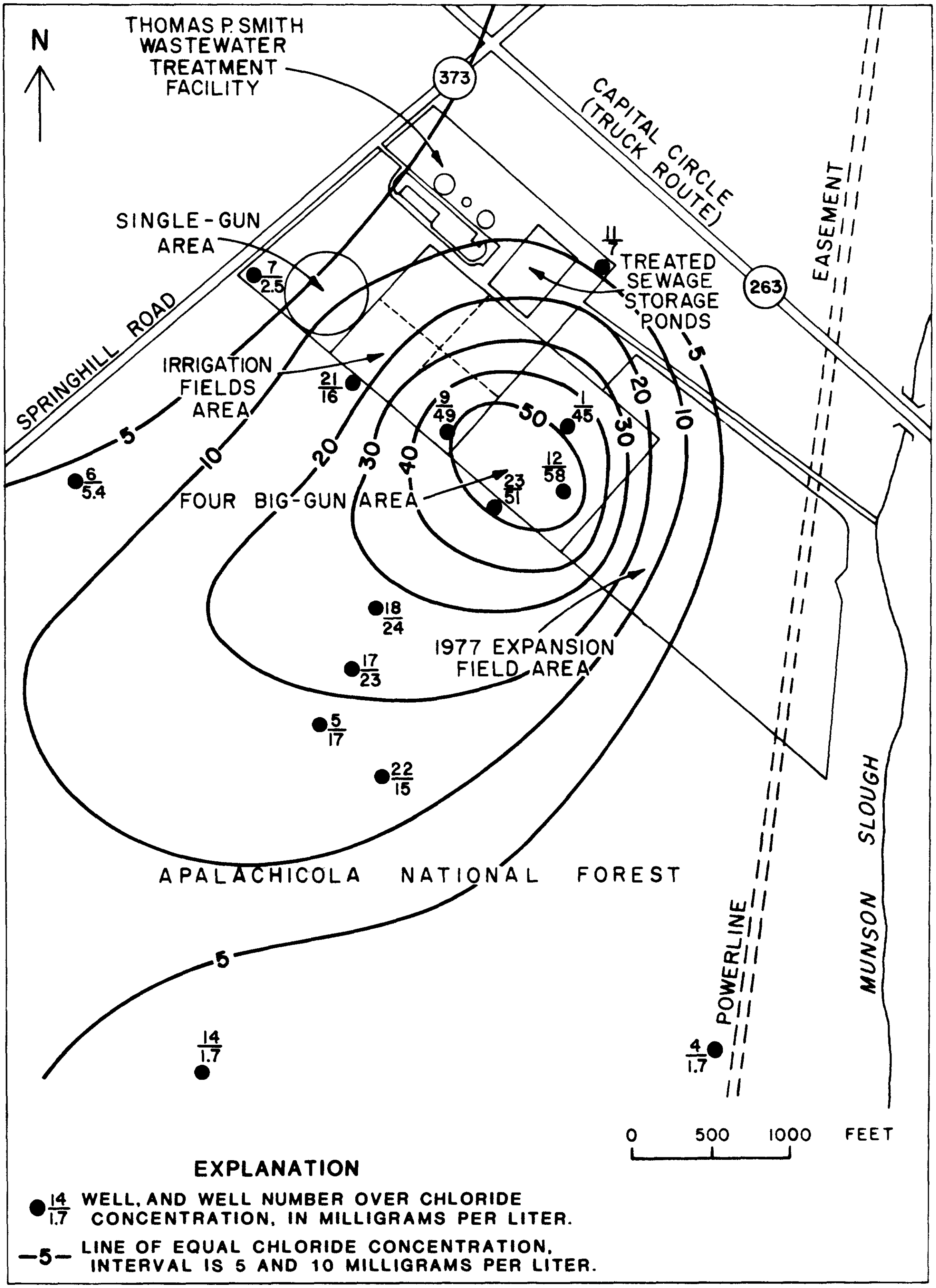

Figure 15.--Approximate areal extent of ground water affected by treated-sewage application, based on chloride concentrations in ground water at the southwest spray field, June 1974.

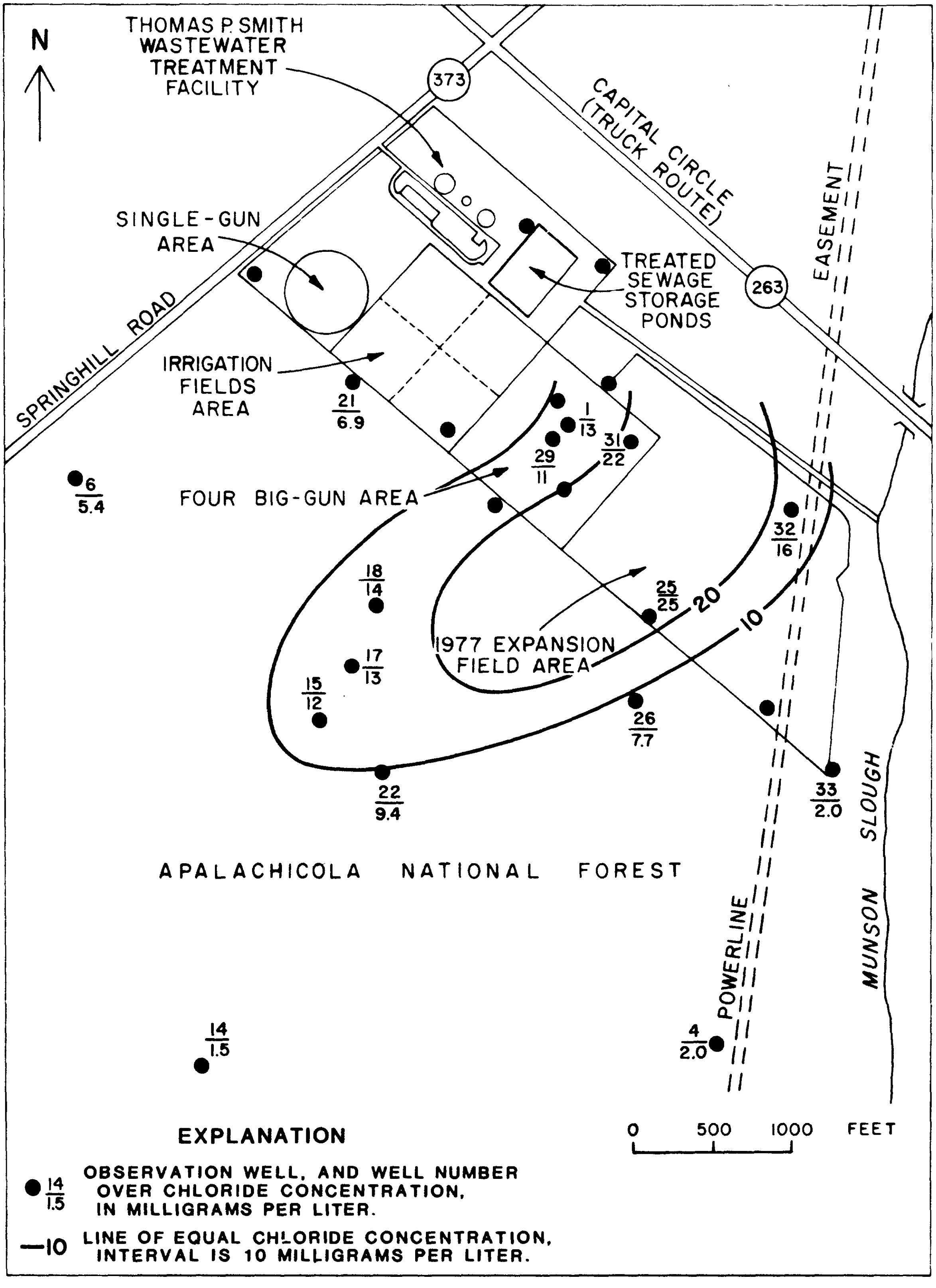

Figure 16.--Approximate areal extent of ground water affected by treated-sewage application, based on chloride concentrations in ground water at the southwest spray field, February 1981.

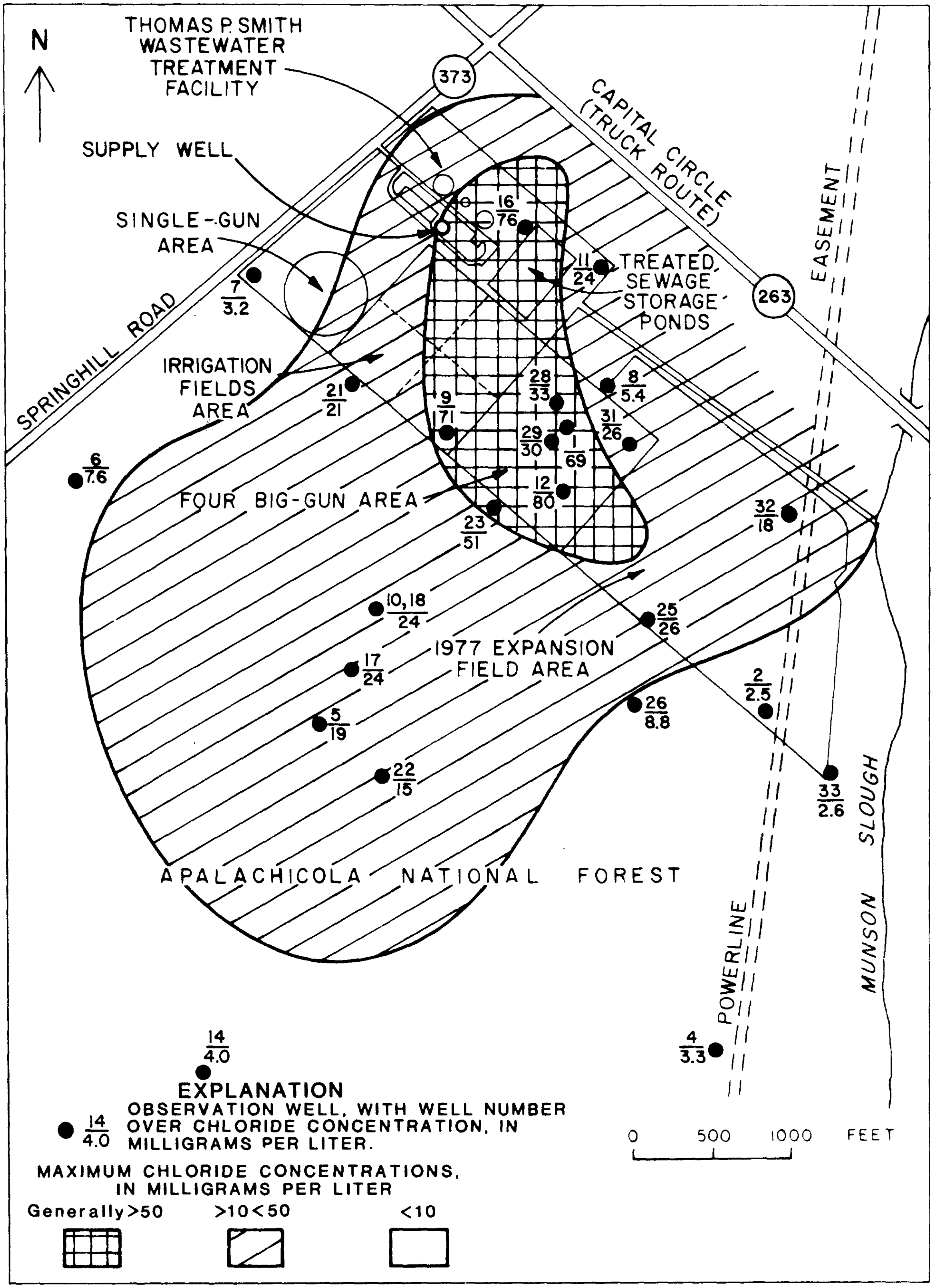

Figure 17.--Approximate areal extent of ground water affected by treated-sewage application, based on maximum chloride concentrations in ground water at the southwest spray field from October 1972 through June 1981.

Figure 17 shows the maximum chloride concentration measured at each site sampled from October 1972 through June 1981. The area generally identified as having chloride concentrations greater than 50 mg/L is the area that had the greatest volume of treated sewage applied from 1966 through 1981. The outer limit of the 10 to 50 mg/L chloride area shows that the treated sewage is generally moving southwest while being diluted by the normal flow of ground water. The sparsity of data in some areas and the lack of water-quality data prior to 1972 limits only slightly the usefulness of the illustration. It reflects the total area affectd by spraying treated sewage on the surface for a 15-year period.

Nitrate nitrogen concentrations of ground water in the Floridan aquifer system have decreased from the June 1974 values reported by Slack (1975). February 1981 sampling (March at site 29) of the same area shows significantly lower nitrate nitrogen concentrations in and downgradient of the areas of application (fig. 18). The overall lower concentration of nitrate nitrogen in the aquifer is attributed to lower monthly treated-sewage application volumes and lower concentrations of total nitrate nitrogen in the treated sewage. The similarity of figures 16 and 18 sewage-affected areas confirms the previously mentioned shift in treated-sewage application as well as the choice of chloride concentrations as the treated-sewage tracer.

Vertical Distribution

Analyses of ground-water samples indicate vertical movement of treated sewage occurs in the subsurface. This is shown by analyses of ground-water samples obtained from sites 23, 17, and 22 (fig. 5). Analyses of multiple-depth ground-water samples collected during the drilling of site 23 in June 1974 indicated that the sprayed treated sewage had moved to a depth of at least 270 feet below land surface where chloride concentrations of 50 mg/L were found (fig. 5). However, it is noted that drilling problems were encountered at depths greater than 60 feet (Slack, 1975, p. 7); thus chloride concentrations reported at site 23 below 60 feet may not reflect the quality of water at the depths indicated. Nevertheless, sites 17 and 22, located further downgradient of the southern edge of the four big-gun area, also show excessive chloride concentrations at depth. At site 17, chloride concentration at a depth of 152 feet ranged from 24 mg/L in December 1973 to 13 mg/L in February 1981. At site 22, chloride concentration at a depth of 268 feet ranged from 13 mg/L in March 1974 to 9.4 mg/L in March 1979. Thus, the sprayed treated sewage, although diluted by ground water, occurs in significant concentrations nearly equal to the mean concentration of about 50 mg/L of chloride in treated sewage (table 3) at depths greater than 200 feet below land surface below the spray site (fig. 17). The decrease in chloride at depth from 1974 to 1980-81 reflects the decrease in treated sewage sprayed at the four big-gun area. A decrease in nitrate also occurred, as mentioned previously.

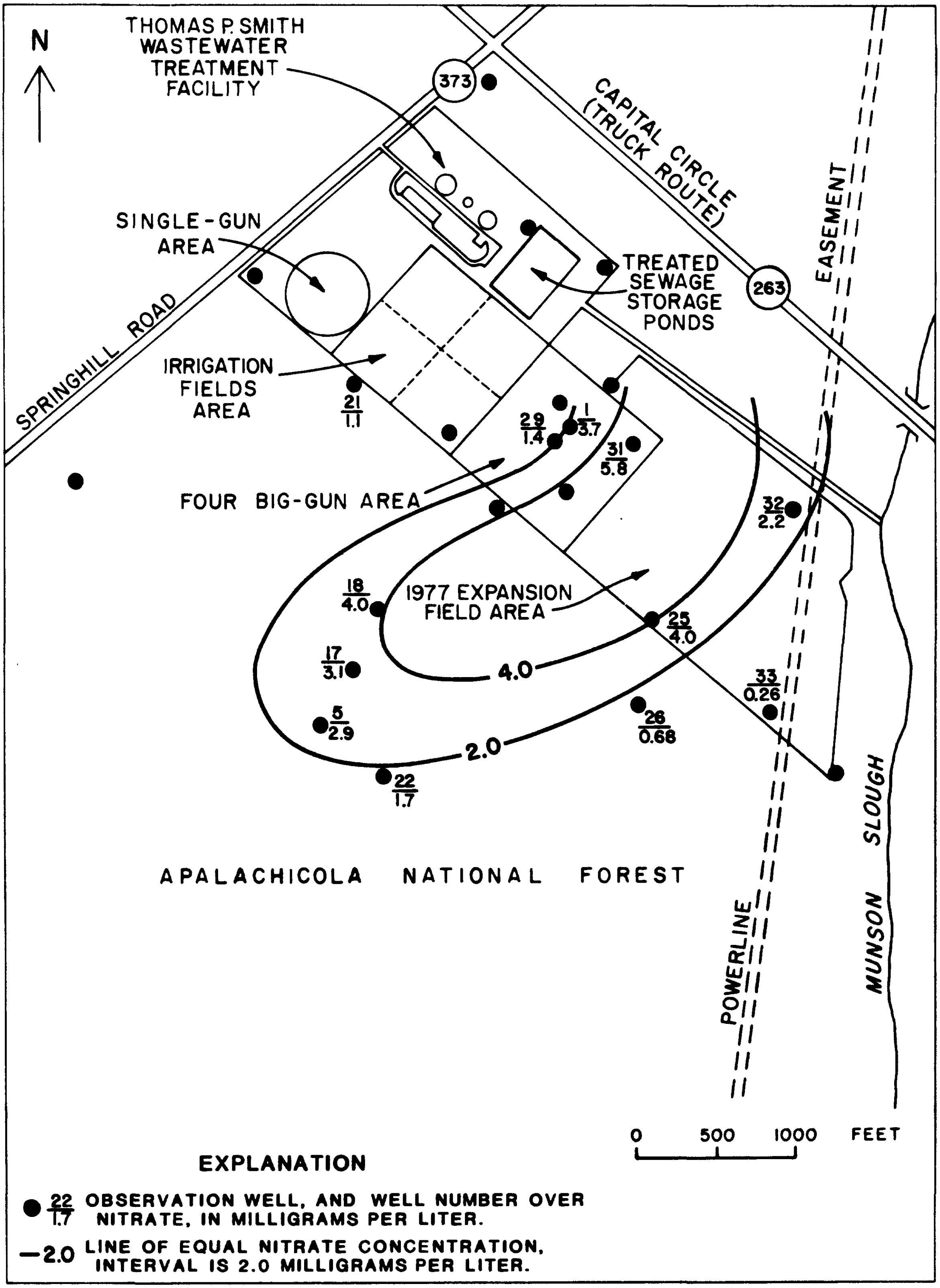

Figure 18.--Areal extent of nitrate concentrations in ground water at the southwest spray field, February 1981.

Temporal Distribution

Figure 19 is a graph of chloride concentrations at four sites located 1,000 to 1,800 feet southwest of the four big-gun area. Site 5 is a shallow well (Yurewicz, 1983, table 1) 51 feet deep; sites 17 and 18 are moderately deep at 152 and 160 feet deep, respectively; and site 22 is 267 feet deep.

Site 5, a shallow well drilled in October 1972, had low background chloride concentrations, 1.5 and less than 0.1 mg/L, when sampled on November 3 and December 15, 1972, respectively. Chloride concentrations had increased to 7 mg/L by March 17, 1973, to 14 mg/L by May 15, to 19 mg/L by April 3, 1974, and thereafter subsided slowly to 12 mg/L by February 3, 1981 (Yurewicz, 1983, table 6). A nitrate concentration of 0.4 mg/L was obtained at site 5 when sampled on February 1, 1973. This concentration, though low, suggests that treated sewage had reached the site by then.

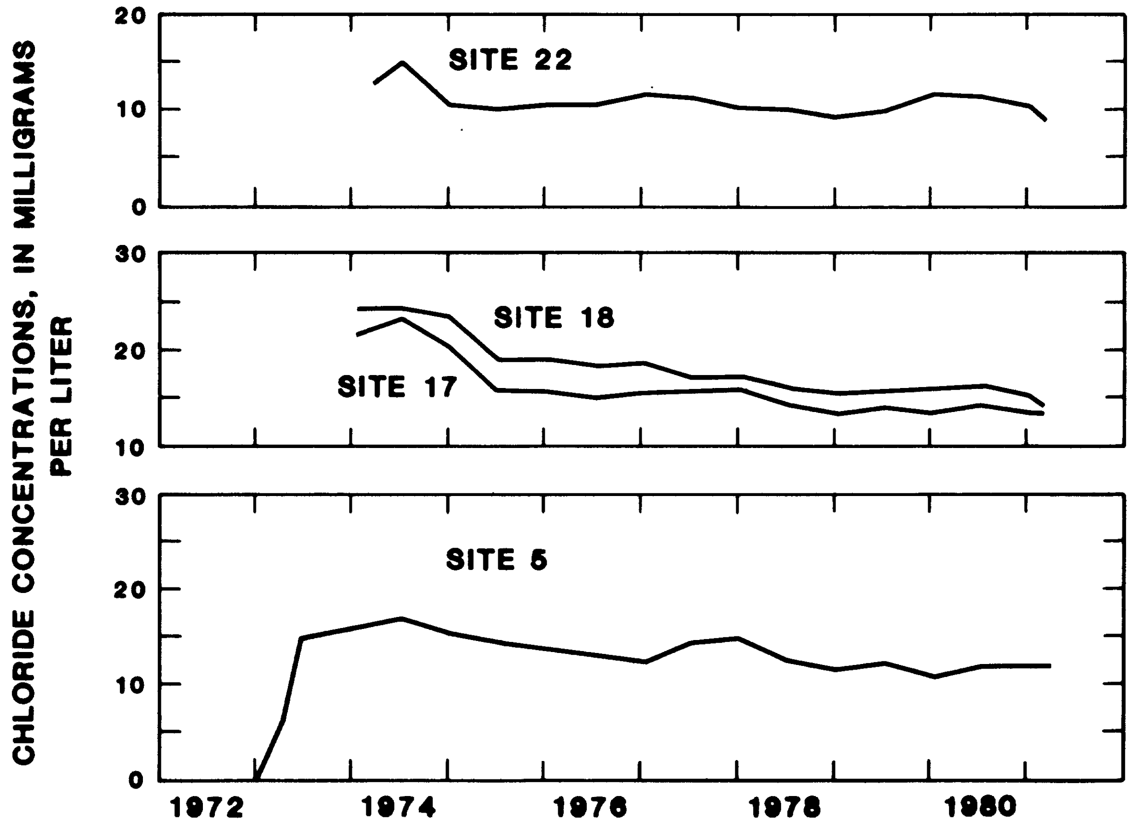

Figure 19.--Chloride concentration November 3, 1972, through February 3, 1981; sites 5, 17, 18, and 22.

These increases in chloride and nitrate concentrations can be used to estimate the rate of treated sewage movement in the upper part of the aquifer. The 30 Mgal/mo treated-sewage application on the four big-gun area that began in March 1972 is believed responsible for the treated sewage reaching site 5 by February 1, 1973, some 11 months after this heavy application began. Site 5 is 1,800 feet downgradient of the four big-gun area. Based upon these data, the treated sewage moved at a rate of approximately 5.5 feet per day away from the four big-gun area in a southwesterly direction to site 5. The specific place, rate, and volume of treated sewage applied, the velocity and direction of ground-water movement in the aquifer, the permeability and extent of solution cavities, and the amount of mixing and dilution all make the computed value of 5.5 feet per day an estimated value.

Sites 17, 18, and 22 were already affected by the treated sewage when drilled and first sampled in 1974. The graphs for these sites presented in figure 19 show chloride concentrations similar to those measured at site 5.

Sites 25 and 32 (69 and 80 feet deep, respectively) were drilled in January 1975 and September 1971, respectively. Figure 20 shows graphs of the chloride concentrations of both sites from 1977 through June 1981 and treated-sewage application, in the 1977 expansion field area, for the same period. Both sites show that they were affected--they had background chloride concentrations (less than 5 mg/L) until 1979. By early 1980, chloride concentrations at both sites were almost 10 mg/L, and by March 1981 sites 25 and 32 had chloride concentrations of 26 and 18 mg/L, respectively. Treated sewage application on the expansion field area began in December 1977 at a time when application in the other areas had been near zero since August 1974 (Yurewicz, 1983, table 3). From September 1978 through July 1979, 200 Mgal, or 0.6 Mgal/d, of treated sewage were applied on the expansion field area (a monthly average of 18 Mgal) and another 200 Mgal through June 1981. Because of their locations, the two sites reflect different chloride concentration patterns. Site 25 was in the direct line of ground water flow and perhaps direct application; its samples apparently showed it had an almost immediate reaction to the heavy treated-sewage applications in early 1980 and in January and February 1981. However, it is possible that the peaks in chloride concentration at sites in 1980 and 1981 are related to peaks in treated-sewage application in 1978-79 and 1980. If so, this would indicate a delayed reaction. Site 32 samples showed a slow or gradual reaction, perhaps owing to its position northeast or upgradient of the area of treated-sewage application.

SUMMARY AND CONCLUSIONS

Effects on the Floridan aquifer system due to spray irrigation with treated municipal sewage southwest of Tallahassee are limited to increases in chloride and nitrate nitrogen concentrations. An estimated volume of 4,220 Mgal of secondary treated municipal sewage was sprayed on various grasses and forage crops from July 1966 through June 1981. Although the first several years of spray irrigation were experimental, this method of treated-sewage disposal has since become routine, partly in an effort to limit the discharge of treated sewage to nearby Munson Slough and Lake Munson.

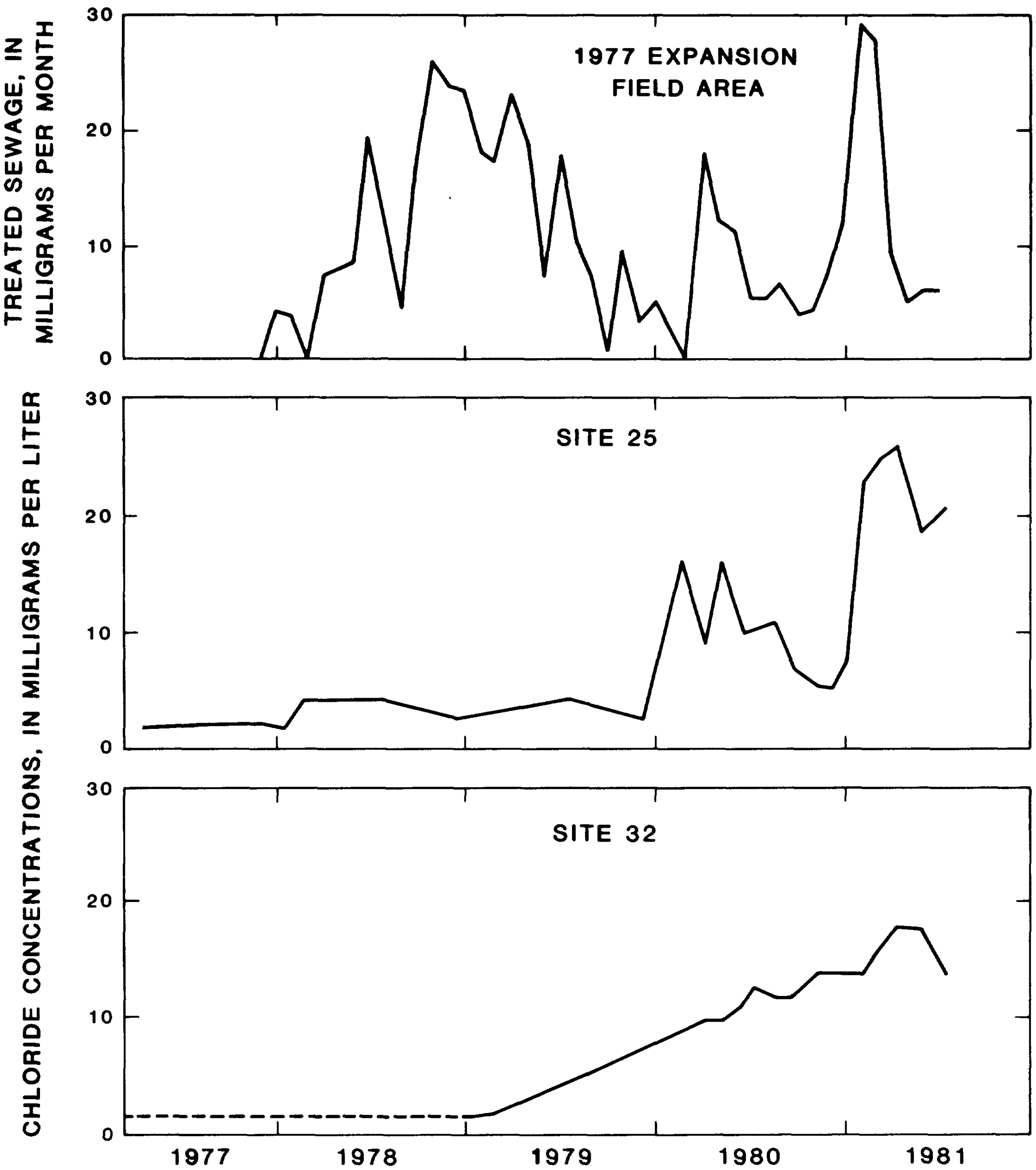

Figure 20.--Chloride concentrations at sites 25 and 32 compared with monthly treated-sewage applications on the 1977 expansion field area, 1977-81.

Although treated sewage was applied at rates of up to 16 inches per week, no measurable effects on ground-water levels of the Floridan aquifer system were observed. This can be primarily attributed to the high permeability of the aquifer, the high recharge rate, and the presence of solution cavities in the limestone. There is direct recharge from the land surface to the underlying aquifer due to rapid infiltration through the sand overburden and a discontinuous clay layer which lies between the sand formation and the Floridan aquifer system.

Upon reaching the Floridan aquifer system, soluble constituents move laterally and vertically with the ground-water flow pattern. Use of chloride as a tracer of water movement indicates that treated sewage occurs at depths greater than 200 feet below land surface below the spray sites. Lateral movement of ground water downgradient from the spray field is in a southwesterly direction at an estimated rate of 5 feet per day, and depends on aquifer permeability, porosity, and solution cavities. Soluble constituents from land application of treated sewage have been detected approximately 3,000 feet downgradient of the spray field areas.

Concentrations of nitrate-nitrogen in ground water greater than 10 mg/L were observed from 1972 through 1976 during a period of high irrigation rates. However, computations suggest that if the monthly application load of nitrogen does not exceed approximately 130 to 180 pounds per acre, the concentration of nitrate in water in the upper Floridan aquifer system in the immediate area of treated-sewage application will not exceed 10 mg/L as nitrogen.

Other ground-water quality characteristics were not significantly changed by the mixing with treated-sewage because of its interaction with subsurface material and dilution of soluble leachates with native ground water. Concentrations of trace metals including arsenic, cadmium, chromium, copper, iron, lead, manganese, mercury, selenium, and zinc remained at background levels. Based upon ground-water samples in 1974 and 1978, concentrations of organochlorine insecticides and chlorinated phenoxy acid herbicides were all below analytical detection limits. Based upon the chloride dilution model, ground-water concentrations of calcium, magnesium, and bicarbonate were initially less than expected for ground water affected by treated-sewage application, but later became greater than expected. This reversal may be caused by precipitation of calcium, magnesium, and bicarbonate until equilibrium conditions are established. Concentrations of phosphorus and organic carbon in ground water remained at background levels. Coliform bacteria were removed.

The investigation of effects of spray irrigation with treated municipal sewage on ground water is being further investigated at a spray field approximately 8 miles southeast of Tallahassee. Low-velocity spray irrigation of grasses and forage crops with chlorinated municipal sewage began on 1,086 acres in November 1981; the area was expanded an additional 750 acres in 1982. Upon completion of construction at the Thomas P. Smith Wastewater Treatment Facility, all of the treated municipal sewage generated by the City of Tallahassee will be spray irrigated at the southeast field, and land application of treated sewage at the southwest field will be either significantly reduced or terminated.

The degree of data interpretation for the investigation at the southeast field is much greater than that for the southwest field. Unlike the southwest field, where the data-collection program began 6 years after spray irrigation began, considerable background hydrologic data are available at the southeast field.

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* GOVERNMENT PRINTING OFFICE: 1986 - 544130 / 40002