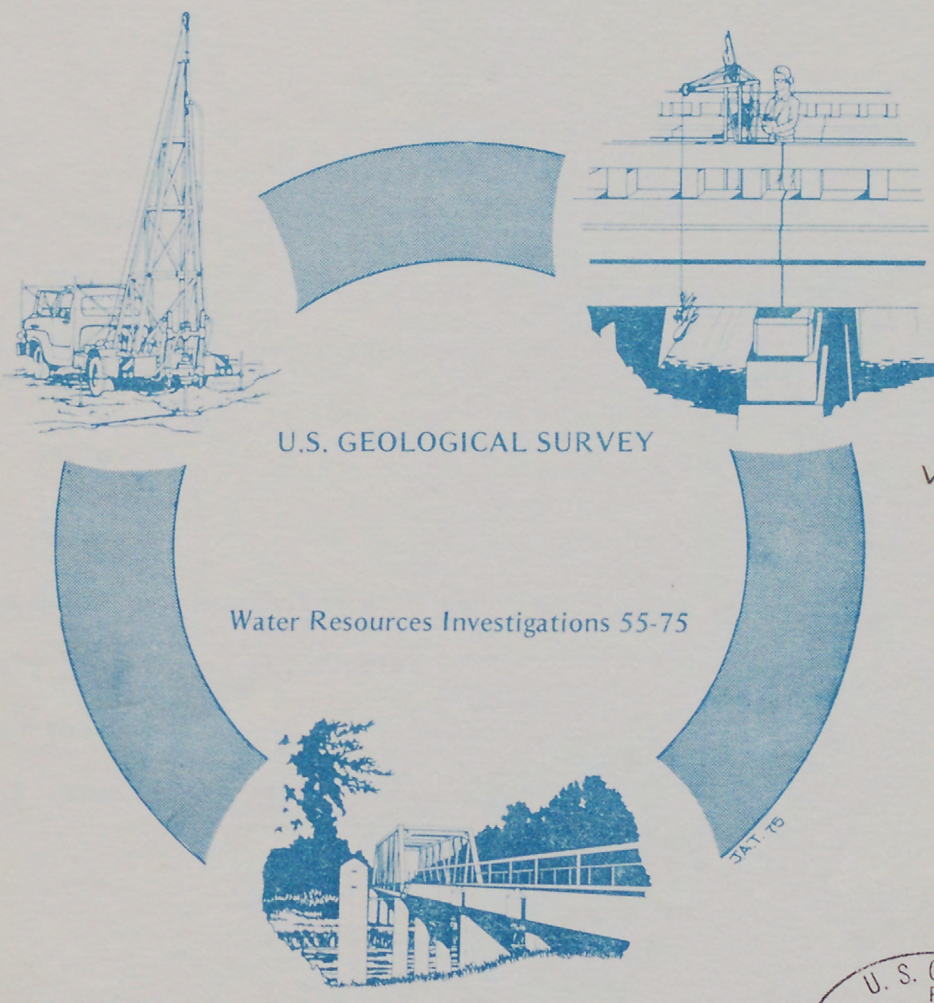
HYDROLOGIC ENVIRONMENTAL EFFECTS OF SPRAYED SEWAGE EFFLUENT, TALLAHASSEE, FLORIDA



U.S. GEOLOGICAL SURVEY

Water Resources Investigations 55-75

Prepared in cooperation with the
CITY OF TALLAHASSEE, FLORIDA and the
U.S. ARMY CORPS OF ENGINEERS

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ABSTRACT

Since 1966, Tallahassee has been experimentally disposing of the effluent from secondarily-treated sewage by spraying at the Thomas P. Smith Wastewater Renovation Plant. This report describes the disposal system, assesses the hydrologic and chemical effects of sewage effluent disposal on ground water in the area around the plant, and provides data useful for the development of basic criteria for land disposal of sewage effluent.

Potentiometric maps indicate ground water moves southwesterly from the spray area. Because of a high rate of natural underflow and large aquifer permeability the application of effluent caused no appreciable distortion of the regional ground-water flow pattern.

The quality of the sprayed effluent was generally improved as it filtered through the soil to the water table. BOD was reduced to less than 5 milligrams per litre and fecal coliform bacteria were reduced to zero. Almost all the phosphorus was removed.

Based on average data (collected from July 1972 to June 1974) there was a reduction in concentration of approximately 12 milligrams per litre of the total nitrogen from the effluent which was applied at a rate of 2 to 8 inches per week in an area with a cover crop. On the same basis there was an approximate concentration reduction of 5 milligrams per litre of the total nitrogen from the effluent applied at a rate of 14 inches per week to an undisturbed forest.

The high-rate application of effluent (14 inches per week) resulted in increased chloride and nitrogen concentrations to a depth of at least 270 feet in the underlying fresh-water aquifer.

Effluent-percolate has moved from the plant at about 2,400 feet per year. The effluent-percolate reached a well about 1,800 feet downgradient of the heavily-sprayed area in 3/4 year; the mixing ratio of effluent to ground water at that well was 1 to 4 in less than 2 years. As of June 1974 the leading edge of the waste front is somewhere between 1,800 and 4,000 feet downgradient from the plant and the ground water in about 140 acres of the underlying aquifer has increased in nitrate-N and chloride concentrations.

ACKNOWLEDGMENTS

The author gratefully acknowledges the cooperation of Mr. Thomas P. Smith, City Sanitary Engineer, and the personnel at the Thomas P. Smith Wastewater Renovation Plant.

Thanks are extended to Mr. William G. Leseman of the city of Tallahassee who supplied data and technical assistance and to the U.S. Forest Service for permission to drill observation wells in the Apalachicola National Forest.

PURPOSE AND SCOPE

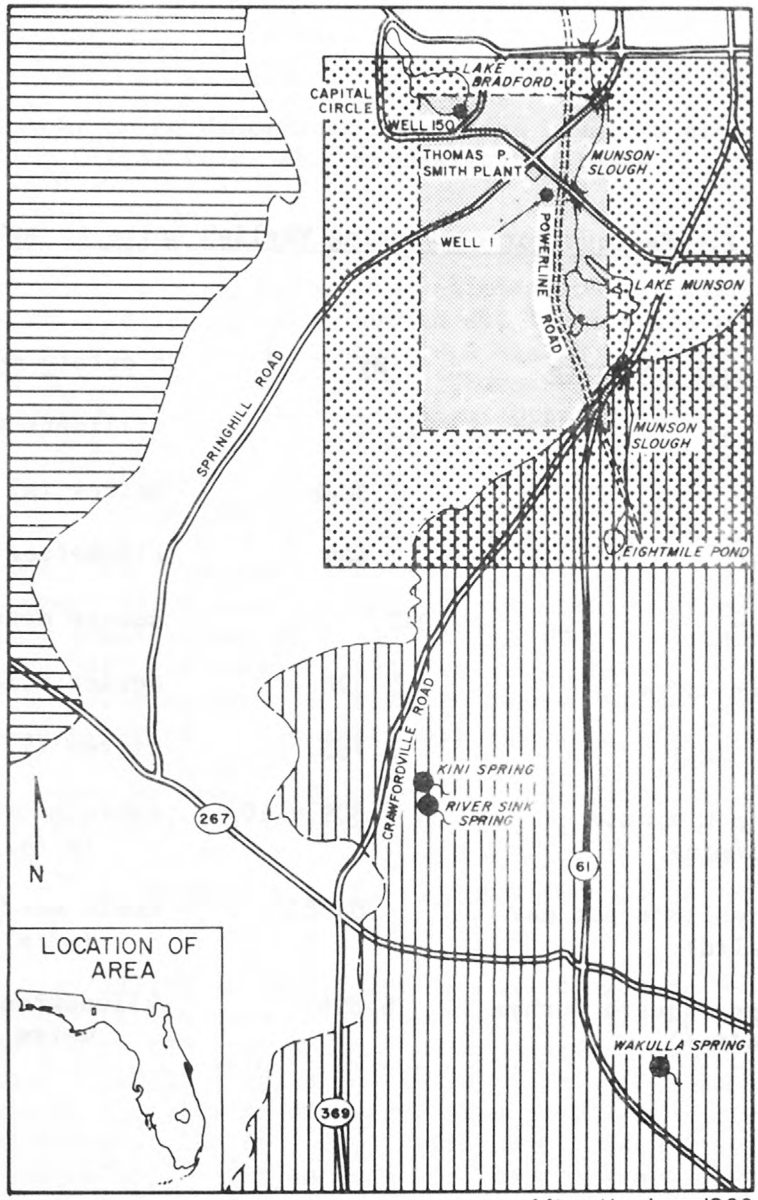
In cooperation with the city of Tallahassee, Florida, and the U.S. Army Corps of Engineers, Mobile District, the U.S. Geological Survey is investigating the hydrologic and chemical effects on the underlying fresh ground-water system of sewage-effluent disposal by spray irrigation on land at the Thomas P. Smith Plant. The plant is also referred to as the Southwest Plant. The investigation is intended to provide data that will be useful for development of basic criteria for land disposal of sewage effluent. Figure 1 indicates the general location of the project area.

This report describes significant results for the period July 1972 through June 1974. It includes: (1) evaluation of the direction and rate of movement of water and the extent and location of the effluent plume in the aquifer underlying the disposal site and, (2) assessment of changes that occur in quality of the effluent and the receiving ground water.

The ground-water system in and adjacent to the plant is being monitored on a continuing basis to detect any long-term trend in water quality chargeable to spray irrigation of sewage effluent at the plant. In the continuation study the application of effluent has been discontinued in part of the study area in order to allow evaluation of recovery rates.

HISTORICAL BACKGROUND AND OPERATING HISTORY

As of June 1974 Tallahassee has four secondary sewage treatment plants: (1) Lake Bradford Road Plant, 4.5 Mgal/d (0.197 m^3/s) capacity; (2) Dale Mabry Field Plant, 0.9 Mgal/d(0.039 m^3/s) capacity; (3) Municipal Airport Plant, 0.06 Mgal/d (0.0026 m^3/s) capacity; and (4) Thomas P. Smith Wastewater Renovation Plant, 2.5 Mgal/d (0.110 m^3/s) capacity.



After Hendry, 1966

0 1 2 3 4 5 Miles

0 1 2 3 4 5 6 7 8 Kilometres

EXPLANATION

Apalachicola Coastal Lowlands

Lake Munson Hills (Limestone about 30-50 feet below general land surface)

Wakulla Sand Hills (Limestone at or near general land surface)

30-square-mile area where general well inventory was made

9-square-mile area of special emphasis

FIGURE 1.--Area of investigation.

Table 1.--Factors for converting English units to metric units.

Multiply English units	By	To obtain metric units
inches (in)	25.4	millimetres (mm)
feet (ft)	.3048	metres (m)
miles (mi)	1.609	kilometres (km)
acres (ac)	4047	square metres (m^2)
square miles (mi^2)	2.590	square kilometres (km^2)
gallons (gal)	3.785	litres (l)
gallons per minute (gal/min)	6.309×10^{-5}	cubic metres per second (m^3/s)
million gallons per day (Mgal/d)	.04381	cubic metres per second (m^3/s)
pounds per square inches (lbs/in^2)	6.896	kilonewton per square metre (kN/m^2)

The Thomas P. Smith Wastewater Renovation Plant is at Springhill Road and Capital Circle (fig. 2), immediately southwest of the city limit.

Mr. Thomas P. Smith, the City Sanitary Engineer, advanced the idea of using spray irrigation as a means of eliminating the discharge of effluent, not only to Lake Munson, but to all local surface waters. In 1966, Tallahassee began disposing about 0.5 Mgal/d (0.02 m^3/s) of secondary-treated sewage effluent at its Thomas P. Smith Wastewater Renovation Plant, on an experimental basis. Other than the effluent disposed of by spray-irrigation methods, all domestic wastewater treatment-plant effluents from the city of Tallahassee, along with almost 85 percent of the runoff from its paved areas, flows to Lake Munson (Bishop, 1971) (fig. 1). The overflow from this lake empties into an area where the limestone of the Floridan aquifer is at or near land surface permitting direct recharge of the lake overflow to this aquifer. Severe algal blooms have caused the lake to become pea green in color and the city has received numerous complaints from local citizens of fish kills alleged to have been caused primarily by the effluent being discharged to the lake.

Nutrient uptake by crops and associated variations in plant growth rate with different application rates of sewage effluent have been investigated by the city of Tallahassee since 1970 in cooperation with researchers from the University of Florida (Overman, 1971; and Overman and Smith, 1973).

To allow flexibility in experimenting with dosing rates, four 4-acre (16,000-m^2) fields were established (fig. 2). Sprinkler heads were installed 100 ft (30.5 m) apart. Each head was capable of delivering 45 gal/min (0.00284 m^3/s) at 40 lb/in^2 (276 kN/m^2) to produce a wetted area 155 ft (47.2 m) in diameter. The pump capacity was 720 gal/min (0.045 m^3/s) at 160 ft (49 m) total head. Each 4-acre field contained 16 sprinklers. Effluent was applied in each field at a different rate--2, 4, 6, and 8 inches (50, 100, 150, and 200 mm) per week, Monday through Friday. The 4.5-acre (18,000 m^2) Single-Gun Area (fig. 2) was sprayed 24 hours a day Saturday and Sunday, or a total of 16 in (406 mm) a week.

In March 1972 the installation of four 1,000-gal/min (0.063 m^3/s) guns was completed in an 18-acre (72,000 m^2) forested area (the 4-Big-Gun Area of fig. 2) east of the plowed field. These guns were set on 400-foot (120-m) centers and were designed to reach 250 ft (76 m) at 90 lbs/in^2 (620 kN/m^2). The guns were operated in pairs: on alternate days guns A' and B' would operate for 8 hours while guns C' and D' would be idle. The 4-Big-Gun Area received an average of 1 Mgal/d (0.0438 m^3/s) 7 days a week or 14 in (360 mm) per week. From 1972 to 1974,

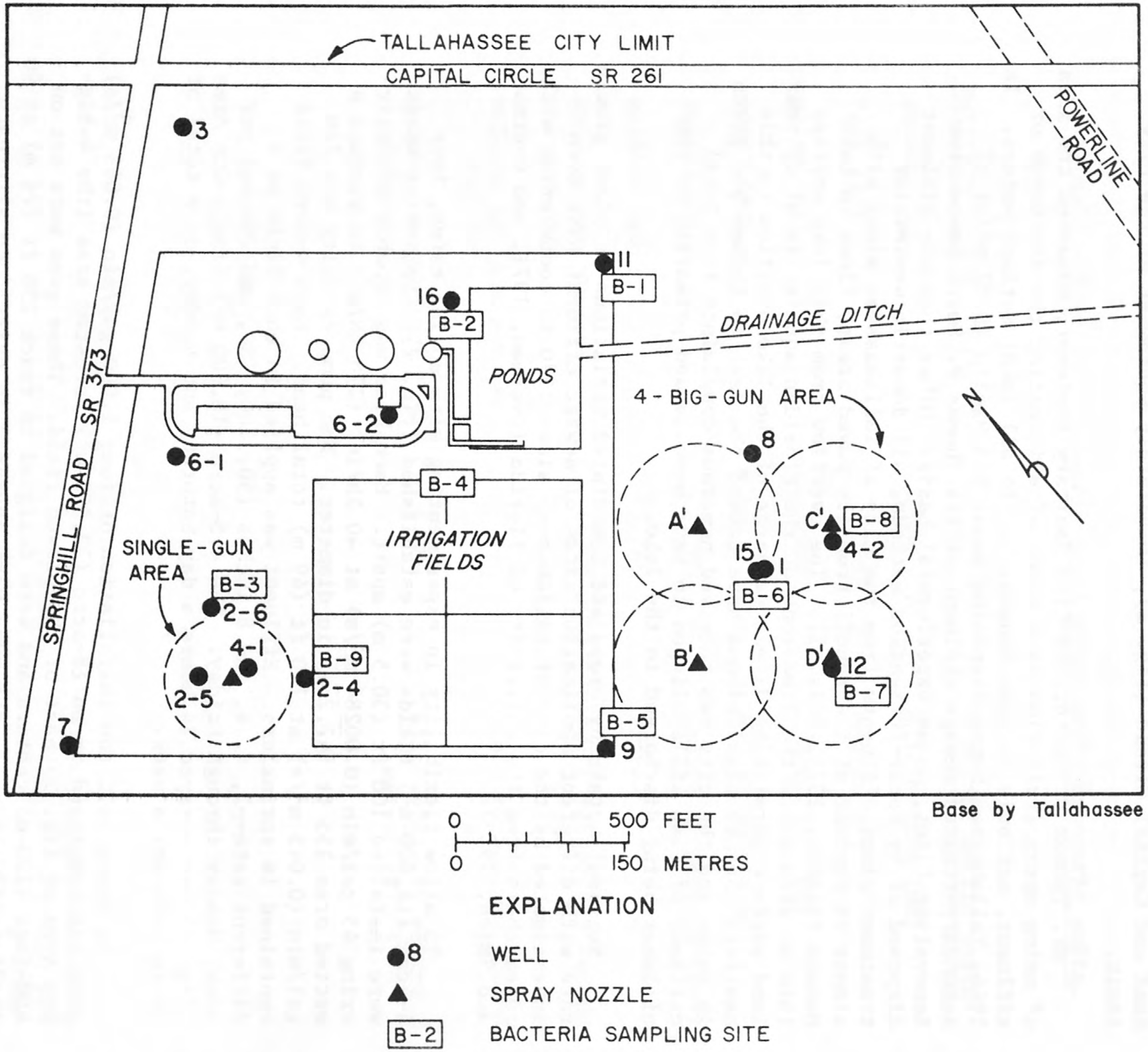


FIGURE 2.--Location of the Thomas P. Smith Wastewater Renovation Plant.

about 140 ft (43 m) of effluent was sprayed on the forested area (the 4-Big-Gun area). This heavy application rate was for the purpose of gathering needed design information and not as a normal spray-irrigation project (Thomas P. Smith, oral commun., July 1972).

Plant effluent in excess of the volume sprayed is discharged to Munson Slough, which drains into Lake Munson.

The spray-irrigation operation was essentially the same as outlined above until February 1973, when spray irrigation was discontinued in the Single-Gun Area. From February 1973 to June 1974, 1 Mgal/d (0.04 m^3/s) or 14 in (360 mm) per week on the average was sprayed on the 4-Big-Gun Area and about 0.3 Mgal/d (0.01 m^3/s) or 5 in (130 mm) per week on the Irrigation-Fields Area.

METHODS OF STUDY

The investigation consisted of the following: (1) reviewing the literature; (2) making an inventory of existing wells in the area; (3) installing observation wells; (4) collecting water samples; (5) collecting soil samples; (6) measuring water levels; (7) obtaining geophysical logs for selected wells; and (8) analyzing and interpretating the data.

Standard U.S. Geological Survey analytical techniques were used in this investigation to provide maximum transferability of results. The standard ground-water techniques used are published in U.S. Geological Survey Water-Supply Papers (WSP) 489, 494, 1536 E, 1536 I, 1544 H, and 1545 C and Techniques of Water-Resources Investigations (TWRI) Book 2, chapter E1. The standard quality-water techniques used are published in WSP's 1454 and 1473 and in TWRI Book 5, chapter A1.

A 30-mi^2 (78-km^2) area was canvassed; emphasis was given the 9-mi^2 (23-km^2) area (fig. 1) surrounding the disposal site. Well owners and operators were interviewed, ground-water levels were measured, and water (both ground water and effluent) samples were collected for chemical analyses. Location of wells in areas where the Floridan aquifer is used as a source of water supply within the study area is shown on figure 3. A table of chemical data for these wells is given in the section on Basic Data.

Sixteen test wells were drilled during the first year of the study and seven during the second year. The location of these wells is shown in figure 4. The test wells were numbered in sequence. Table 2 gives a brief summary of well data. Well cuttings were collected at each site except wells 6 and 20. Cuttings from well 23 at depths greater than 60 ft (18 m) were considered unreliable due to drilling problems. All the chemical data for these wells are available from the U.S. Geological Survey, Florida District Office, Tallahassee, Florida.

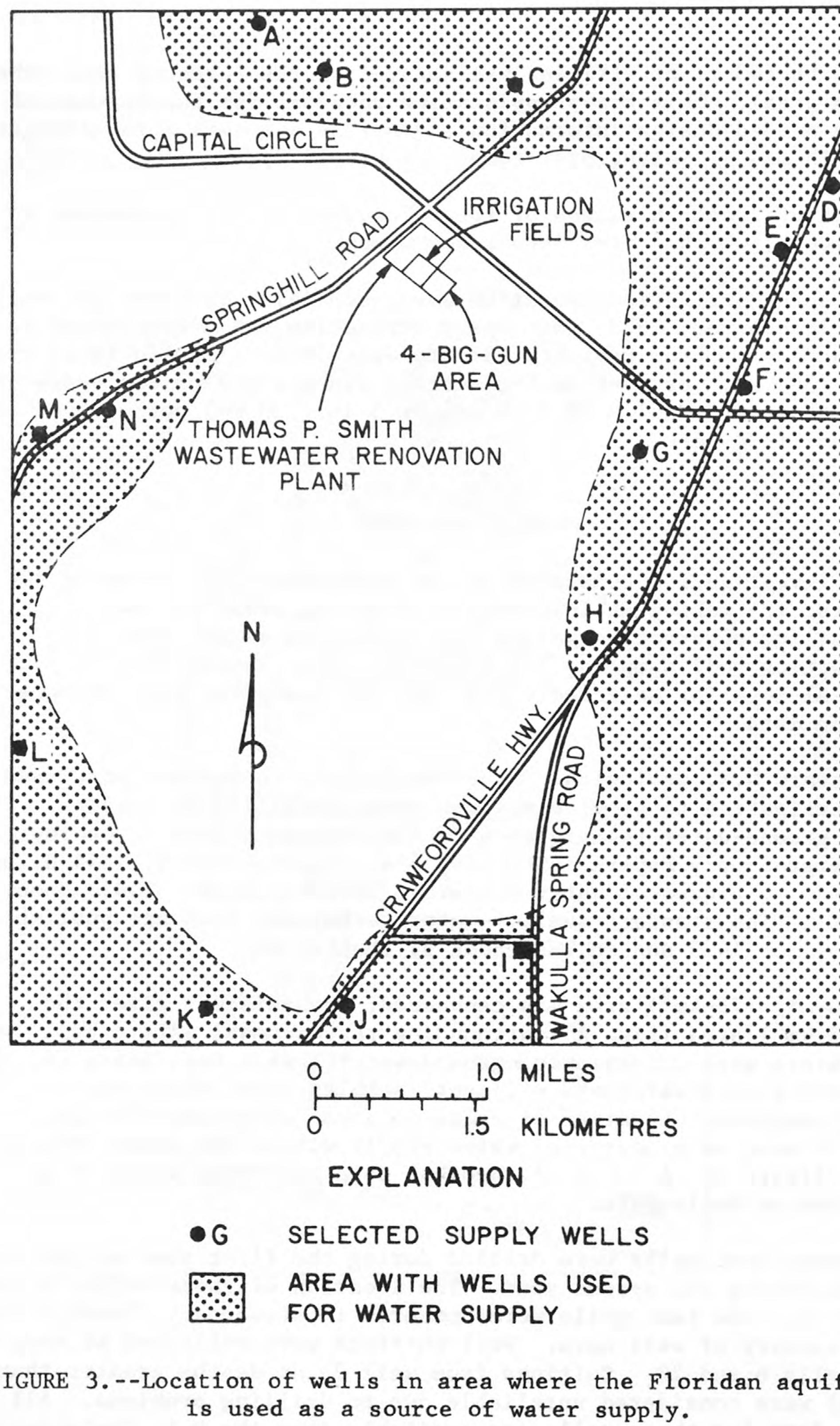


FIGURE 3.--Location of wells in area where the Floridan aquifer is used as a source of water supply.

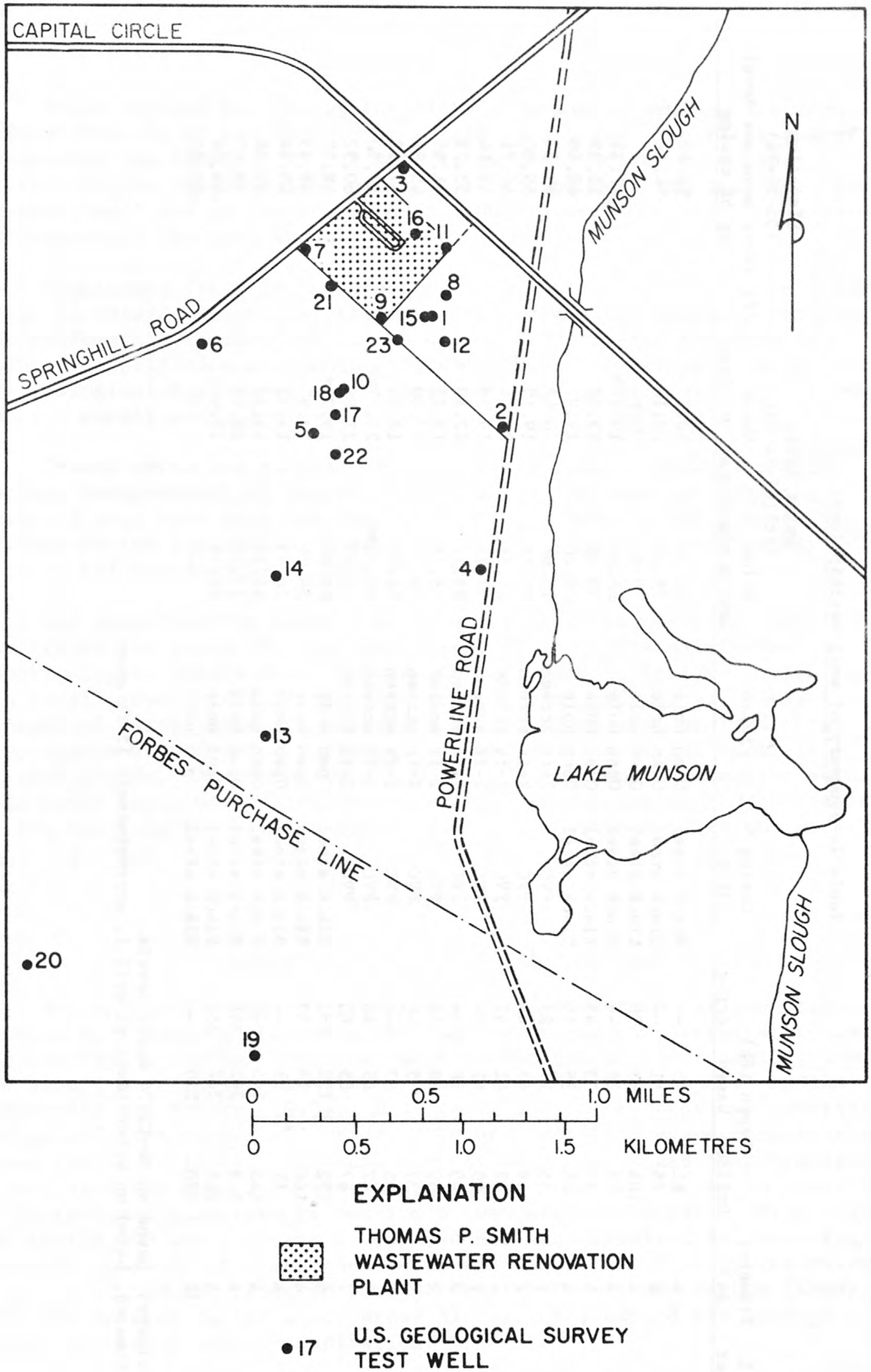


FIGURE 4.--Location of U.S. Geological Survey test wells.

Table 2.--Summary of well descriptions.

Well number	Diameter (in)	Depth (ft) Drilled	Depth (ft) Cased	Depth (ft) Logged	Casing type	Finish	Water Level (ft)(05-24-74) Below land surface	Water Level (ft)(05-24-74) Above mean sea level	Elevation (05-24-74) (ft above mean sea level) Top of casing
1	4	61	45	--	Black steel	Open hole	35.24	20.77	59.42
2	4	75	51	--	Black steel	Open hole	29.48	22.18	54.16
3	4	104	93	98	Black steel	Open hole	Dry	Dry	--
4	4	53	38	--	Black steel	Open hole	24.5*	19.71*	47.31
5	4	51	33	45	Black steel	Open hole	30.25	19.78	52.09
6	4	45	35	45	Black steel	Open hole	20.20	19.98	42.66
7	2	35	27	25	PVC	2-ft screen	16.6*	20.4*	39.52
8	2	49	47	47	PVC	2-ft screen	37.77	19.13	59.90
9	2	42	42	42	PVC	2-ft screen	27.55	20.66	50.71
10	2	43	41	--	PVC	2-ft screen	37.7*	19.3*	59.64
11	2	40	38	--	PVC	2-ft screen	29.22	22.10	53.32
12	2	50	48	48	PVC	2-ft screen	38.75	19.21	61.96
13	2	37	35	--	PVC	2-ft screen	24.72	17.09	45.31
14	2	55	53	--	PVC	2-ft screen	26.18	17.94	47.12
15	2	47	45	45	PVC	2-ft screen	35.24**	20.77**	57.50
16	2	67	65	65	PVC	2-ft screen	36.25	21.89	60.37
17	4	152	152	152	Black steel	Open hole	29.08*	19.75*	48.83
18	4	160	54	53	Black steel	Open hole	38.00	19.90	58.35
19	4	75	53	--	Black steel	Open hole	24.63	14.31	40.94
20	4	145	145	--	Black steel	Open hole	14.52	14.32	30.84
21	4	248	247	248	Black steel	Open hole	37.50	20.42	58.92
22	4	268	267	268	Black steel	Open hole	28.79	19.45	48.74
23	4	270	240	--	Black steel	Open hole	--	--	53.67

*Estimated, based on 06-12-74 water levels.
**Estimated, based on water level at well 1, approximately 15 ft away.

Wells drilled earlier by the Florida Bureau of Geology are identified (fig. 2) by two numbers separated by a dash. The first number represents the diameter of the well in inches; the second number represents the chronological order in which the well was drilled. For example, well 4-2 is the second 4-in (100-mm) well drilled by the Bureau of Geology in the test area.

Continuous water-level recorders were installed: (1) on well 150 (fig. 1) outside the spray effluent area--to monitor ground-water levels for benchmark purposes; and (2) on well 1 (fig. 1)--in the area of heaviest application of sewage effluent. Water levels were measured in the Geological Survey wells and Bureau of Geology wells 2-4, 2-5, 2-6, and 4-1 weekly until April 1974 and monthly until July 1974.

Ground water was sampled monthly; the effluent bimonthly; and springs downgradient of the plant, quarterly for chemical analyses. Rainfall data were obtained from the National Oceanic and Atmospheric Administration for the Tallahassee Municipal Airport approximately 2 mi (3 km) west-northwest from the study area.

The investigation began 6 years after effluent was first applied to the irrigation plots (Overman and Smith, 1973). This eliminated an opportunity to obtain data "before the fact" and to follow changes in the local ground waters from point zero in time and space. However, historical perspective of activities at the plant was obtained through discussions with Messrs. Smith and Overman and the review of their related papers. Also, the total effect of application of wastes before this study began was evaluated by areal determination of the character of the water in the aquifer beyond the area of influence of the effluent.

HYDROGEOLOGY

Importance of Hydrogeologic Factors

Hydrogeologic factors are especially important to the investigation because they largely determine the quality of the effluent that reaches the underlying aquifer. For any such investigation, hydrogeology limits the the amount of treatment wastewater receives from the disposal medium (Goldstein and Moberg, 1973). Most soils and cover crops can beneficiate sewage effluent when application rates are less than evapotranspiration rates (Parizek, 1973). The more irrigation rates exceed evapotranspiration rates the more important hydrogeologic factors become in insuring sufficient and long-term renovation of wastewater (Parizek, 1973). The 730 in (18,500 mm) per year of sprayed effluent received by the 4-Big-Gun Area is about 16 times the average annual potential evapotranspiration of 46 in (1,170 mm) reported for the area by Visher and Hughes (1969). Effluent sprayed in the other areas also greatly exceed the average annual potential evapotranspiration.

Regional Hydrogeology

Geologically, the Thomas P. Smith Wastewater Renovation Plant is situated on the Lake Munson Hills sediments of the Woodville Karst Plain (Hendry and Sproul, 1966). The Plain extends from the south edge of Tallahassee to the Gulf. Its western boundary is approximately along the range line between townships 1 and 2 west, and its eastern edge extends into Jefferson County. The Plain is characterized by loose quartz sands thinly veneering a limestone substratum--a sinkhole-sand dune topography. Elevations are 20 to 60 ft (6 to 18 m), with dune tops to 80 ft (24 m) above mean sea level. The dunes are of barchan type, oriented to northeasterly winds. The porous and permeable sand allows quick entry of rain to the soluble and sink-dotted limestone and permits little stream development.

Although some water is contained in the overlying sand, silt, and clay, the principal source of ground water in Leon County consists of a sequence of limestones and dolomites that generally act as a hydrologic unit (Hendry and Sproul, 1966) and is referred to as the Floridan aquifer (Parker and others, 1955). The Floridan aquifer underlies all of Florida and parts of southern Alabama and Georgia. Recharge to the aquifer in Leon County is derived from rain which falls on Gadsden, Leon, and Jefferson Counties, and on adjacent areas in Georgia. Discharge from the aquifer is generally southerly, to the gulf. Over 95 percent of all water used in Leon County is obtained from the Floridan aquifer (Hendry and Sproul, 1966). All of the city and industrial-supply wells are upgradient of the Smith Plant.

The limiting factors to downward percolation of the effluent or rain at the plant are the clay layers above the limestone. The movement of soil water, especially excess water that moves downward as a result of gravity drainage is limited by the least permeable strata (those having the lowest hydraulic conductivity) through which it must pass.

Lithologic logs and natural-gamma logs of 21 Survey wells and 4 Bureau of Geology wells (Basic Data B) were used in determining the positions and thicknesses of clay layers penetrated by cased wells. The natural-gamma radioactivity of quartz sand and pure limestone is negligible. Because clays tend to concentrate the heavy radioactive elements through the processes of ion exchange and adsorption, the natural-gamma activity of clay-bearing sediments generally is much higher than that of quartz sands and carbonates. Thus, an increase in natural-gamma count (which is directly proportional to radioactivity) may indicate an increase in clay content of the material (Keys and MacCary, 1971).

The lithologic logs and natural-gamma logs indicate that sandy clay, clayey sand, or clay were present in one or more layers at shallow depths beginning within the first 32 ft (9.6 m) at all the wells logged except wells 2 and 3. Well 2 passed through a thin limestone layer but was still in sand at 75 ft (23 m). Well 3 penetrated its first clay layer at 82 ft (25 m).

The location of two hydrogeologic sections is shown on figure 5. In both sections wells were projected into the line at section as shown. Section A-A' (fig. 6) was drawn based on lithologic and natural-gamma logs. Section B-B' (fig. 7) was drawn based on lithologic, driller, and natural-gamma logs and chemical analyses of ground water. The midpoint or center of the minimum-maximum intensity value on the gamma-ray curve was assumed to represent the correct point for determining the top and bottom of the clay zones (Mercier, 1950). For the convenience of the reader, on figure 6 gamma-ray curves were plotted to the immediate left of the well-location lines at the same scale. Tic marks were then drawn on the well-location lines to represent the boundaries of the clay layers. The potentiometric surface shows the altitude at which water level would have stood in tightly cased wells open to the uppermost Floridan aquifer in February 1974.

The sand aquifer and the limestone aquifer appear to act as one hydraulic unit. Apparently the clay layers are discontinuous; otherwise, little of the effluent would be reaching the limestone aquifer at well 1 and there would be a large amount of water perched above the clay layer. On the contrary, no water was observed by the drillers above the clay at well 1 when it was drilled after the area received 2 in (50 mm) of sewage effluent per day for 6 months. Furthermore, chloride concentrations for water samples collected at well 1 from the limestone aquifer have been approximately equal to that of the sprayed effluent, indicating that large volumes of the effluent are reaching the underlying aquifer regardless of the clay layers. The movement of large volumes of water through the limestone is related to solution openings rather than "primary" porosity. (This point is discussed in detail in the "Changes in Quality of Effluent" section.) The effective porosities (table 3) for the clay and limestone at well 10 are approximately twice as great as those at well 8, indicating they may not represent portions of the same layers.

Basic Hydrogeologic Concepts

Hydraulic conductivity, as reported in table 3, is the rate of flow, in cubic feet per day, through a cross-sectional area of 1 square foot, under a hydraulic gradient of 1 foot per foot, at the prevailing kinematic viscosity in units of feet per day (Lohman, 1972). For convenience it is also shown in metres per day. The older "field

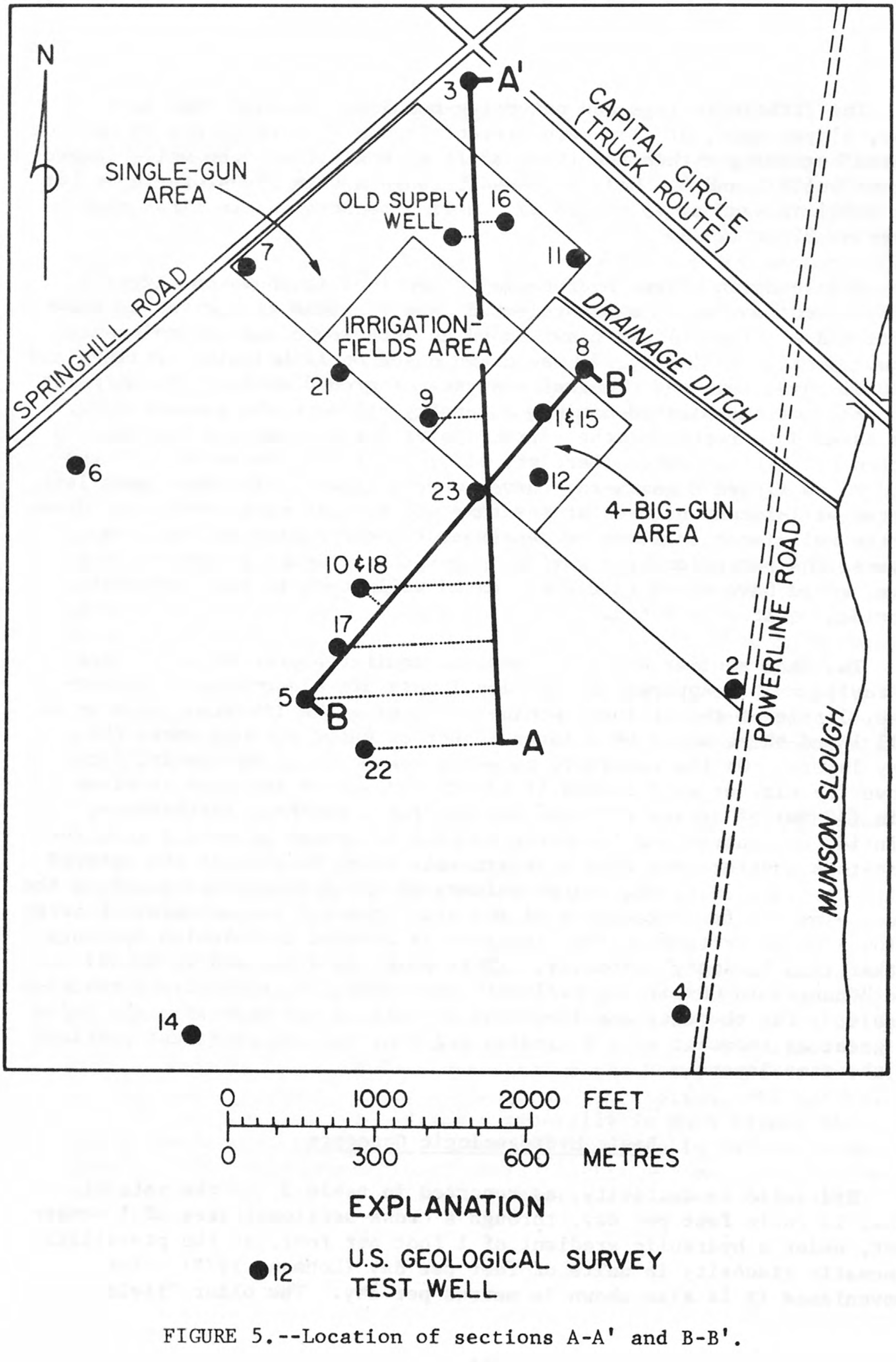


FIGURE 5.--Location of sections A-A' and B-B'.

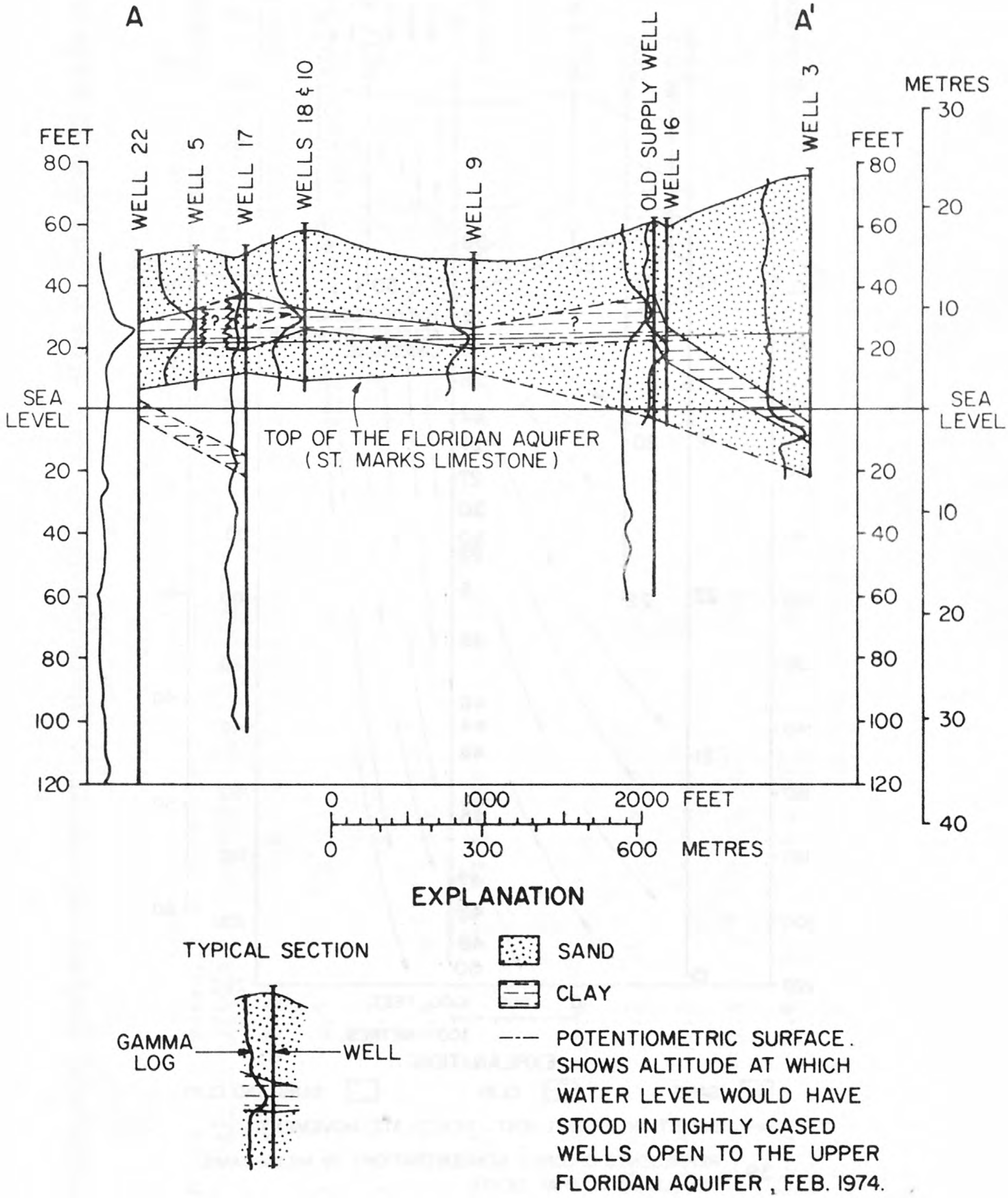


FIGURE 6--Hydrogeologic section A-A'.

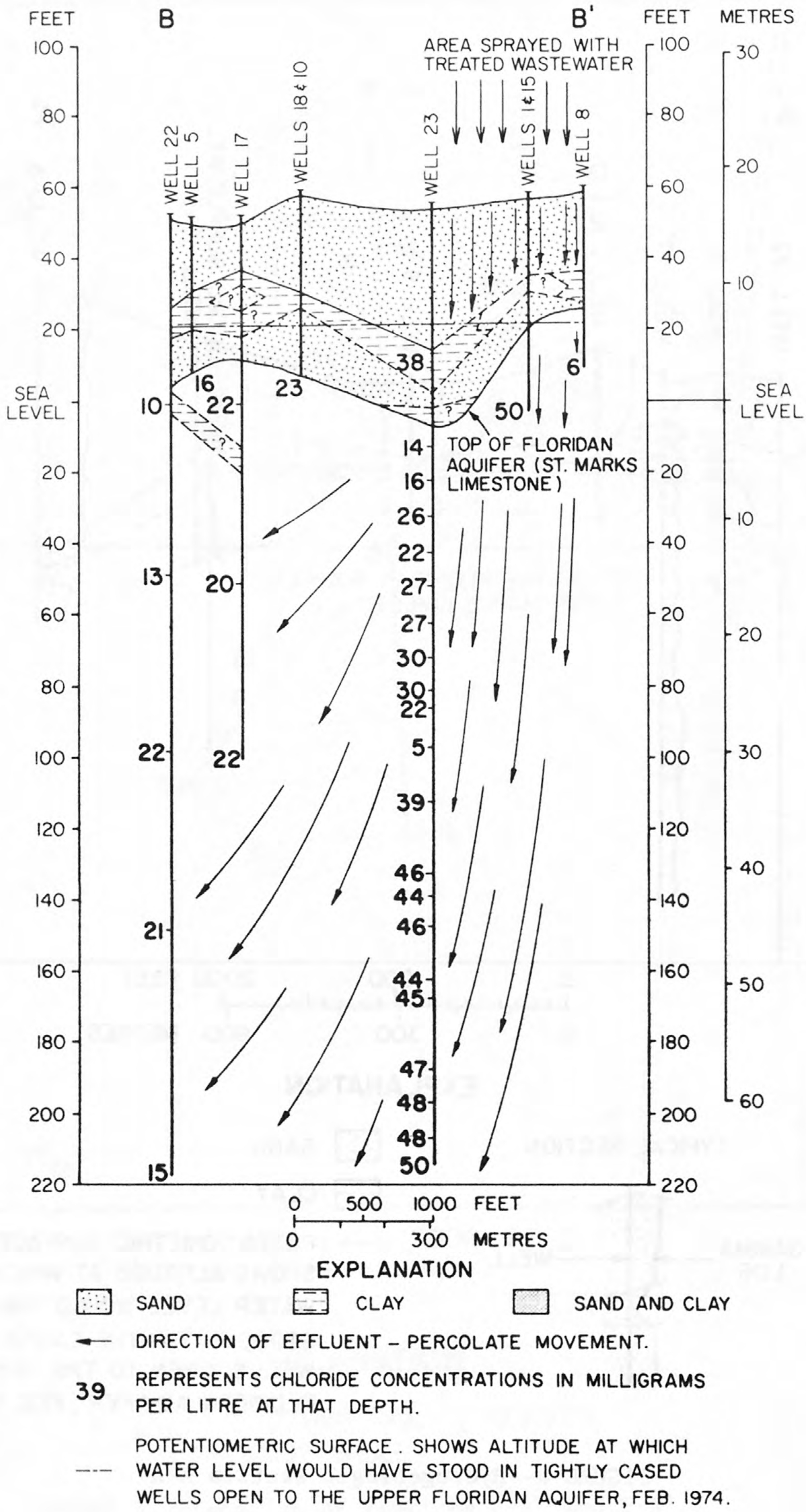


FIGURE 7.--Hydrogeologic section B-B'.

Table 3.--Laboratory analyses and statistical characteristics of grain sizes of core samples collected at wells 8 and 10.

Location	Depth (feet)	Vertical hydraulic conductivity (ft/day)	(metres/day)	Median diameter (millimetres)	Effective porosity (percent)	Sorting coefficient	Lithology
Well 8	7- 8	5.9	1.8	0.25	36.0	1.6	Sand
Well 8	13-14	4.3	1.3	.23	34.1	1.7	Sand
Well 8	17-18	6.2	1.9	.13	35.8	1.6	Sand
Well 8	27-28	4.6×10^{-6}	1.4×10^{-6}	$>$ .001	5.3	--	Clay
Well 8	37-38	3.05×10^{-3}	9.3×10^{-4}	.012	12.5	830	Limestone
Well 10	3- 4	14.4	4.4	.26	35.5	--	Sand
Well 10	13-14	7.5×10^{-1}	2.3×10^{-1}	.20	28.3	1.6	Sand
Well 10	23-24	1.3	3.9×10^{-1}	.21	21.8	1.6	Sand
Well 10	33-34	1.5×10^{-6}	4.7×10^{-7}	$>$ .001	12.4	--	Clay
Well 10	41-42	4.6×10^{-4}	1.4×10^{-4}	.026	26.6	8.0	Limestone

coefficient of permeability" in gallons per day per square foot introduced by Meinzer and Wenzel (1942) can be obtained by multiplying the hydraulic conductivity value in feet per day by 7.48 gallons per cubic foot.

In unconsolidated granular material the hydraulic conductivity is largely a function of the size and shape of the component grains, their degree of sorting, and the amount of interconnected pore space available for fluid transmission. Commonly, median diameter is used as an index of particle size; effective porosity, of pore space available for fluid transmission; and sorting coefficient, the degree of sorting in a sample. Hydraulic conductivity generally decreases with a decrease in median diameter and effective porosity and an increase in sorting coefficient. Median diameter and effective porosity decrease with increasing clay content. This was true for the core samples of wells 8 and 10, as shown in table 3. For core samples collected at wells 8 and 10 (see fig. 5 for location) the hydraulic conductivity was lowest for clay, next lowest for limestone, and highest for sand. The median diameter of 10 core samples collected at wells 8 and 10 ranged from less than 0.001 mm for dense clay to 0.26 mm for sand (table 3). The median diameter is the particle size that is larger than 50 percent of the sample and smaller than the other 50 percent. The average of all the median diameters was 0.13 mm, and for samples without an appreciable silt and clay fraction, 0.21 mm. These sizes are in the fine sand range (0.125 to 0.25 mm) of the Wentworth classification (Krumbein and Sloss, 1955). Sand particles of medium size (0.25 to 0.5 mm) constituted from 0 to 51 percent of the samples. Sand particles in the coarse (0.5 to 1 mm) and very coarse (1 to 2 mm) sizes constituted from 0 to 9.3 percent and 0 to 0.2 percent, respectively. None of the core samples contained gravel-size particles (greater than 2 mm).

Effective porosity (table 3) is expressed as a percentage of the total volume occupied by the interconnected interstices having entrance diameters larger than 10^{-7} m. As pointed out by Lohman and others (1972), the present definition of effective porosity differs from that of Meinzer (1923b). The effective porosity is roughly 2 to 7 times greater for the samples without an appreciable silt or clay fraction than for those containing appreciable clay.

The sorting coefficient is a statistical parameter developed by Trask (1932) and defined as the extent to which the grains spread on either side of the average and is equal to the square root of the ratio of the particle diameter that is larger than 75 percent of the sample to the particle diameter that is larger than 25 percent of the sample. According to Trask, well-sorted sediments (which allow water to move through them rapidly) have sorting coefficients less than 2.5; moderately-sorted sediments, 2.5 to 4.0; and poorly-sorted sediments, greater than 4.0. Except for core samples of clay or limestone, the sorting coefficients listed in table 3 are less than 2.5, indicating the sand overlying the clay and limestone is well sorted.

Evaluation of Regional Ground-Water Flow Pattern

Potentiometric maps for April 1973 (fig. 8) and May 1974 (fig. 9) (periods of high and low water-level conditions, respectively) indicate movement of the ground water from the spray area is southwesterly. Because of the large rate of flow of natural ground water under the site and the large aquifer permeability, distortion of the regional pattern of ground-water flow by the effluent applied is not appreciable.

As shown in figure 10, the variation in water levels at well 1 (the area most heavily sprayed) corresponds closely with the variation in water levels at well 150 (outside the area affected by the sprayed effluent, fig. 8). Water levels in both wells are controlled primarily by rainfall and antecedent conditions (such as previous water levels). Water-level hydrographs (not shown) for the other wells drilled by the U.S. Geological Survey for this investigation correspond closely with that of well 1.

QUALITY OF EFFLUENT AND NATIVE GROUND WATER

Quality of the Effluent

The chemical analyses of the sewage effluent (table 4) indicate that although actual concentrations of chemical constituents have some variation, the chemical type (presence and ratios of major ions) has remained relatively constant. The only chemical constituents in the sewage effluent analyzed for and found in concentrations above those allowed or recommended by the U.S. Public Health Service (USPHS) Drinking Water Standards (1962) are: Arsenic (recommended, 10 ug/l (micrograms per litre); maximum, 50 ug/l) and iron (recommended, 300 ug/l). However, if the ammonia-nitrogen (NH_4-N) were converted to nitrate-nitrogen (NO_3-N), nitrate would exceed the recommended limit of 10 mg/l (milligrams per litre). The Florida Department of Pollution Control limits for "minimum treatment. . . or advanced waste treatment as deemed necessary. . . by the Department" (Rules, Chapter 17-3.04) for Biochemical Oxygen Demand (BOD_5) (90 percent removal or 5 mg/l), total phosphorus expressed as P (1 mg/l) and total nitrogen expressed as N (3 mg/l) are exceeded. In addition, fecal coliform organisms have been detected in the effluent in concentrations from 4,000 to 80,000 colonies per 100 millilitres (ml) (William Leseman, Laboratory Director, Smith Plant, oral commun., December 1974), greatly exceeding the 1 colony per 100 ml recommended limit for drinking water (USPHS, 1962). No evaluation was made of the occurrence of viruses in this investigation.

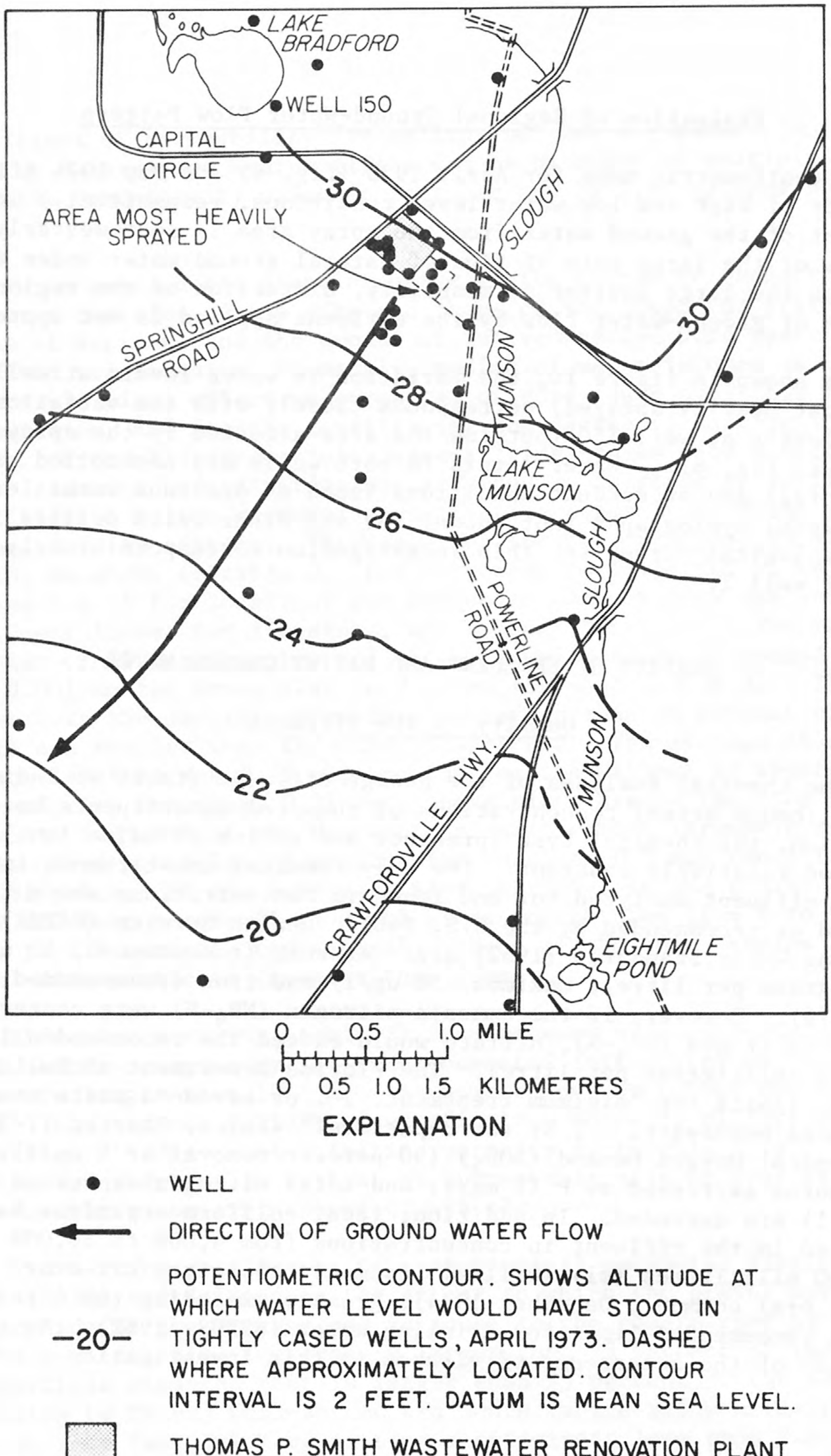


FIGURE 8.--Potentiometric surface of upper part of Floridan aquifer in April 1973 (high-water period), Tallahassee vicinity.

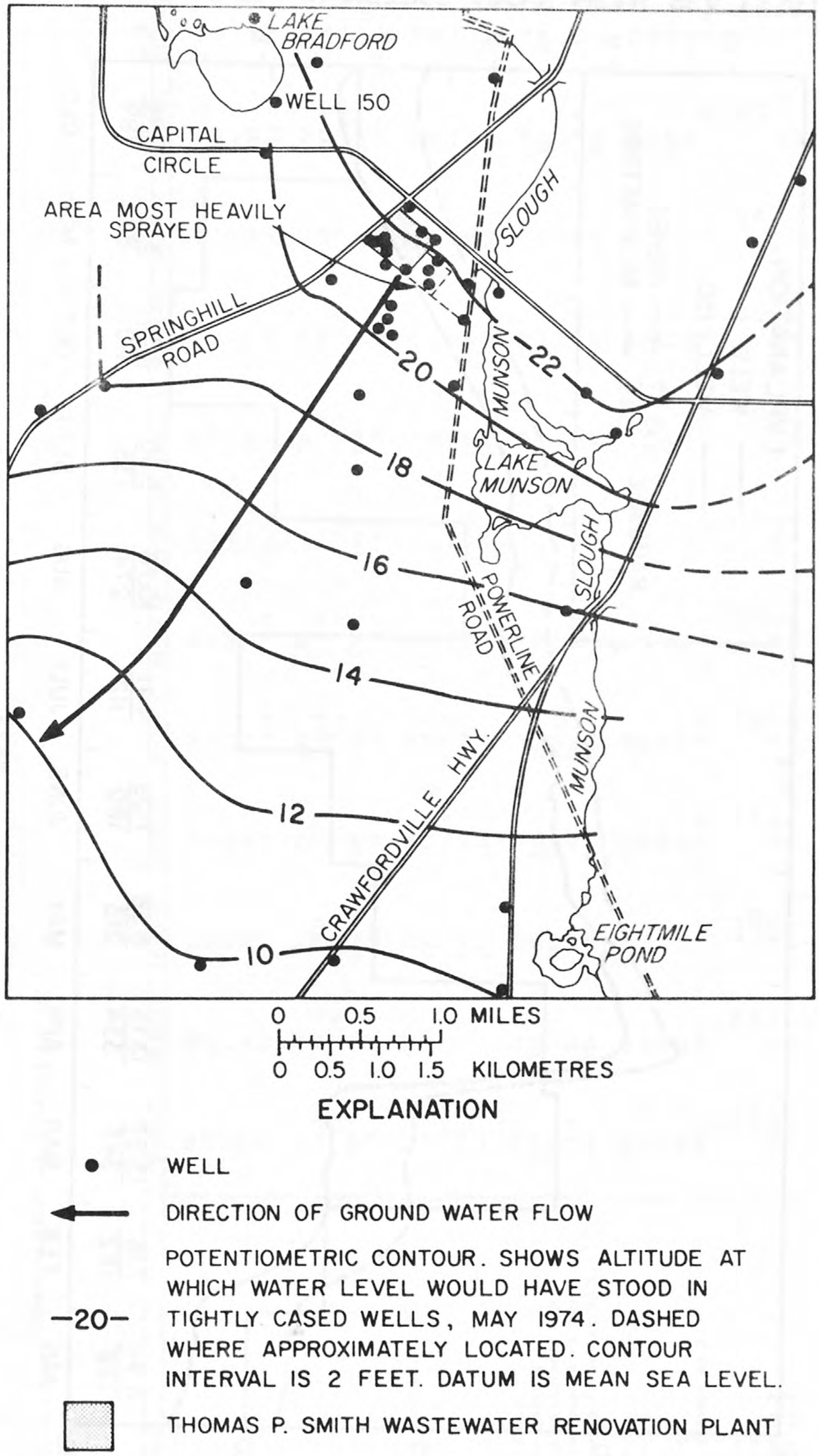


FIGURE 9.--Potentiometric surface of upper part of Floridan aquifer in May 1974 (low-water period), Tallahassee vicinity.

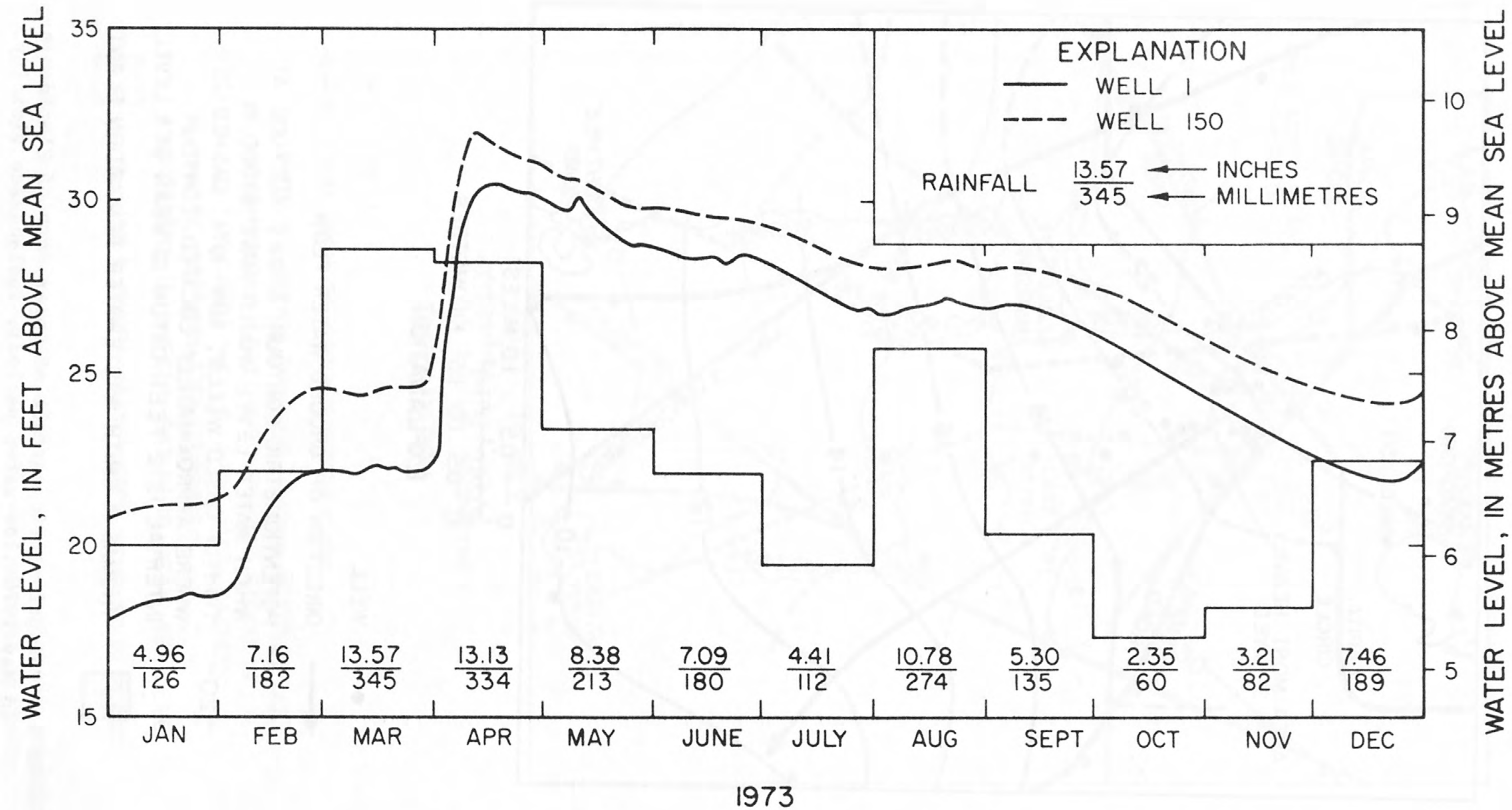


FIGURE 10.--Hydrographs of wells 1 and 150 and rainfall at Tallahassee.

Table 4.--Analyses of sewage effluent.

(Concentrations are in milligrams per litre except for constituents indicated by * which are in micrograms per litre.)

Date of Collection	09-20-72	10-31-72	12-28-72	03-05-73	04-24-73	06-28-73	08-30-73	11-07-73	12-20-73	02-13-74	04-30-74	06-27-74
Color (units)	50	65	55	30	50	60	--	--	--	--	--	--
Turbidity (JTU)	20	100	10	25	4	35	--	--	20	--	27	24
Silica	18	17	15	16	15	18	--	--	--	--	--	--
Calcium	39	42	39	38	33	33	--	39	37	36	39	40
Magnesium	11	12	12	11	9.2	8.8	--	11	14	10	15	20
Sodium	51	56	46	51	41	40	--	54	47	50	50	45
Potassium	9.4	11	8.8	7.2	6.7	6.8	--	3.0	16	13	12	10
pH (units)	7.3	7.8	8.2	7.6	7.2	7.6	7.1	7.9	7.4	7.3	7.8	--
Bicarbonate	240	--	150	180	190	170	190	220	72	270	270	--
Carbonate	0	0	0	0	0	0	0	0	0	0	0	--
Sulfate	25	30	25	34	26	18	--	--	--	--	21	20
Chloride	52	80	100	92	57	58	40	62	42	48	51	50
Fluoride	1.4	.7	1.7	2.9	1.2	1.0	--	--	--	--	--	--
Alkalinity	200	--	140	160	160	150	160	190	68	220	230	--
Total Hardness	140	--	150	130	120	120	--	140	150	130	160	180
Noncarbonate Hardness	0	--	25	0	0	0	--	0	91	0	0	0
Dissolved Solids--Residue	355	351	390	329	282	270	--	--	--	--	314	278
Dissolved Solids--Calculated Sum	330	--	360	360	300	290	--	--	--	--	--	--
Biochemical Oxygen Demand (5 Day)	7.1	30	20	51	62	30	--	7.8	8.0	38	8.4	45
Specific Conductance (umhos at 25°C)	650	728	718	702	560	570	--	698	649	541	700	--
Inorganic Carbon	65	40	22	42	30	35	--	47	47	50	59	53
Total Organic Carbon	8	43	14	56	47	42	--	47	28	17	101	39
Total Carbon	73	83	36	98	77	77	--	94	75	67	160	92
Ammonia--NH_4 as N	20	22	21	20	17	15	11	22	22	23	25	21
Nitrogen, Total Organic as N	14	10	4.4	5.0	2.2	4.9	2.7	3.0	1.8	5.8	.85	2.9
Nitrate--NO_3 as N	.00	.00	2.6	.00	.04	.01	1.2	.00	.03	.09	.07	.06
Nitrite--NO_2 as N	.06	.06	.33	.06	.04	.55	.17	.01	.01	.06	.03	.11
Phosphorus, Ortho as P	8.2	10	9.0	8.8	6.5	5.9	6.1	9.5	9.4	10	11	9.2
Phosphorus, Total as P	9.9	12	10	9.0	7.4	5.9	6.4	9.5	9.6	10	12	9.2

Table 4.--Analyses of sewage effluent.--Continued

Date of Collection	09-20-72	10-31-72	12-28-72	03-05-73	04-24-73	06-28-73	08-30-73	11-07-73	12-20-73	02-13-74	04-30-74	06-27-74
*Arsenic--Dissolved	--	--	--	--	--	--	--	--	--	--	0	--
*Cadmium--Dissolved	0	--	--	--	0	--	--	--	--	--	--	--
*Chromium--Dissolved Hexavalent	0	--	--	--	0	0	--	--	--	--	0	--
*Chromium--Dissolved	10	--	10	30	--	--	--	--	--	--	--	--
*Cobalt--Dissolved	0	--	--	--	--	--	--	--	--	--	--	--
*Copper--Dissolved	30	--	--	--	40	--	--	--	--	--	--	--
*Iron--Dissolved	70	--	--	--	130	--	--	--	--	--	80	--
*Lead--Dissolved	6	--	--	--	6	--	--	--	--	--	15	--
*Lithium--Dissolved	10	--	--	--	--	--	--	--	--	--	--	--
*Manganese--Dissolved	20	--	--	--	50	--	--	--	--	--	25	--
*Strontium--Dissolved	300	400	320	140	40	300	--	--	--	--	--	--
*Zinc--Dissolved	70	--	--	--	40	--	--	--	--	--	20	--
*Aluminum--Total Recoverable	350	--	80	0	--	260	--	--	--	--	--	90
*Arsenic--Total Recoverable	20	--	10	6	5	7	--	--	1	--	0	10
*Cadmium--Total Recoverable	1	--	1	1	--	2	--	--	9	--	1	1
*Chromium--Total Recoverable	30	--	--	--	--	60	--	--	--	--	--	0
*Cobalt--Total Recoverable	0	--	1	1	--	0	--	--	--	--	--	10
*Copper--Total Recoverable	30	--	40	60	--	40	--	--	5	--	--	28
*Iron--Total Recoverable	390	--	310	470	--	630	--	--	630	--	--	620
*Lead--Total Recoverable	18	--	12	17	--	19	--	--	6	--	--	18
*Lithium--Total Recoverable	10	--	0	10	--	0	--	--	--	--	--	8
*Manganese--Total Recoverable	30	--	40	40	--	50	--	--	67	--	--	38
*Mercury--Total Recoverable	.5	--	--	.5	--	.6	--	--	--	--	.2	.0
*Nickel--Total Recoverable	4	--	8	1	--	6	--	--	--	--	--	13
*Zinc--Total Recoverable	120	--	120	220	--	130	--	--	120	--	--	30

*Micrograms per litre

Quality of Native Ground Water

The natural quality of the ground water in the upper part of the Floridan aquifer immediately beneath the Thomas P. Smith Wastewater Renovation Plant was assumed to be the same as that at well 14 (fig. 4), approximately 4,000 ft (1,200 m) southwest of the area most heavily sprayed. (No samples were collected prior to spraying.) The quality of the ground water at well 14 (tables 5 and 6) remained practically constant throughout the investigation and was unaffected by the activities at the Plant, as evidenced by the chloride concentrations at well 14 being as low or lower than those observed at wells upgradient of the plant (wells A, B, C. D, E, Basic Data A). Natural chloride and nitrate-N concentrations are 2 and 0.05 mg/l, respectively. Table 6 compares averages of concentrations of major ions and nutrients present in the effluent and in ground water at wells 1, 5, 9, and 14.

CHANGES IN QUALITY OF EFFLUENT

The quality of effluent is modified in several ways as it percolates downward, mixes with the underlying ground water, and eventually leaves the area. Major among these are: nitrification--denitrification, vegetative response, phosphate fixation, ion exchange, and dilution. Although dilution is normally the last of these mechansims to occur, it will be discussed first because of its importance in evaluating the others.

Dilution

The effluent contains higher concentrations of major chemical constituents than the native ground water. Consequently, when effluent and native ground water are mixed, the concentrations of major chemical constituents of the resultant ground water fall between those of the effluent and the native ground water.

From the principles of dilution we know that for a well-mixed fluid: $C_eN_e + C_bN_b = (100)N_w$, where C_e and C_b represent the percent by volume of effluent and natural ground water ("background"), respectively, which combined to form the ground water at any given well. For cases of simple dilution of conservative parameters such as chloride (those not lost through adsorption, fixation, denitrification, precipitation, plant uptake, or ion exchange) N_e, N_b, and N_w represent the concentration, in milligrams per litre, of the particular chemical constituent present in the effluent, "background" water, and the ground water at well w, respectively.

To solve for the percent of effluent-percolate in water from a given well, such as well 1, substitute the average chloride concentrations (table 6) present in the effluent and in water from well 14

Table 5.--Analyses of ground water at well 14.
(Concentrations in milligrams per litre)

Date of Collection	12-20-72	02-01-73	03-05-73	04-12-73	05-30-73	07-25-73
Color (units)	--	--	--	10	5	0
Turbidity (JTU)	--	--	--	--	--	--
Silica	6.5	6.3	--	6.3	5.0	7.0
Calcium	--	--	28	16	25	--
Magnesium	--	--	1.2	.9	1.0	--
Sodium	--	--	1.6	1.7	1.4	--
Potassium	--	--	.6	.6	.6	--
pH (units)	--	--	--	7.4	7.7	--
Bicarbonate	--	--	--	56	70	56
Carbonate	--	--	--	0	0	0
Sulfate	5.8	--	--	3.2	13	--
Chloride	2.0	--	--	3.0	2.1	2.0
Fluoride	.2	--	--	.2	.2	--
Alkalinity	--	--	--	46	57	46
Total Hardness	--	--	75	44	67	--
Noncarbonate Hardness	--	--	--	0	9	--
Dissolved Solids--Residue	--	--	--	68	89	--
Dissolved Solids--Calculated Sum	--	--	--	60	83	--
Biochemical Oxygen Demand (5 Day)	--	--	--	--	.5	.6
Specific Conductance (umhos at 25^{o}C)	164	--	--	108	145	129
Inorganic Carbon	--	--	--	7.5	19	8.0
Total Organic Carbon	--	--	--	8.0	5.0	2.0
Ammonia--NH_4 as N	.04	.03	--	.04	.04	.01
Nitrogen, Total Organic as N	.60	.38	--	.65	.06	.37
Nitrate--NO_3 as N	.00	.03	--	.07	.06	.00
Nitrite--NO_2 as N	.01	.01	--	.00	.00	.00
Phosphorus, Ortho as P	--	--	--	--	--	.00
Phosphorus, Total as P	.00	.00	--	.00	.01	.00

Table 5.--Analyses of ground water at well 14.--Continued

08-29-73	10-04-73	11-06-73	01-24-74	02-13-74	03-13-74	04-25-74	05-15-74	06-27-74
--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--
7.0	6.7	--	--	--	--	--	--	--
--	20	16	14	13	14	14	12	13
--	.8	1.1	.9	.7	.7	.7	.7	.7
--	1.5	1.3	1.6	1.3	1.3	1.2	1.2	.9
--	.5	.7	.3	.4	.4	.6	.4	.3
--	7.8	--	--	7.9	7.4	7.0	--	--
--	74	--	--	38	74	42	--	--
--	0	--	--	0	0	0	--	--
--	--	--	--	--	--	--	.4	2.1
--	2.5	2.2	1.3	1.4	1.6	2.3	1.6	1.7
--	--	--	--	--	--	--	--	.0
--	61	--	--	31	61	34	--	--
--	53	44	39	35	38	38	33	35
--	0	--	--	4	0	4	--	--
--	--	--	--	--	--	--	36	48
--	--	--	--	--	--	--	--	--
--	2.2	--	--	1.4	1.3	.6	--	.4
--	131	87	87	76	86	81	100	130
--	--	11	--	8.0	10	7.0	9.0	--
--	--	--	--	.0	.0	2.0	.0	--
.00	.03	--	--	.03	.02	.03	.06	.05
.54	.63	--	--	.71	.06	.32	.17	.01
.00	.09	--	--	.04	.07	.06	.04	.09
.00	.00	--	--	.00	.00	.00	.03	.03
.00	.00	--	--	.00	.00	.00	--	--
.00	.00	--	--	.00	.00	.00	.02	.05

Table 6.--Comparison of averages of concentrations of major ions and nutrients present in the effluent and in ground water at wells 1, 5, 9, and 14.

	Average concentrations, milligrams per litre*									
Identifier	Ca	Mg	Na	K	Cl	NH_4-N	NO_2-N	NO_3-N	Org-N	Total P
Effluent	38	12	48	9.4	62	20	0.12	0.34	4.8	9.2
Well 1	62	7.3	35	2.9	55	.04	.01	18	.24	.02
Well 5	31	5.6	7.3	.5	16	.02	.01	3.8	.18	.03
Well 9	--	--	36	1.8	56	.34	.07	19	.22	.01
Well 14**	17	.8	1.4	.5	2.0	.03	.01	.05	.38	.01

* Average of all analyses for the 2-year study period (July 1972 to June 1974).

** Chemical concentrations at well 14 are assumed to represent natural "background" conditions.

(taken as representing the "background" concentration), and from well 1 into the previous equation as follows:

C_e (62) + C_b (2) = (100)(55). And since $C_e + C_b = 100$ percent,

C_e (62) + (100- C_e) (2) = (100)(55). Rearranging and combining forms,

60 C_e = 5,300. Thus,

$$C_e = 88 \text{ percent. Rounding off,}$$

$$C_e = 90 \text{ percent.}$$

Based on chloride concentrations, then, the water sampled at well 1 was approximately a mixture of 90 percent effluent and 10 percent natural water.

However, the calcium concentration at well 1, instead of falling between the concentration of that of the effluent and that at well 14, is actually 63 percent higher than that of undiluted effluent. Furthermore, the concentrations of sodium, potassium, and magnesium present at well 1 are all much lower than the predicted concentrations based on 10-percent dilution. This observation can be explained in part by cation exchange.

Ion Exchange

The quality of the ground water at well 1 in the upper Floridan aquifer immediately beneath the 4-Big-Gun Area, as compared with the quality of the effluent and of the ground water at well 14 (table 6), indicates some important changes are occurring as the effluent percolates through the soil and rock.

The physical and chemical activity that takes place on the surface of particles within the soil column is largely determined by particle size. Ion exchange refers to the replacement of adsorbed ions (electrically charged atoms or groups of atoms) by ions in solution. Although nearly all soil and rock minerals have some ion-exchange capacity (Hem, 1970), the ion-exchange property of a soil is due almost entirely to its clay and silt fractions and organic matter (Winklander, 1964). Goldstein and Moberg (1973) attributed the increasing ion-exchange capacity of a soil with increasing clay content to the increasing surface area with decreasing particle size.

Cation exchange refers to the replacement of adsorbed cations (positively charged ions) by cations in solution. Inasmuch as the effluent contains relatively high amounts of sodium, potassium, and magnesium, and calcareous sand and clay are abundant above the limestone (see section on Basic Data, lithologic logs), the potential for cation exchange exists at the plant.

If cation exchange is occurring, the dilution equation still is valid for conservative parameters. However, for the major cations: N_e, N_b, and N_w become the sum of calcium + magnesium + sodium + potassium, expressed in milliequivalents per litre, in the effluent, "background" water, and the ground water at well w, respectively. Converting the concentrations listed in table 6 for wells 1 and 14 and the effluent to milliequivalents per litre, substituting into the equation and solving it yields C_e = 100 percent effluent at well 1. Apparently, then cation exchange is occurring with calcium adsorbed to the clay being replaced by sodium, potassium, and magnesium. The difference between C_e values obtained by the two methods (calculated on the basis of chlorides versus sums of milliequivalents of cations) is relatively small and could be explained by the fact that we are using average concentrations rather than single specific concentrations.

The correctness of this interpretation (cation exchange) is corroborated by similar calculations based on average concentrations at well 5. Based on the summation method, water at well 5 has averaged 21 percent effluent. Based on the conservative-parameter method and substituting for chloride, water at well 5 has averaged 23 percent effluent. The difference is negligible.

Nitrification-Denitrification

Nitrification-denitrification is the process by which effluent-nitrogen is converted to different forms and in some cases removed from the ground-water system (Broadbent, 1973). The nitrogen cycle is an extremely complex biochemical phenomenon which is in a constant state of interaction. It is not the intent of this report to review the nitrogen cycle in detail, but to give in general terms a brief discussion of how it is involved in changing the chemical character of the effluent. The effluent nitrogen exists primarily as ammonia-nitrogen (NH_4-N) and organic nitrogen when the effluent is sprayed (table 4). The "ammonia-nitrogen" determination as performed by the U.S. Geological Survey is a method which determines the total concentration of gaseous ammonia (NH_3) and the ammonium ion (NH_4) present in an aqueous solution and does not differentiate between the two species (Brown and others, 1970).

Nitrification and denitrification occurred in each of the sprayed areas, as indicated by the nitrifying and denitrifying bacteria numbers being much higher in the sprayed than the unsprayed areas. This is consistent with the results of a similar study (Cherry, and others, 1973) in St. Petersburg, Florida. Table 7 shows nitrifying and denitrifying bacteria concentrations determined on soil samples collected in July 1973 from selected sites in and near the area sprayed. The locations of these sites are indicated on figure 2. The most probable number per gram (MPN/g) of dry soil of Nitrosomonas (nitrifying bacteria which convert NH_4-N to nitrite-nitrogen (NO_2-N)), was from 23 to 580 times

Table 7.--Numbers of nitrifying and denitrifying bacteria in soil samples collected in the project area.

Site	Date collected	Nitrifiers Nitrosomonas	Nitrifiers Nitrobacter	Denitrifiers All types
B-1	07-19-73	990	240	990
B-2	07-19-73	980	240	240
B-3	07-19-73	96	990	2,600
B-4	07-19-73	46,000	2,600,000	2,600,000
B-5	07-19-73	100,000	480,000	1,700,000
B-6	07-19-73	580,000	13,000,000	3,100,000
B-7	07-19-73	270,000	2,700,000	2,600,000
B-8	07-19-73	260,000	260,000	460,000
B-9	07-19-73	23,000	2,600,000	12,000,000

higher in the area sprayed than outside the area. The Nitrobacter (nitrifying bacteria which convert NO_2-N to nitrate-nitrogen (NO_3-N)) concentration was from 1,000 to 54,000 times greater in the area sprayed than outside the area. Concentration of denitrifiers (bacteria which convert NO_3-N to gaseous nitrogen (N_2) which is then lost to the soil atmosphere (Broadbent, 1973)) was from 460 to 12,000 times greater in the area sprayed than outside the area. This indicates the bacteria are feeding on the nutrients in the effluent.

Almost complete nitrification occurred in the effluent-percolate in both the Irrigation-Fields Area and the 4-Big-Gun Area, but appreciable nitrogen uptake by plants occurred only in the Irrigation-Fields Area. The NH_4-N, which is the most significant form of inorganic nitrogen in the effluent, was almost completely converted to NO_3-N, as evidenced by analyses of ground water from well 1 (table 6). Table 8 compares the January to June 1974 chloride and total nitrogen (organic-N + NH_4-N + NO_2-N + NO_3-N) data for ground water at well 5, downgradient of the 4-Big-Gun Area, and well 21, downgradient of the irrigation fields. From the chloride data, the ground water at both wells is estimated to consist of 25 percent effluent-percolate. If no nitrogen had been removed, the ground water at both wells should contain 0.25 times 25 mg/l (the average concentration of total nitrogen in the effluent, and obtained by summing and averaging the individual nitrogen species shown on table 4) or 6.2 mg/l. However, the average total nitrogen concentrations at wells 5 and 21 are 5.0 and 3.3 mg/l, respectively. Based on average data approximately 12 mg/l ((6.2-3.3)/0.25) of the total nitrogen was removed from the effluent which was applied in the Irrigation-Fields Area and reached well 21 as effluent-percolate, and approximately 5 mg/l of the total nitrogen was removed from the effluent which was applied in the 4-Big-Gun Area and eventually reached well 5. However, the three-dimensional distribution of sampling points is insufficient to show the percentage of nitrogen being removed throughout the effluent plume. Of prime importance in the continuation study is definition of the plume with depth.

Phosphate-Fixation

The low phosphorus concentrations in the ground water at well 1 and well 9 (table 6) indicate that almost all the phosphorus is removed. Since Overman and Smith (1973) have already established that the soil at the Smith Plant has a large capacity to fix phosphorus, it appears likely that the phosphorus removal is due to fixation and adsorption before the effluent reaches the Floridan aquifer. The soil at the plant is Lakeland sand (U.S. Dept. of Agri., written commun., 1975). Hortenstine (1966) summarized the conclusions of other researchers in Florida by saying the phosphate-fixing capacity of the Lakeland sand increases progressively with increases in phosphorus concentration as a result of continuous breakdown of the clay materials and subsequent

Table 8.--Comparison of chloride and total nitrogen concentrations in ground water at wells 5 and 21.

Date	Well 5 Cl (milligrams per litre)	Well 5 Total N * (milligrams per litre)	Well 21 Cl (milligrams per litre)	Well 21 Total N (milligrams per litre)
01-22-74	17	4.8	17	3.2
02-12-74	16	3.0	16	1.3
03-14-74	16	6.2	16	4.1
04-03-74	19	5.3	16	3.9
05-09-74	18	5.1	--	--
06-20-74	17	5.8	16	4.2
Average	17	5.0	16	3.3

* Total N = Organic N + NH_4-N + NO_2-N + NO_3-N

release predominantly of aluminum and also iron. Similar studies by Hook and others (1973) and Kardos and Sopper (1973) in Pennsylvania have determined that more than 90 percent of the phosphorus was removed after water percolated through only 6 in (150 mm) of soil.

Vegetative Response

Vegetative response to the applied sewage effluent at the plant has been reported in detail (Overman and Smith, 1973). For composite samples of pearl millet irrigated at 2, 4, 6, and 8 in per week during April 5, 1972 to September 27, 1972, the nutrients removed in the vegetation, expressed as percent of those in effluent were: nitrogen, 75 to 30; phosphorus, 93 to 24; potassium, 280 to 110; calcium, 18 to 7; magnesium, 73 to 27; and sodium, 1.1 to 0.9. Overman and Smith (1973, p. 43-44) suggested the effluent is "slightly deficient in potassium, since more potassium was harvested at all rates than was applied."

Some lateral movement of the effluent-percolate to the west of the general downgradient (southwesterly) flow from the 4-Big-Gun Area has taken place in the vicinity of well 9 (fig. 2). The average concentrations of nitrogen, phosphorus, chloride, and sodium at well 9 (25 ft (7.6 m) west of the area heavily sprayed) are nearly the same as those at well 1 (table 4). Since Overman and Smith (1973) have reported up to 75 percent "nitrogen recovery" by harvested pearl millet grown in the irrigation fields, it appears that the high-nitrogen ground water at well 9 had its origins in the heavily sprayed forest area.

Other Important Effluent Changes

BOD concentrations were reduced before the effluent mixed with the underlying ground water. The median 5-day BOD values at well 1 and well 9 were 0.3 mg/l and 1.0 mg/l, respectively. The median 5-day BOD value for the effluent was 30 mg/l. This is consistent with the results of the Flushing Meadows Project (Bouwer, 1973).

No fecal coliform organisms were detected in the ground water at any of the test wells used in this investigation. As previously mentioned, the concentration of fecal coliform organisms in the effluent ranged from 4,000 to 80,000 colonies per 100 ml. Evidently the fecal coliform organisms were removed or died before the effluent reached the underlying ground water.

Pesticide analyses were performed on one water sample collected from the effluent and from the ground water at wells 4, 5, 6, 17, 18, 19, and 22. No aldrin, DDD, DDE, DDT, dieldrin, endrin, heptachlor, lindane, chlordane, PCB, PCN, 2,4-D, 2,4,5-T, or silvex were present in any of the samples.

CHANGES IN QUALITY OF GROUND WATER

Variations of Ground-Water Quality with Time and Areal Extent of Effluent Plume

Variations in chemical quality of ground water with time have been most noticeable at well 5. Well 5 (fig. 4) is approximately 1,800 ft (550 m) downgradient of the 4-Big-Gun Area. It took the effluent plume approximately 3/4 year (from the beginning of spray-effluent application upgradient of well 5 in March 1972 until January 1973) to reach well 5. This indicates that the effluent-percolate is migrating at an apparent rate of about 2,400 ft (730 m) per year within the aquifer. By January 1974, the chloride concentration at well 5 had increased to 17 mg/l. During the next 6 months, the chloride concentrations remained relatively constant, still averaging 17 mg/l. This indicates that perhaps the effluent percolate has reached equilibrium with the underlying ground water reaching well 5 and has stabilized at a mixing ratio of ground water to effluent-percolate of about 1 to 4 (based on chlorides). Although variations have occurred, nitrate-nitrogen concentrations have been increasing at well 5, as shown by figure 11. This trend is sharpest during the first 6 months after the effluent arrived at well 5 and appear to be diminishing with time.

The downgradient edge of the effluent plume at shallow depths progressed from between well 10 and well 5 in December 1972 (fig. 12) to between well 5 and well 14 in June 1974 (fig. 13). The outlines of the effluent plumes are based on chloride concentrations in ground water in November and December 1972, and June 1974, as determined from water samples from wells 27 to 270 ft (8.2 to 82 m) deep. It should be noted that differences in well depths and the limited number of control points make it impossible to define the exact limits of the plume. Chloride concentrations greater than 6 mg/l were assumed to indicate the presence of effluent in ground water. As of June 1974, the effluent plume extended between 1,800 and 4,000 ft (550 and 1,200 m) downgradient from the plant site and encompassed an area of about 140 acres (570,000 m^2). The NO_3-N concentrations in ground water throughout the 140-acre area exceeded the Florida DPC limit (advanced wastewater treatment) of 3 mg/l; however, only the ground waters in areas beneath or downgradient of the heavily sprayed areas exceeded the 10 mg/l limit for drinking water (U.S. Public Health Service, 1962) (fig. 14).

The applied effluent has not resulted in higher concentrations of trace metals in the ground-water sampling network downgradient of the plant. This is due, at least in part, to the low trace-element concentrations in the effluent. Table 9 compares U.S. Public Health Service (1962) recommended upper limits for trace elements in drinking water with data for samples collected from the effluent and ground water at representative wells and springs (see figs. 3 and 4). The chloride concentrations in wells 5 and 17 indicate they are affected by the

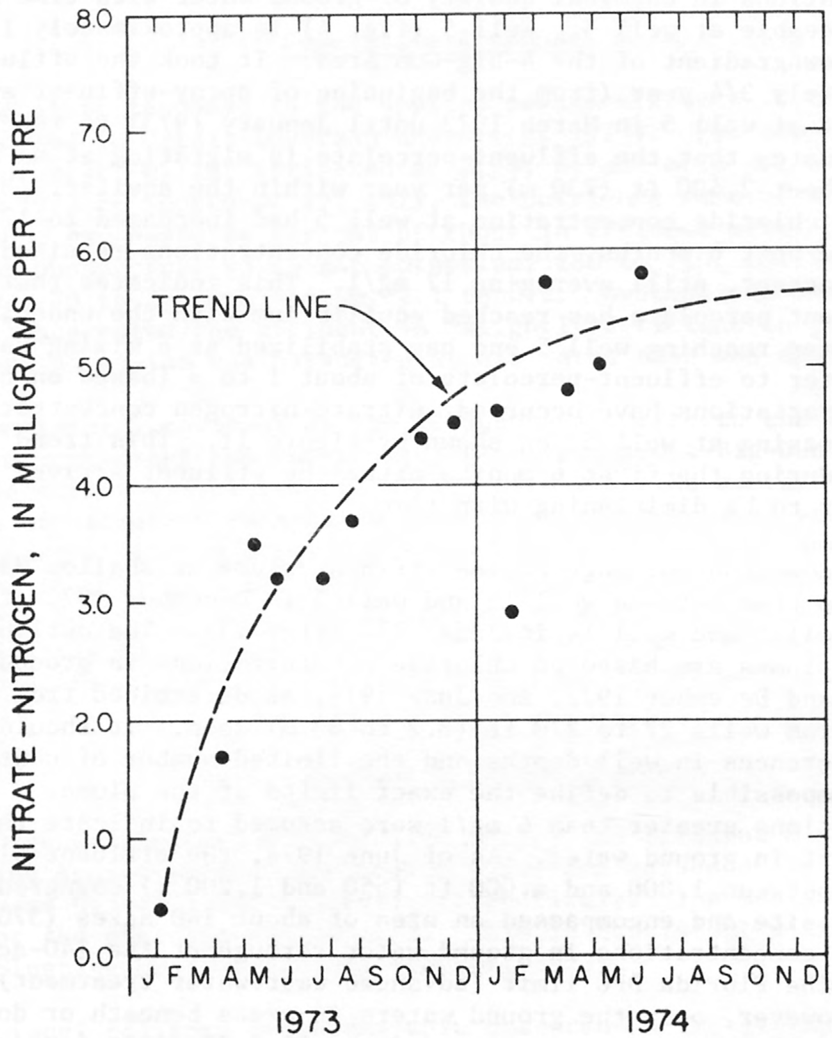


FIGURE 11.--Variation of nitrate-nitrogen with time at well 5.

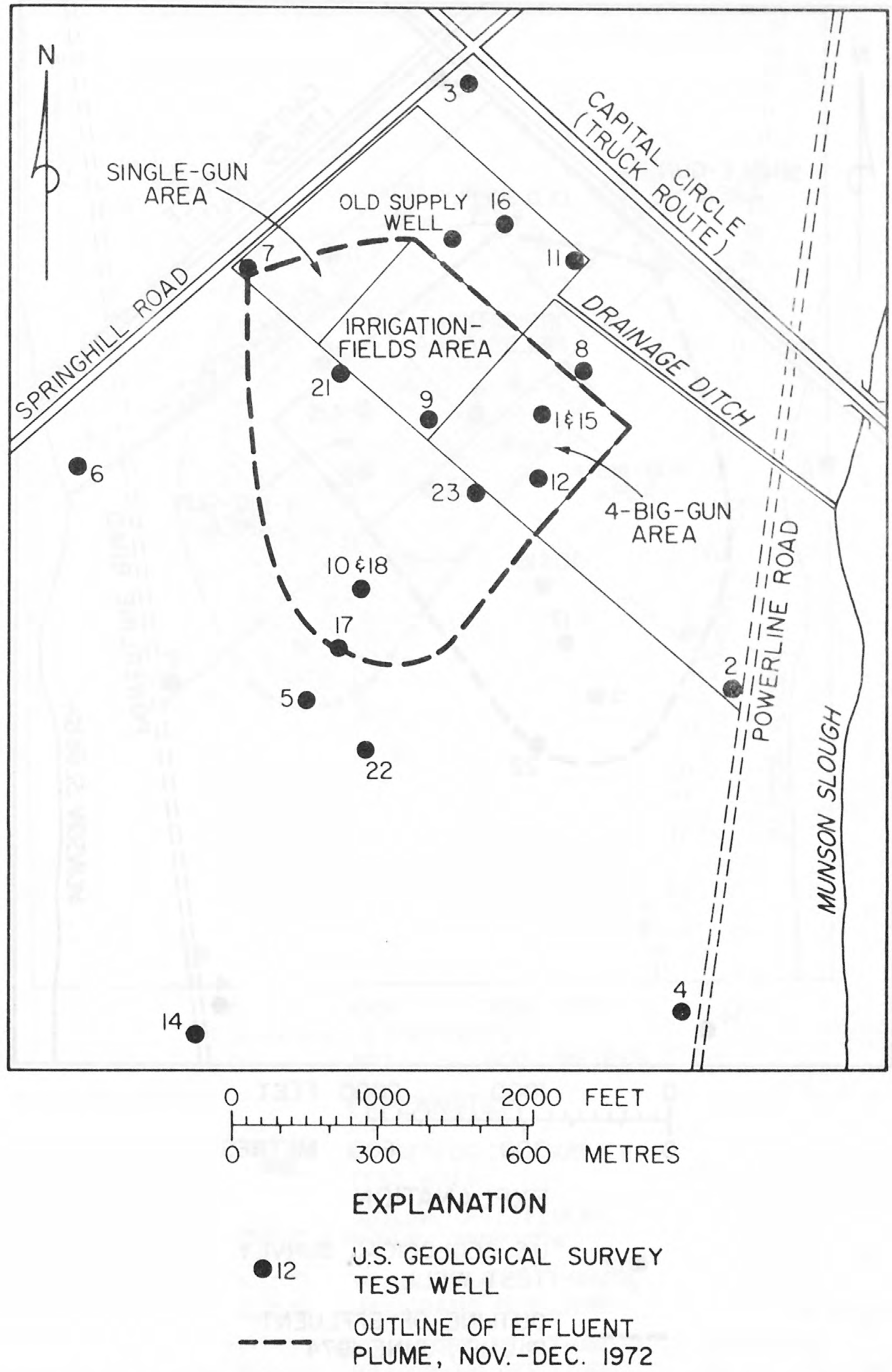


FIGURE 12.--Outline of the effluent plume based on chloride concentrations in ground water in November and December 1972.

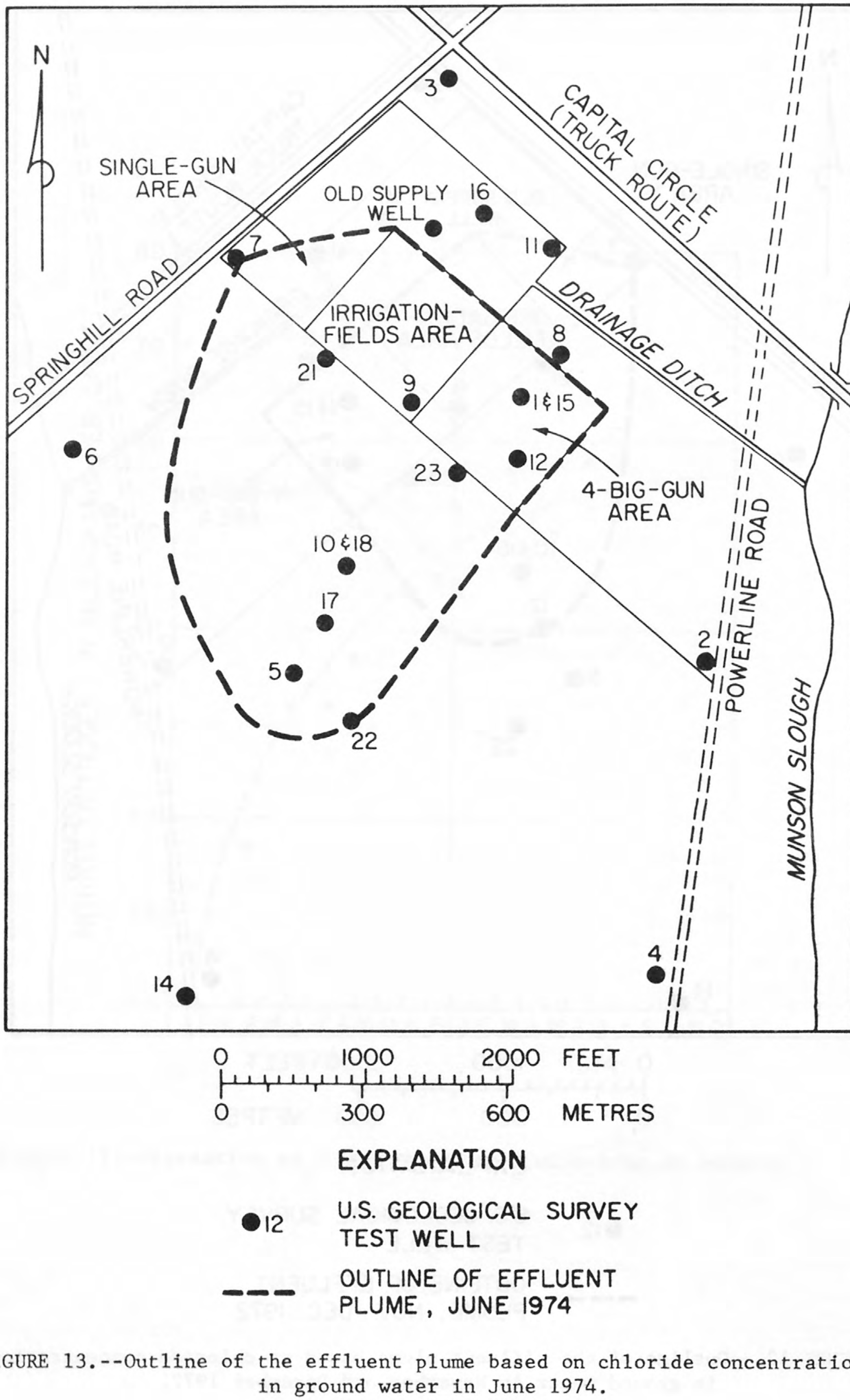


FIGURE 13.--Outline of the effluent plume based on chloride concentrations in ground water in June 1974.

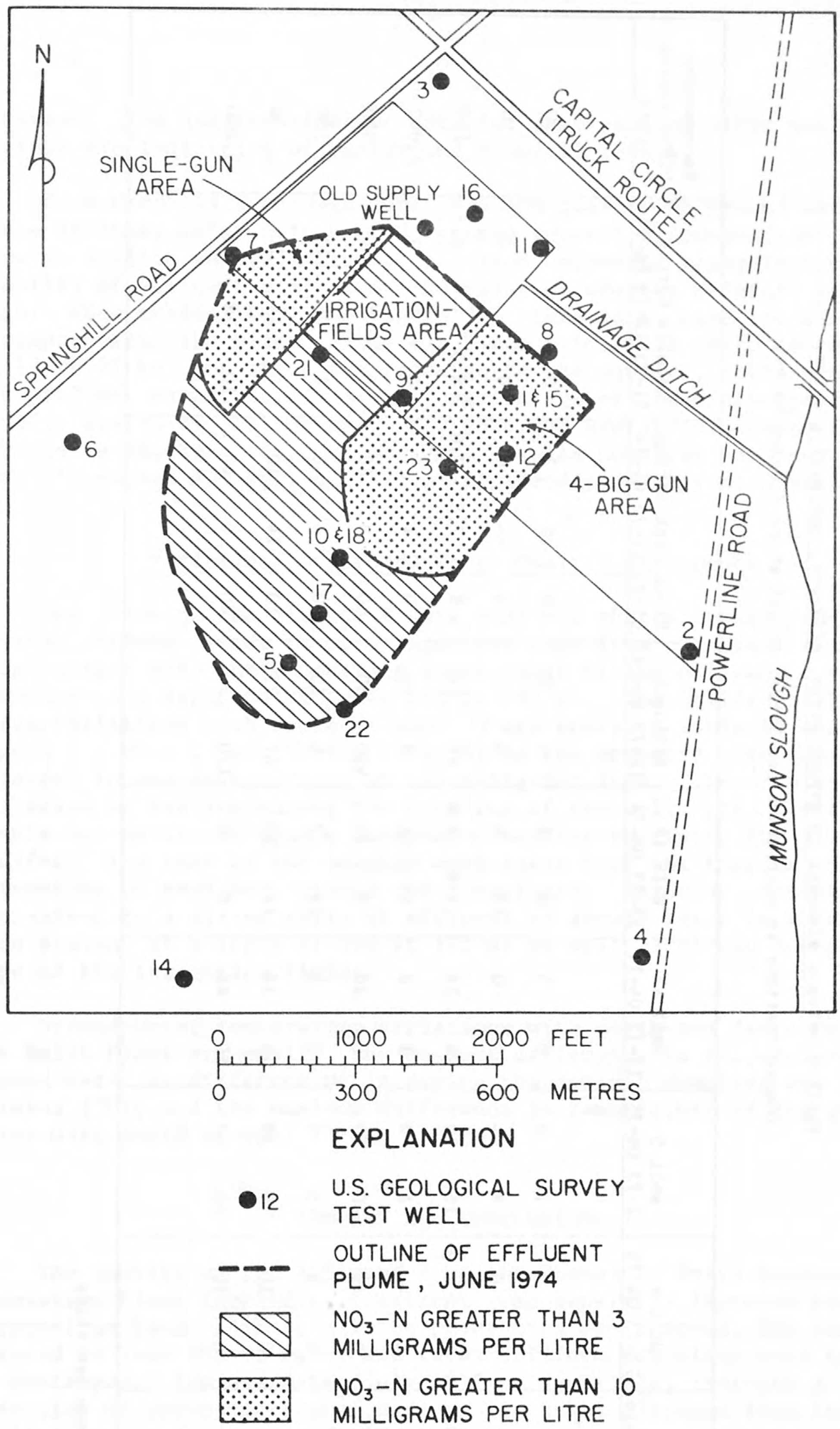


FIGURE 14.--June 1974 nitrate-nitrogen concentrations.

Table 9.--Trace elements in ground water, effluent, and spring water.

(Concentrations in micrograms per litre, except where flagged by **)

Element	Well 4		Well 5		Well 17		Well 19		Effluent		River Sink Spring			Wakulla Spring			Recommended USPHS Limits
Date	12-73	04-74	12-73	04-74	12-73	04-74	12-73	06-74	12-73	04-74	01-73	12-73	04-74	01-73	12-73	04-74	1962
Arsenic	0	3	1	0	0	3	4	2	1	0	10	6	2	0	0	3	50
Cadmium	9	0	8	--	9	0	10	0	9	1	0	--	0	0	--	0	10
Chloride**	1.8	2.3	16	19	24	23	1.8	2.6	42	51	8.0	7.5	7.8	8.0	4.0	6.5	250
Copper	1	--	1	2	1	0	1	1	5	--	0	1	2	0	1	1	1,000
Iron	0	10	0	10	0	40	0	0	630	80	80	0	40	0	0	60	300
Lead	4	5	5	9	8	1	28	7	6	15	0	8	8	1	25	11	50
Manganese	0	10	0	20	14	10	14	50	67	25	10	14	10	0	14	10	50
Zinc	0	20	40	0	50	40	0	0	120	20	40	0	40	10	20	5	5,000

**Milligrams per litre

effluent. The quality-of-water data for samples from other wells and springs are indicative of background chemical levels.

From March 1972 through June 1974 the quality of ground water at three springs, major points of discharge generally downgradient from the area of applied sewage effluent, remained unchanged regardless of the quantity of effluent applied at the plant or whether rainfall was low or high. (See tables 10-12 and figure 3.) This is as expected since the distances from the plant to the discharge points are large (8 to 13 mi or 13 to 21 km) and since the recharge to the aquifer, represented by the effluent magnitude, is a small percentage of the discharge from the aquifer system by the springs. The combined average discharge from the springs in southern Leon and northern Wakulla Counties has been estimated to exceed 400 Mgal/d (17.5 m^3/s) (Hendry and Sproul, 1966).

Variations of Ground-Water Quality with Depth

The chloride and nitrate-N data indicate that although some of the sprayed effluent tends to move laterally away from the application area upon contact with the underlying water, most of the effluent moves downward to a depth of at least 270 ft (82 m). The quality-of-ground-water variations with depth at well 23 are shown in table 13 and in figure 7. Well 23 is located (fig. 4) on the property line immediately adjacent to and downgradient of the 4-Big-Gun Area. The samples were collected by bailing during the drilling of the well. The 42-ft (13-m) sample was collected from a sandy-clay aquifer overlying the limestone aquifer. The rest of the samples were taken from the Floridan aquifer (limestone or sand body within the limestone). Chloride concentrations equivalent to a mixing ratio of effluent to ground water of 1 to 4 were also present at a depth of 248 ft (75 m) in well 21 at the downgradient edge of the irrigation fields.

Ground-water temperature variations with depth and distance from the Smith Plant are small. The maximum difference in temperature of the ground water at different wells during the monthly sampling was 2.0° Celsius (°C), and the maximum difference in temperature of the ground water with depth at well 23 was 2.0°C.

SUMMARY AND CONCLUSIONS

The quality of the effluent from the Thomas P. Smith Wastewater Renovation Plant (secondary treatment) was generally improved by spray disposal on land. Almost all the phosphorus was removed, BOD was reduced to less than 5 mg/l, and fecal coliform organisms were removed or destroyed. Average data (July 1972 to June 1974) indicate a reduction of approximately 12 mg/l of the total nitrogen from the effluent applied to the irrigation fields, which received from 2 to 8 in (50 to

Table 10.--Analyses of water at Kini Spring.

(Concentrations are in milligrams per litre except for constituents indicated by * which are in micrograms per litre.)

Date of Collection	03-21-72	01-21-73	04-25-73	06-27-73	09-27-73	12-21-73	04-04-74	06-26-74
Color (units)	--	60	60	100	--	--	--	--
Turbidity (JTU)	--	2	1	1	2	--	--	--
Silica	6.0	7.2	5.8	7.0	6.6	--	--	--
Calcium	25	23	26	25	27	24	26	30
Magnesium	5.8	5.1	5.6	5.3	6.3	5.6	5.5	7.2
Sodium	5.3	4.4	4.9	4.9	5.0	5.0	5.3	5.0
Potassium	.6	.4	.4	.5	.4	.7	.7	.4
pH (units)	7.0	7.4	7.7	7.5	7.2	8.0	7.7	--
Bicarbonate	90	83	88	83	--	93	91	--
Carbonate	0	0	0	0	--	0	0	--
Sulfate	12	12	13	12	--	--	--	13
Chloride	9.0	8.0	7.9	7.5	9.0	7.9	8.1	8.5
Fluoride	.2	.2	.2	.3	--	--	--	.2
Alkalinity	74	68	72	68	--	76	75	--
Total Hardness	87	79	88	84	--	83	88	100
Noncarbonate Hardness	13	11	16	16	--	7	--	--
Dissolved Solids--Residue	122	115	127	126	--	--	--	--
Dissolved Solids--Calculated Sum	110	100	110	100	--	--	--	--
Biochemical Oxygen Demand (5 Day)	--	.4	.3	1.2	--	.6	.7	.4
Specific Conductance (umhos at 25°C)	200	180	190	189	205	205	189	350
Inorganic Carbon	--	14	14	13	20	20	19	20
Total Organic Carbon	--	6	6	8	4	10	7	3
Total Carbon	--	20	20	21	24	30	26	23
Ammonia--NH_4 as N	--	.03	.02	.02	.05	.02	.03	.04
Nitrogen, Total Organic as N	--	.24	.29	.39	.48	.15	.35	.07
Nitrate--NO_3 as N	.03	.01	.08	.05	.06	.00	.03	.10
Nitrite--NO_2 as N	.00	.00	.00	.01	.00	.00	.00	.01
Phosphorus, Ortho as P	--	.02	.02	.02	.01	.02	.01	.02
Phosphorus, Total as P	--	.02	.02	.02	.06	.02	.02	.02

Table 10.--Analyses of water at Kini Spring.--Continued

*Arsenic--Dissolved	--	--	--	--	--	7	0	0
*Cadmium--Dissolved	--	0	0	--	--	--	--	--
*Chromium--Dissolved Hexavalent	--	0	0	0	--	--	--	0
*Chromium--Dissolved	--	--	--	--	--	--	--	--
*Cobalt--Dissolved	--	--	--	--	--	--	--	--
*Copper--Dissolved	--	0	0	--	--	1	1	1
*Iron--Dissolved	--	80	50	--	--	50	90	50
*Lead--Dissolved	--	0	1	--	--	5	7	0
*Lithium--Dissolved	--	--	--	--	--	--	--	--
*Manganese--Dissolved	--	0	10	--	--	14	20	0
*Strontium--Dissolved	--	180	130	100	--	--	--	--
*Zinc--Dissolved	--	10	40	--	--	8	9	3
*Aluminum--Total Recoverable	--	--	--	220	--	--	--	--
*Arsenic--Total Recoverable	--	10	8	14	--	--	--	--
*Cadmium--Total Recoverable	--	--	--	1	--	--	0	0
*Chromium--Total Recoverable	--	--	--	10	--	--	--	--
*Cobalt--Total Recoverable	--	--	--	0	--	--	--	--
*Copper--Total Recoverable	--	--	--	20	--	--	--	--
*Iron--Total Recoverable	--	--	--	160	--	--	--	--
*Lead--Total Recoverable	--	--	--	4	--	--	--	--
*Lithium--Total Recoverable	--	--	--	0	--	--	--	--
*Manganese--Total Recoverable	--	--	--	10	--	--	--	--
*Mercury--Total Recoverable	--	.0	.0	.2	--	--	.0	.0
*Nickel--Total Recoverable	--	--	--	4	--	--	--	--
*Zinc--Total Recoverable	--	--	--	8	--	--	--	--

Table 11.--Analyses of water at Wakulla Spring.

(Concentrations are in milligrams per litre except for constituents indicated by * which are in micrograms per litre.)

Date of Collection	03-21-72	01-21-73	04-25-73	06-27-73	09-27-73	12-21-73	04-04-74	06-26-74
Color (units)	--	10	20	10	--	--	--	--
Turbidity (JTU)	1	1	4	1	2	--	--	--
Silica	10	11	8.2	10	10	--	--	--
Calcium	39	38	38	37	38	32	37	39
Magnesium	8.7	8.6	7.6	8.4	8.8	12	8.9	9.6
Sodium	3.7	4.1	4.3	4.2	3.9	4.0	4.5	3.7
Potassium	.3	.6	.6	1.2	.5	.6	.8	.5
pH (units)	7.3	7.9	8.0	7.8	7.6	8.1	8.0	--
Bicarbonate	150	150	140	150	--	143	143	--
Carbonate	0	0	0	0	--	0	0	--
Sulfate	17	11	10	9.2	--	--	--	9.9
Chloride	3.4	8.0	7.0	6.0	5.0	4.0	6.5	5.9
Fluoride	.3	.3	.3	.3	--	--	--	.3
Alkalinity	130	120	120	120	--	117	117	--
Total Hardness	130	130	130	130	--	130	130	140
Noncarbonate Hardness	8	9	15	9	--	12	--	--
Dissolved Solids--Residue	162	154	161	159	--	--	--	178
Dissolved Solids--Calculated Sum	160	160	140	150	--	--	--	--
Biochemical Oxygen Demand (5 Day)	.4	.2	.2	1.8	--	.5	.2	.5
Specific Conductance (umhos at 25°C)	279	260	255	265	270	270	269	340
Inorganic Carbon	--	22	14	19	31	27	30	29
Total Organic Carbon	--	5	6	9	1	10	0	3
Total Carbon	--	27	20	28	32	37	30	32
Ammonia--NH_4 as N	.00	.02	.01	.01	.00	.02	.04	.03
Nitrogen, Total Organic as N	.14	.40	.55	.26	.46	.38	.06	.00
Nitrate--NO_3 as N	.25	.23	.10	.25	.22	.21	.23	.31
Nitrite--NO_2 as N	.00	.00	.00	.01	.00	.00	.00	.01
Phosphorus, Ortho as P	.03	.04	.05	.06	.05	.04	.05	.06
Phosphorus, Total as P	.04	.05	.07	.08	.06	.05	.05	.07

Table 11.--Analyses of water at Wakulla Spring.--Continued

*Arsenic--Dissolved	--	--	--	--	--	--	--	--
*Cadmium--Dissolved	0	0	0	--	--	--	--	--
*Chromium--Dissolved Hexavalent	0	0	0	0	--	--	--	0
*Chromium--Dissolved	--	--	--	--	--	--	--	--
*Cobalt--Dissolved	--	--	--	--	--	--	--	--
*Copper--Dissolved	--	0	0	--	--	1	1	0
*Iron--Dissolved	30	0	30	--	--	0	60	0
*Lead--Dissolved	2	1	1	--	--	25	11	0
*Lithium--Dissolved	--	--	--	--	--	--	--	--
*Manganese--Dissolved	10	0	10	--	--	14	10	0
*Strontium--Dissolved	110	150	120	100	--	--	--	--
*Zinc--Dissolved	--	10	20	--	--	20	5	0
*Aluminum--Total Recoverable	--	--	--	110	--	--	--	--
*Arsenic--Total Recoverable	0	0	6	5	--	--	--	--
*Cadmium--Total Recoverable	--	--	--	2	--	--	0	10
*Chromium--Total Recoverable	--	--	--	2	--	--	--	--
*Cobalt--Total Recoverable	0	--	--	0	--	--	--	--
*Copper--Total Recoverable	--	--	--	2	--	--	--	--
*Iron--Total Recoverable	--	--	--	5	--	--	--	--
*Lead--Total Recoverable	--	--	--	3	--	--	--	--
*Lithium--Total Recoverable	--	--	--	0	--	--	--	--
*Manganese--Total Recoverable	--	--	--	0	--	--	--	--
*Mercury--Total Recoverable	.0	.0	.0	.0	--	.0	.0	.0
*Nickel--Total Recoverable	--	--	--	5	--	--	--	--
*Zinc--Total Recoverable	20	--	--	10	--	--	--	--

Table 12.--Analyses of water at River Sink Spring.

(Concentrations are in milligrams per litre except for constituents indicated by * which are in micrograms per litre.)

Date of Collection	03-21-72	01-21-73	04-25-73	06-27-73	09-27-73	12-21-73	04-04-74	06-26-74
Color (units)	50	60	30	100	--	--	--	--
Turbidity (JTU)	--	2	1	2	2	--	--	--
Silica	6.1	7.2	5.7	7.0	6.7	--	--	--
Calcium	25	23	26	25	27	23	25	30
Magnesium	5.8	5.1	5.6	5.3	6.3	8.0	5.5	7.2
Sodium	4.8	4.5	4.6	4.7	5.0	5.0	5.3	5.1
Potassium	.6	.4	.4	.5	.4	.7	.9	.4
pH (units)	7.4	7.4	7.5	7.5	7.2	7.6	7.7	--
Bicarbonate	90	83	88	90	--	94	89	--
Carbonate	0	0	0	0	--	0	0	--
Sulfate	12	12	11	12	--	--	--	13
Chloride	8.0	8.0	7.7	6.0	9.0	7.9	7.8	8.7
Fluoride	.2	.2	.3	.3	--	--	--	.2
Alkalinity	74	68	72	74	--	77	73	--
Total Hardness	87	79	88	84	--	90	85	100
Noncarbonate Hardness	13	11	16	10	--	12	--	--
Dissolved Solids--Residue	121	129	123	132	--	--	--	146
Dissolved Solids--Calculated Sum	110	100	100	110	--	--	--	--
Biochemical Oxygen Demand (5 Day)	--	.5	.3	.7	--	.9	--	.8
Specific Conductance (umhos at 25°C)	195	180	189	188	205	207	193	350
Inorganic Carbon	--	14	15	13	20	20	18	20
Total Organic Carbon	--	6	4	10	2	8	7	5
Total Carbon	--	20	19	23	22	28	25	25
Ammonia--NH_4 as N	--	.03	.02	.01	.02	.02	.01	.02
Nitrogen, Total Organic as N	--	.52	.28	.24	.32	.19	.81	.03
Nitrate--NO_3 as N	.04	.03	.06	.07	.05	.03	.04	.10
Nitrite--NO_2 as N	.00	.00	.00	.01	.01	.00	.00	.01
Phosphorus, Ortho as P	--	.01	.01	.02	.01	.02	.02	.02
Phosphorus, Total as P	--	.01	.02	.04	.24	.03	.02	.05

Table 12.--Analyses of water at River Sink Spring.--Continued.

*Arsenic--Dissolved	--	--	--	--	--	--	--	--
*Cadmium--Dissolved	--	0	0	--	--	--	--	--
*Chromium--Dissolved Hexavalent	--	0	0	0	--	--	--	0
*Chromium--Dissolved	--	--	--	--	--	--	--	--
*Cobalt--Dissolved	--	--	--	--	--	--	--	--
*Copper--Dissolved	--	0	0	--	--	1	2	1
*Iron--Dissolved	--	80	60	--	--	0	100	190
*Lead--Dissolved	--	0	1	--	--	8	8	0
*Lithium--Dissolved	--	--	--	--	--	--	--	--
*Manganese--Dissolved	--	10	10	--	--	14	10	17
*Strontium--Dissolved	--	60	140	100	--	--	--	--
*Zinc--Dissolved	--	40	0	--	--	0	40	0
*Aluminum--Total Recoverable	--	--	--	220	--	--	--	--
*Arsenic--Total Recoverable	--	10	8	13	--	--	--	--
*Cadmium--Total Recoverable	--	--	--	1	--	--	0	1
*Chromium--Total Recoverable	--	--	--	0	--	--	--	--
*Cobalt--Total Recoverable	--	--	--	0	--	--	--	--
*Copper--Total Recoverable	--	--	--	10	--	--	--	--
*Iron--Total Recoverable	--	--	--	140	--	--	--	--
*Lead--Total Recoverable	--	--	--	2	--	--	--	--
*Lithium--Total Recoverable	--	--	--	0	--	--	--	--
*Manganese--Total Recoverable	--	--	--	10	--	--	--	--
*Mercury--Total Recoverable	--	.0	.0	.1	--	--	.1	.1
*Nickel--Total Recoverable	--	--	--	4	--	--	--	--
*Zinc--Total Recoverable	--	--	--	10	--	--	--	--

Table 13.--Chemical analyses of water from well 23.

Date	(ft) Depth	(°Celsius) Temp.	(umhos) Specific Conductance	Chloride	(milligrams per litr NH$_4$-N	NO$_2$-N	NO
06-13-74	42	- -	235	38	0.01	0.01	20
06-14-74	65	- -	150	14	.03	.01	4
06-14-74	75	- -	148	16	.06	.01	3
06-14-74	85	- -	210	26	.02	.01	9
06-14-74	95	23.5	188	22	.01	.01	8
06-14-74	105	22.0	210	27	.04	.01	10
06-14-74	115	22.0	215	27	.02	.01	11
06-14-74	125	22.0	220	30	.02	.01	12
06-14-74	135	22.5	230	30	.06	.01	12
06-14-74	137	- -	210	22	.12	.10	-
06-15-74	150	22.5	390	51	.08	.09	20
06-16-74	165	22.0	360	39	.06	.01	19
06-17-74	185	21.5	420	46	.84	.43	32
06-17-74	187	22.0	- -	- -	- -	- -	-
06-17-74	190	22.5	370	44	.12	.07	2[illegible]
06-17-74	200	22.0	420	46	.49	.49	21
06-18-74	215	22.0	350	44	2.6	1.7	1[illegible]
06-18-74	220	22.0	400	45	.61	.74	2[illegible]
06-19-74	240	- -	450	47	.14	.11	2[illegible]
06-20-74	250	- -	470	48	.16	.06	2[illegible]
06-20-74	260	- -	470	48	.26	.11	2[illegible]
06-20-74	270	- -	470	50	.24	.27	2[illegible]

200 mm) of effluent per week. On the same basis there was a reduction of approximately 5 mg/l of the total nitrogen from the effluent that had been applied at a rate of 14 in (350 mm) per week to the undisturbed forest (the 4-Big-Gun Area). This effluent-percolate appeared at shallow depths 1,800 ft downgradient. However, it was not possible to define the vertical extent of the effluent plume. Nitrification occurred in both the irrigation fields and the undisturbed forest. The NH_4-N, the most abundant form of nitrogen in the effluent, was almost completely converted to NO_3-N before dilution by the underlying ground water.

As a result of the application of about 140 ft (43 m) of effluent to the forest area from March 1972 to June 1974, chloride and nitrogen concentrations equivalent to undiluted effluent were found from depths of 150 to 270 ft (46 to 82 m) in ground water at the downgradient edge of this heavily-sprayed area. Chloride concentrations indicated a mixing ratio of effluent to native ground water of 1 to 4 at a depth of 248 ft (75 m) at the downgradient edge of the irrigation fields.

Effluent-percolate has moved from the plant at about 2,400 ft (730 m) per year. It took the effluent 3/4 year to reach a well about 1,800 ft (550 m) downgradient of the heavily-sprayed area, and less than 2 years for the effluent to mix with ground water in a ratio of 1 to 4 at the same well. No changes in the quality of the ground water were observed beyond that point. As of June 1974, the water in about 140 acres (570,000 m^2) of the underlying aquifer had increased NO_3-N and chloride concentrations.

Of prime importance in the continuation of this study of the environmental effects of spray irrigation of effluent on the ground-water system is the establishment of a comprehensive well network to define the three-dimensional extent of the plume.

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BASIC DATA

A. Chemical data for water-supply wells.

Well (see fig. 3)	Date	Chloride* (Cl)	pH (units)	Specific conductance (umhos/cm)	Bicarbonate* (HCO_3)
A**	09-19-72	7.5	7.4	335	200
B**	09-18-72	5.0	7.6	220	130
C**	09-18-72	4.0	7.6	240	150
D**	09-23-72	3.5	8.1	160	80
E**	09-23-72	5.0	7.8	255	150
F	09-23-72	4.5	8.0	240	140
G	09-21-72	5.0	8.2	130	70
H	03-15-73	4.0	8.3	160	104
I	03-15-73	5.0	8.0	140	80
J	03-15-73	5.0	8.0	140	87
K	03-15-73	5.0	8.0	175	60
L	03-15-73	5.0	8.0	170	96
M	03-15-72	2.0	7.8	115	70
N	09-20-72	3.0	8.2	158	88

* Milligrams per litre.
** Wells upgradient from area of applied sewage effluent.

B. Lithologic logs and natural gamma logs of selected wells.

Well 1

Depth (ft)	Description
1	SAND, brown, fine to medium
3	SAND, light brown, fine to medium
18	SAND, light brown, fine to medium
28	SAND, yellow-brown, fine
30	CLAY, SANDY, orange-brown, fine; with black organic matter
34	CLAY, SANDY, orange-brown, fine; with fragments of limestone
38	do
43	LIMESTONE, white, fine
52	do

Well 2

Depth (ft)	Description
6	SAND, light brown, medium to coarse
12	SAND, light brown, fine to coarse
19	do
25	do
30	SAND, very light brown, fine to medium
36	do
44	SAND, brown, fine to coarse
49	do
50	SAND, almost black, fine to medium
51	LIMESTONE, white, fine
52	SAND, black, fine to medium

Well 3

Depth (ft)	Description
0	SAND, light brown, fine to medium
3	SAND, light brown, slightly orange, fine to medium
8	do
24	SAND, orange-brown, fine to coarse
30	SAND, light brown, fine to coarse
39	SAND, white, fine to coarse
50	do
56	do
70	SAND, light brown, fine to medium
76	do
82	SAND, CLAYEY, orange-brown, fine to coarse
85	do
90	SAND, calcareous, brown, fine to coarse, with white limestone particles
91	SAND, calcareous, white-brown, fine to coarse
95	SAND, calcareous, white-brown, fine to coarse
100	CLAY, SANDY, calcareous, white-brown, fine to coarse

Well 4

Depth (ft)	Description
4	SAND, light brown, fine to medium
20	SAND, tan, fine to medium
30	CLAY, SANDY, brown, fine
41	SAND, calcareous, light brown, fine
52	SAND, calcareous, light brown, fine to coarse

Well 5

Depth (ft)	Description
3	SAND, gray-pink, fine to medium
9	SAND, light orange, fine to medium
12	SAND, pale orange, fine to medium
15	do
22	SAND, dark yellow-orange, fine to medium
27	CLAY, SANDY, calcareous, with reddish brown layers
30	SAND, calcareous, dark yellow-orange, fine to medium
33	SAND, gray, fine
42	LIMESTONE, powdery
43	LIMESTONE, hard

Well 7

Depth (ft)	Description
0	SAND, light tan, fine, medium, and coarse
10	SAND, light tan, very fine and fine to coarse
20	do
22	do
25	do
28	CLAY, SANDY, very fine with limestone particles
30	CLAY, SANDY, very fine and LIMESTONE, white, fine
33	LIMESTONE, white, fine

Well 8

Depth (ft)	Description
9	SAND, light reddish-orange, very fine and fine to coarse
14	SAND, light reddish-orange, very fine and fine to medium
15	CLAY, SANDY, gray, very fine and fine to medium
25	CLAY, SANDY, red, brown, and white streaks, very fine
29	CLAY, SANDY, brown, very fine
33	LIMESTONE
35	do
49	do

Well 9

Depth (ft)	Description
10	SAND, white and tan, very fine and fine to coarse, with fossils
12	do
15	SAND, brownish-orange, very fine to coarse
19	CLAY, SANDY, brown, very fine to coarse
20	SAND, light yellow, very fine to coarse
22	SAND, CLAYEY, yellow-brown, very fine to fine
27	CLAY, SANDY, purple, white, and orange-brown streaks
32	SAND, CLAYEY, orange-brown, very fine, formed balls with white limestone particles
35	LIMESTONE

Well 10

Depth (ft)	Description
1	SAND, brown-gray, very fine to coarse
4	SAND, light brown, fine to medium
5	SAND, light brown, fine to medium
14	SAND, orange-brown, fine to medium
24	SAND, light brown, fine to medium
34	CLAY, SANDY, white, gray, and black; very fine
42	LIMESTONE

Well 11

Depth (ft)	Description
2	SAND, dark brown, fine to medium
7	do
12	SAND, orange-brown, fine to medium
17	SAND, mixed shades of brown, fine to coarse
22	SAND, red-brown, fine to coarse
27	SAND, CLAYEY, red-brown, fine to medium
37	SAND, light brown, fine to medium, with fragments of limestone
40	LIMESTONE

Well 12

Depth (ft)	Description
2	SAND, brown, fine to medium
12	SAND, light brown, fine to medium
17	do
22	do
27	SAND, yellow-brown, fine
32	SAND, calcareous, brown and red, with blue clay layers
37	SAND, calcareous, dark brown, fine to medium
42	SAND, calcareous, light brown, fine to medium
47	CLAY, SANDY, with LIMESTONE streaks

Well 13

Depth (ft)	Description
2	SAND, calcareous, dark brown, fine to coarse
7	SAND, light brown, fine to coarse
12	SAND, calcareous, brown, fine to medium
17	do
20	SAND, calcareous, white, fine; and LIMESTONE
22	SAND, orange-brown, fine to medium
27	do
30	LIMESTONE, thin (2") layer
32	SAND, calcareous, orange-brown, fine

Well 14

Depth (ft)	Description
2	SAND, dark brown, fine to medium
6	SAND, light brown, fine to medium
12	SAND, tan, fine to medium
14	do
17	do
22	SAND, light brown, fine to medium
25	CLAY, SANDY, red-brown layers
27	SAND, calcareous, orange-brown, fine to medium
32	do
37	do
42	do
52	LIMESTONE, white

Well 15

Depth (ft)	Description
2	SAND, brown, fine to coarse
7	SAND, orange-brown
12	SAND, darker, partially calcareous
17	do
22	do
27	SAND, more orange, partially calcareous
32	SAND, white, fine grain, calcareous
34	LIMESTONE

Well 16

Depth (ft)	Description
2	SAND, light brown, fine to medium
7	SAND, light brown, fine to coarse
12	SAND, calcareous, grayish orange, fine to coarse
17	do
22	SAND, grayish-orange, fine to medium
27	SAND, yellow-orange, fine to coarse
32	SAND, pale orange, fine to medium
37	SAND, light orange, fine to medium
42	SAND, calcareous, grayish-orange, fine to coarse
47	SAND, calcareous, dark yellow-orange, fine to coarse
52	SAND, calcareous, grayish-orange, fine to coarse
55	SAND, calcareous, dark yellow-orange, fine to medium
57	SAND, calcareous, dark yellow-orange, fine to coarse; limestone specks; saturated zone (water)
62	SAND, calcareous, dark yellow-orange, fine to medium
67	LIMESTONE, SANDY

Well 17

Depth (ft)	Description
17	SAND, yellow-orange; with gravel-size limestone and carbon particles
19	LIMESTONE, gray; with orange sand and carbon and fossil particles
35	SAND, calcareous, gray and pale orange, fine to medium
40	do
50	LIMESTONE, gray, fine to coarse gravel
55	do
61	LIMESTONE, gray and pale orange; with sand and carbon and fossil particles
65	do
73	LIMESTONE, gray and tan, fine to gravel; with turquoise particles of fine gravel to coarse gravel sizes
78	LIMESTONE, gray, fine to coarse gravel
84	LIMESTONE, hard, white; with fossils and sand streaks
90	LIMESTONE, gray, fine to coarse gravel
96	LIMESTONE, hard, white; with fossils and sand streaks
100	LIMESTONE, gray; with orange sand and carbon and fossil particles
105	SAND, calcareous, gray and pale orange, fine to medium
110	do
115	LIMESTONE, gray, fine to coarse gravel
120	SAND, calcareous, gray and pale orange, fine to medium
125	SAND, calcareous, gray, fine to medium
130	do
135	do
140	do
145	LIMESTONE, hard, white; with fossils and sand streaks

Well 18

Depth (ft)	Description
65	SAND, calcareous, orange-tan, very fine to coarse
70	do
75	do
85	do
90	do
95	do
100	SAND, calcareous, tan and white, very fine to medium
105	do
110	SAND, calcareous, tan, very fine to medium; with gravel-size limestone flakes
115	SAND, calcareous, tan and white, very fine to medium
120	SAND, tan, very fine to medium; with fine to medium quartz particles and limestone particles
125	SAND, calcareous, pale orange, tan, very fine
130	do
135	SAND, calcareous, pale orange, fine to gravel
140	do
145	do
150	do
155	do
160	do

Well 19

15	SAND, tan, fine
20	SAND, tan to light brown, fine
25	SAND, calcareous, tan to light brown, fine
30	CLAY, SANDY, calcareous, light brown to tan, fine
35	CLAY, SANDY, calcareous, light brown to tan, fine; with black (carbon) streaks
45	LIMESTONE, gray, powdery; with fine tan sand
55	do
65	LIMESTONE, gray, fine gravel to coarse gravel
70	do
75	do
80	do

Well 21

Depth (ft)	Description
20	SAND, reddish-orange, fine to medium
25	do
30	do
35	do
40	LIMESTONE, gray; with red-orange sand streaks
45	do
50	do
55	do
60	LIMESTONE, gray
65	SAND, calcareous, tan, medium to coarse; with particles of limestone
70	do
75	SAND, calcareous, gray, fine to coarse
80	SAND, calcareous, gray, fine to medium gravel
85-250 (5-ft increments)	do

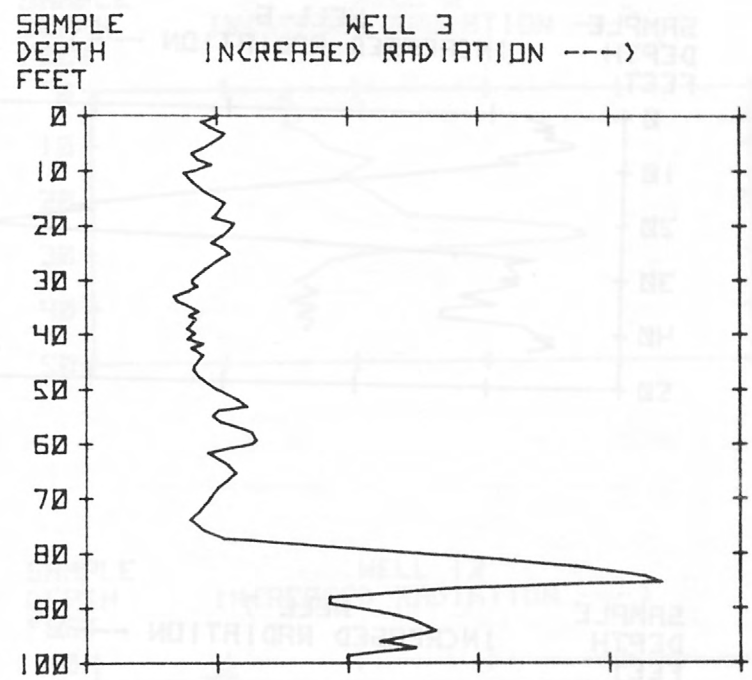
Well 22

20	SAND, calcareous, red-orange, fine to medium
30	do
35	do
40	do
45	SAND, calcareous, red-orange, fine to medium; with fine to medium gravel particles of white limerock with black streaks
75	LIMESTONE, gray-white, fine to coarse gravel
80	SAND, calcareous, tan, very fine to medium
95	SAND, calcareous, tan, fine to fine gravel
120	SAND, calcareous, tan, very fine to medium
165	do
175	do
185	do
200	LIMESTONE, tan and gray, fine to medium gravel
225	do
235	do
240	LIMESTONE, gray and white, fine to coarse gravel
245	SAND, calcareous, tan and gray, fine to coarse gravel; with black fossils
250	do
255	do
260	do

Well 23

Depth (ft)	Description
0	SAND
39	SAND
40	CLAY
50	CLAY
51	SAND
55	SAND
56	CLAY
59	CLAY
60*	LIMESTONE

*Drilling problems precluded certainty in knowing the origin of the well cuttings beyond a depth of 60 feet.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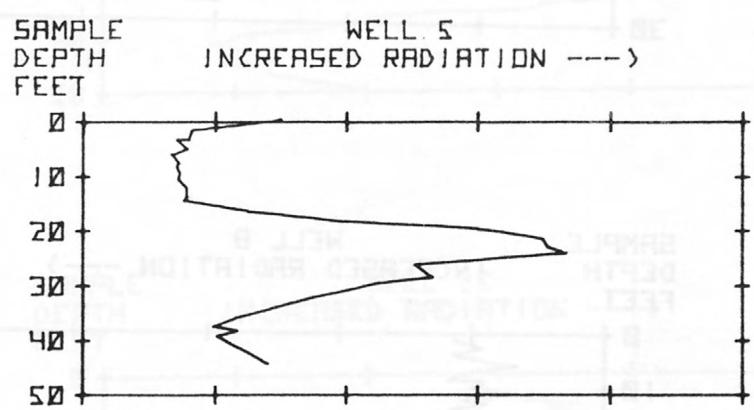
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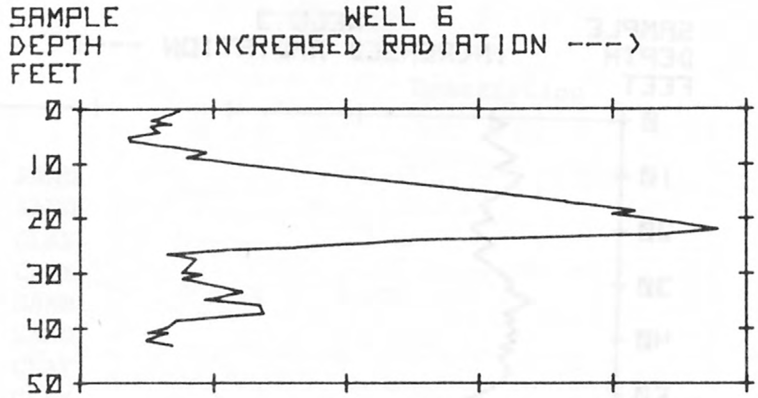
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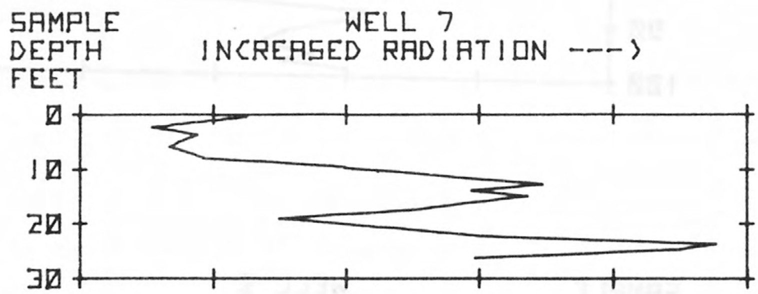
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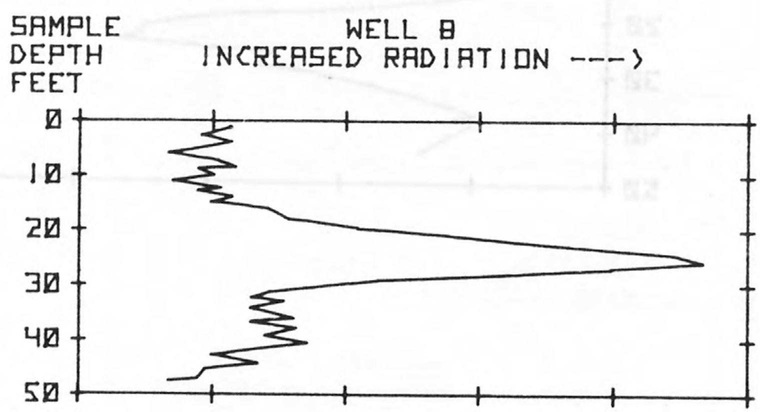
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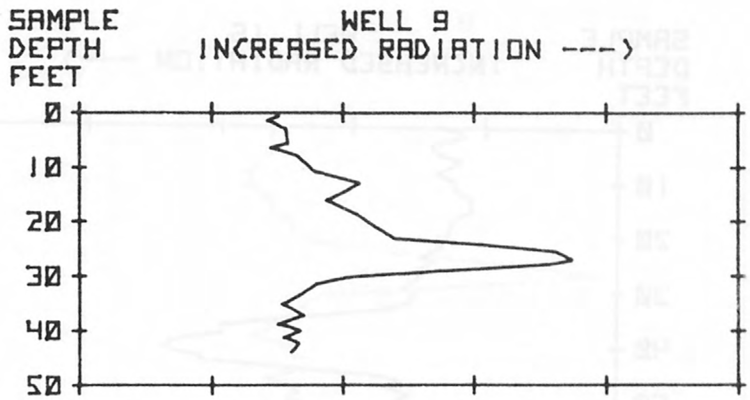
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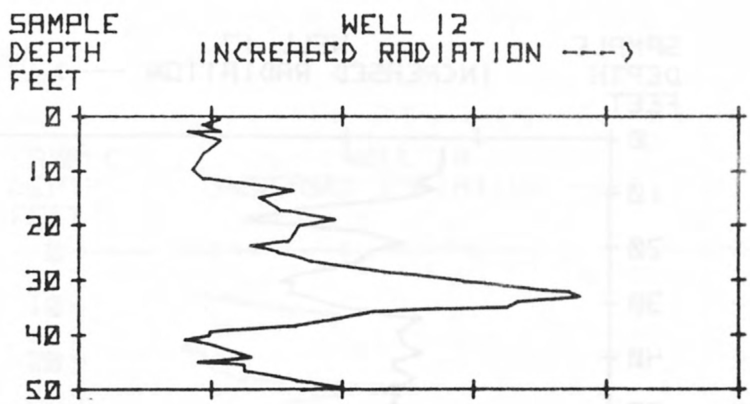
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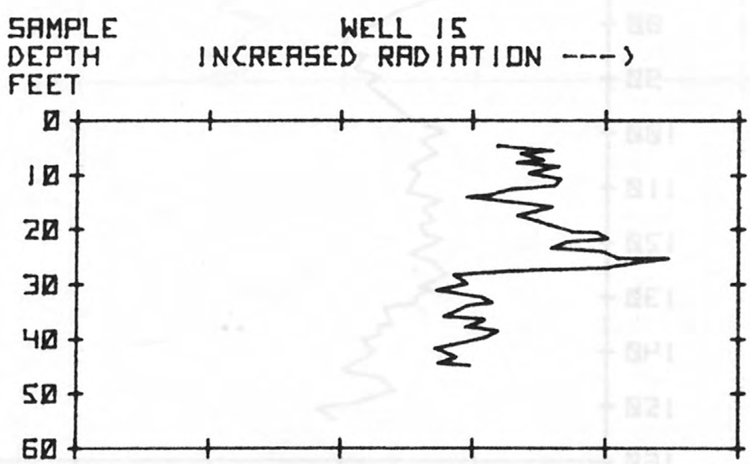
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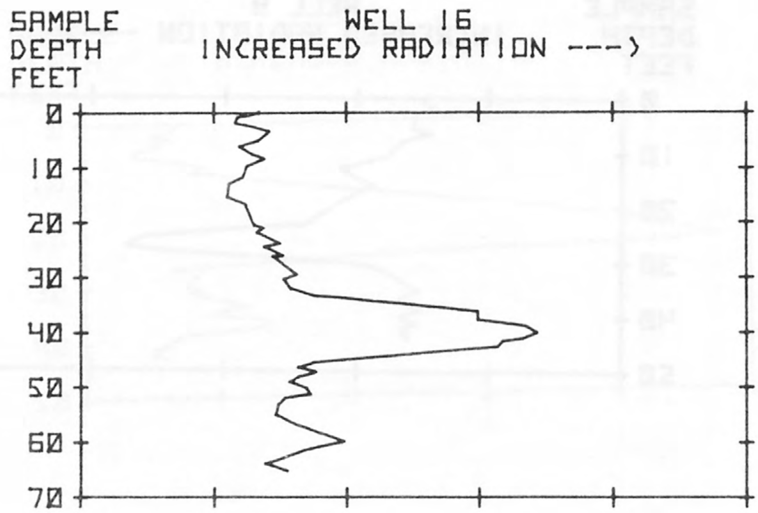
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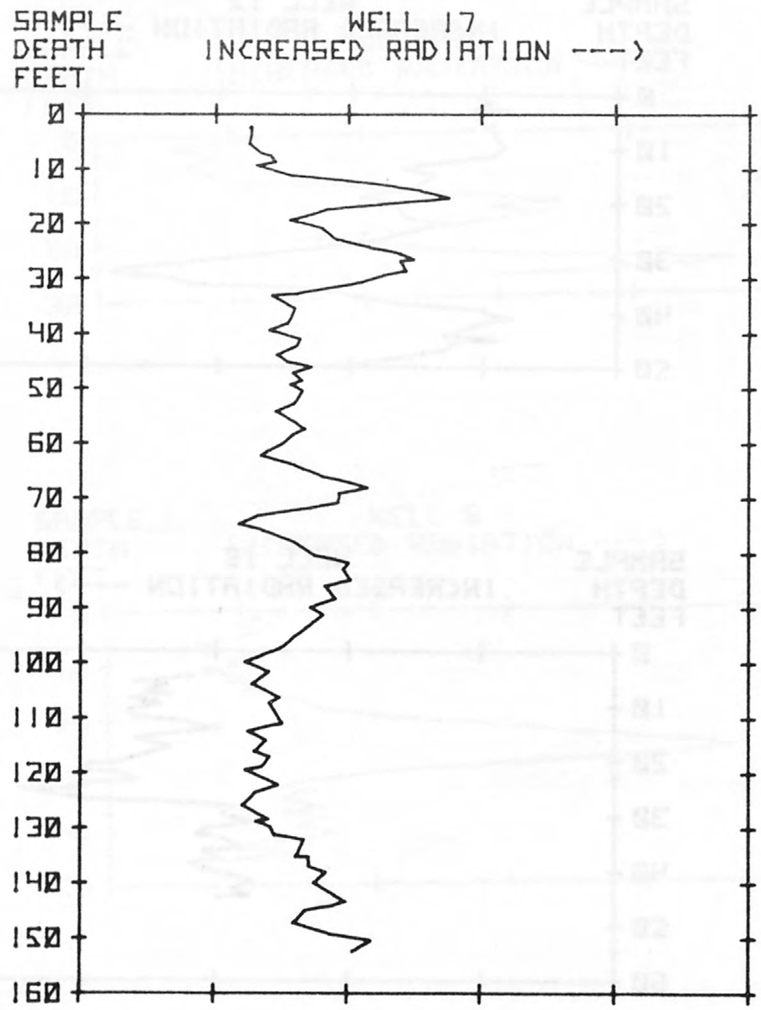
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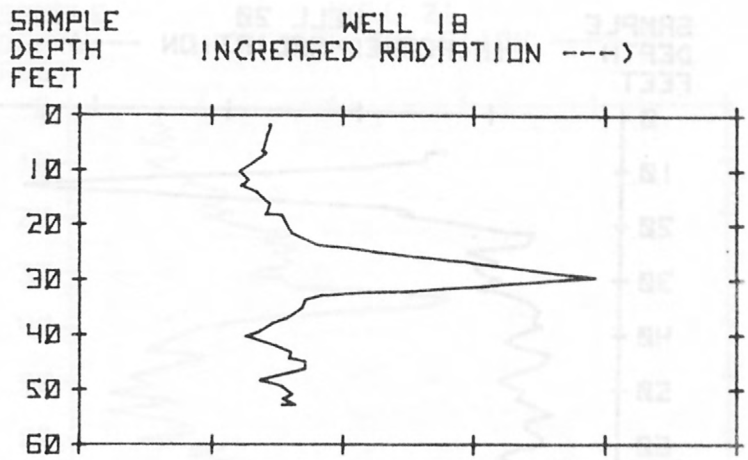
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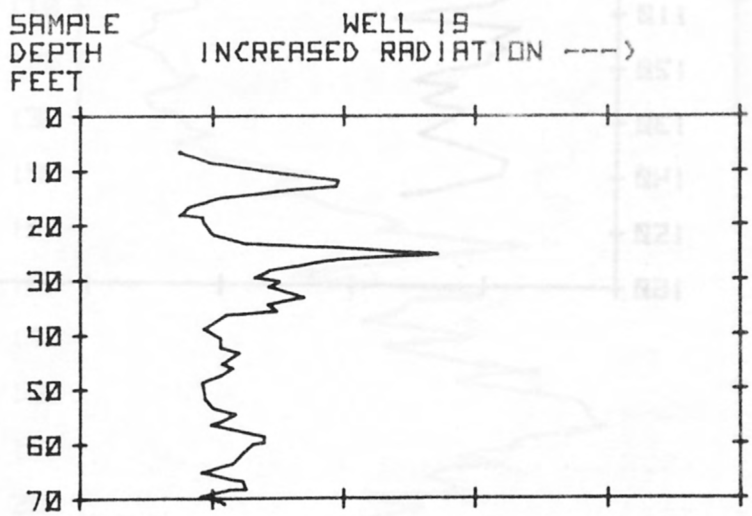
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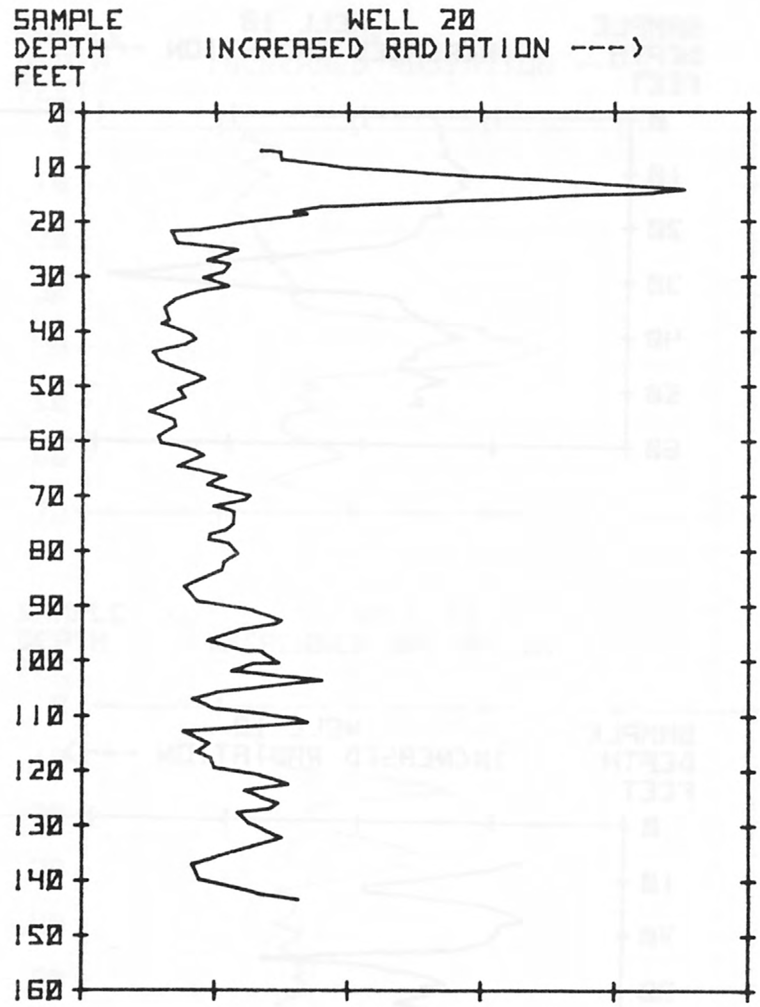
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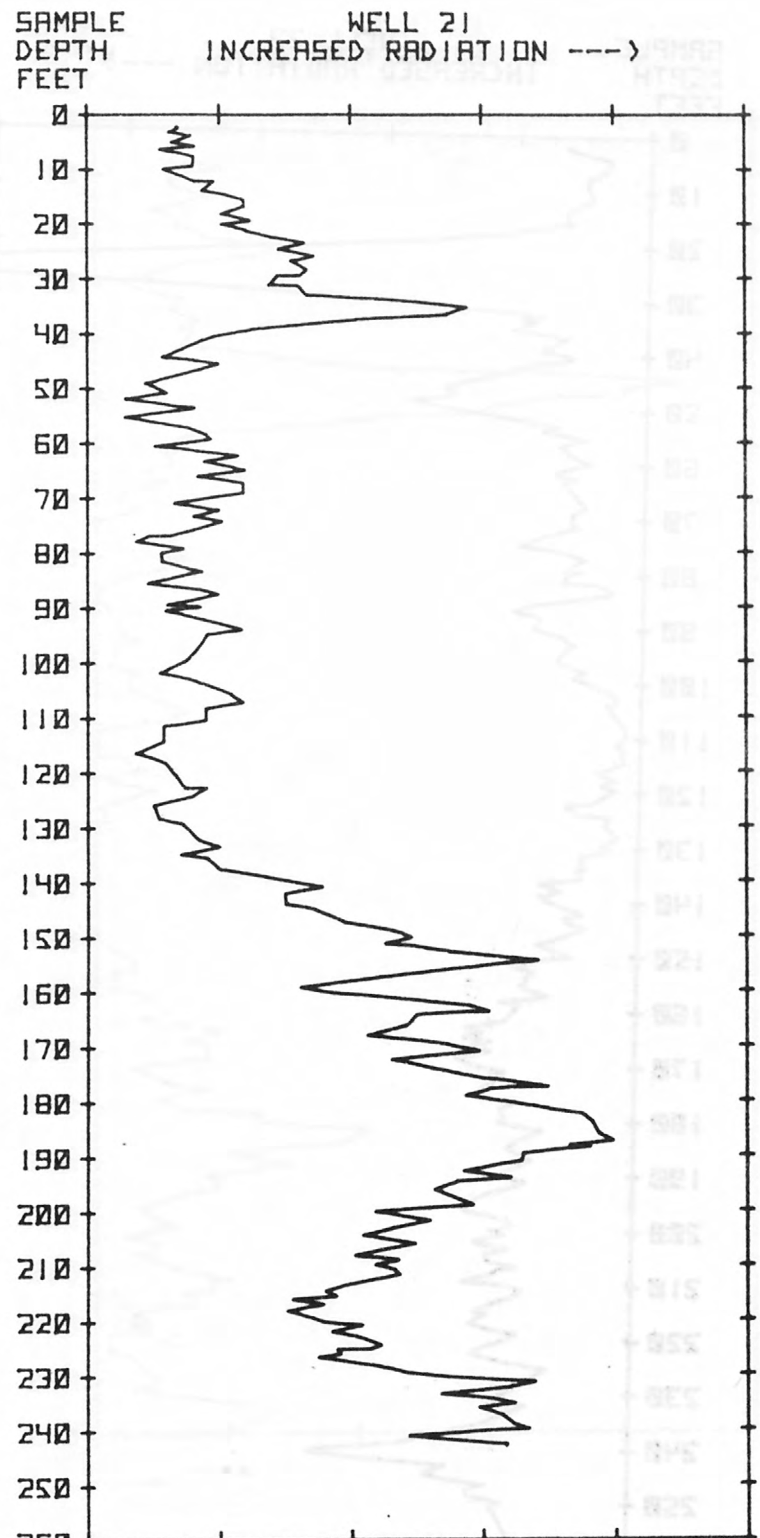
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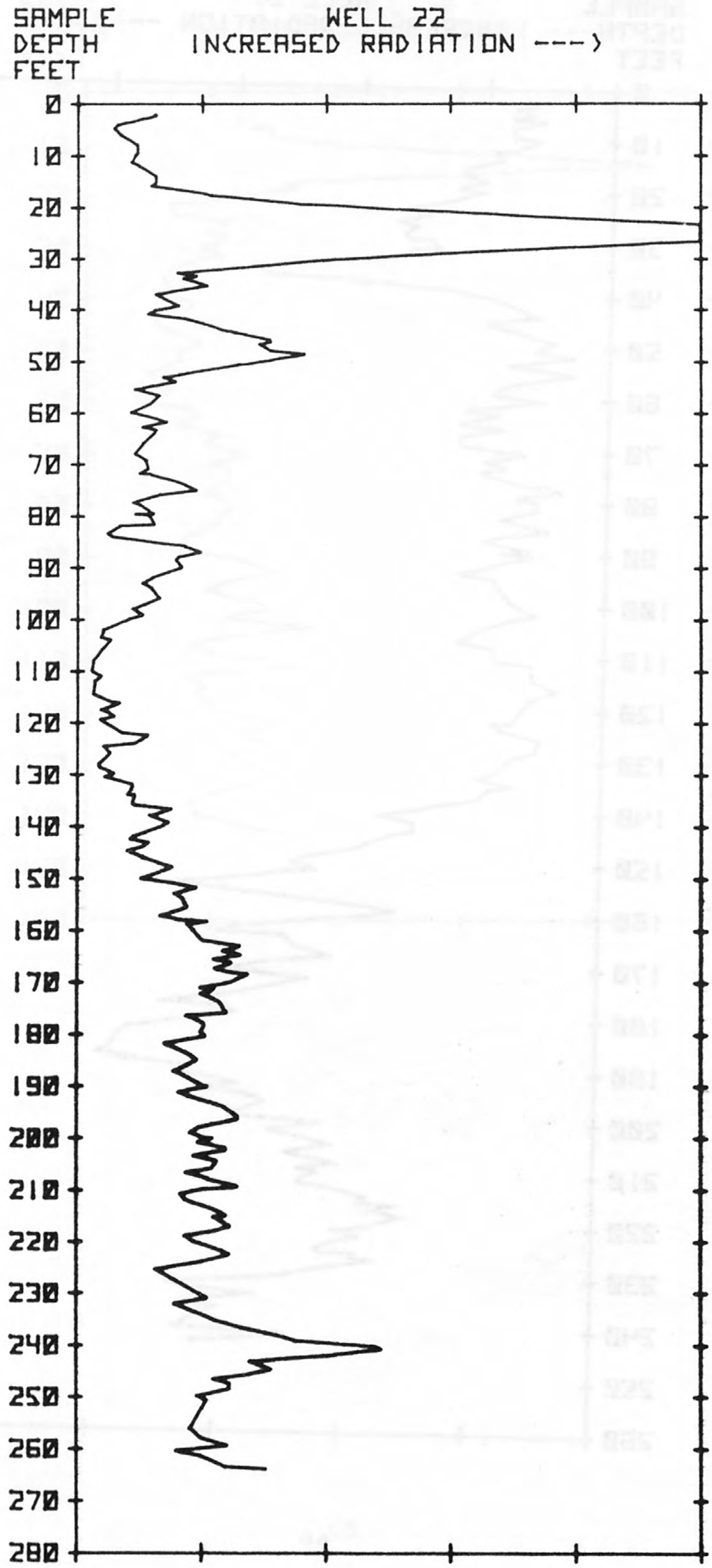
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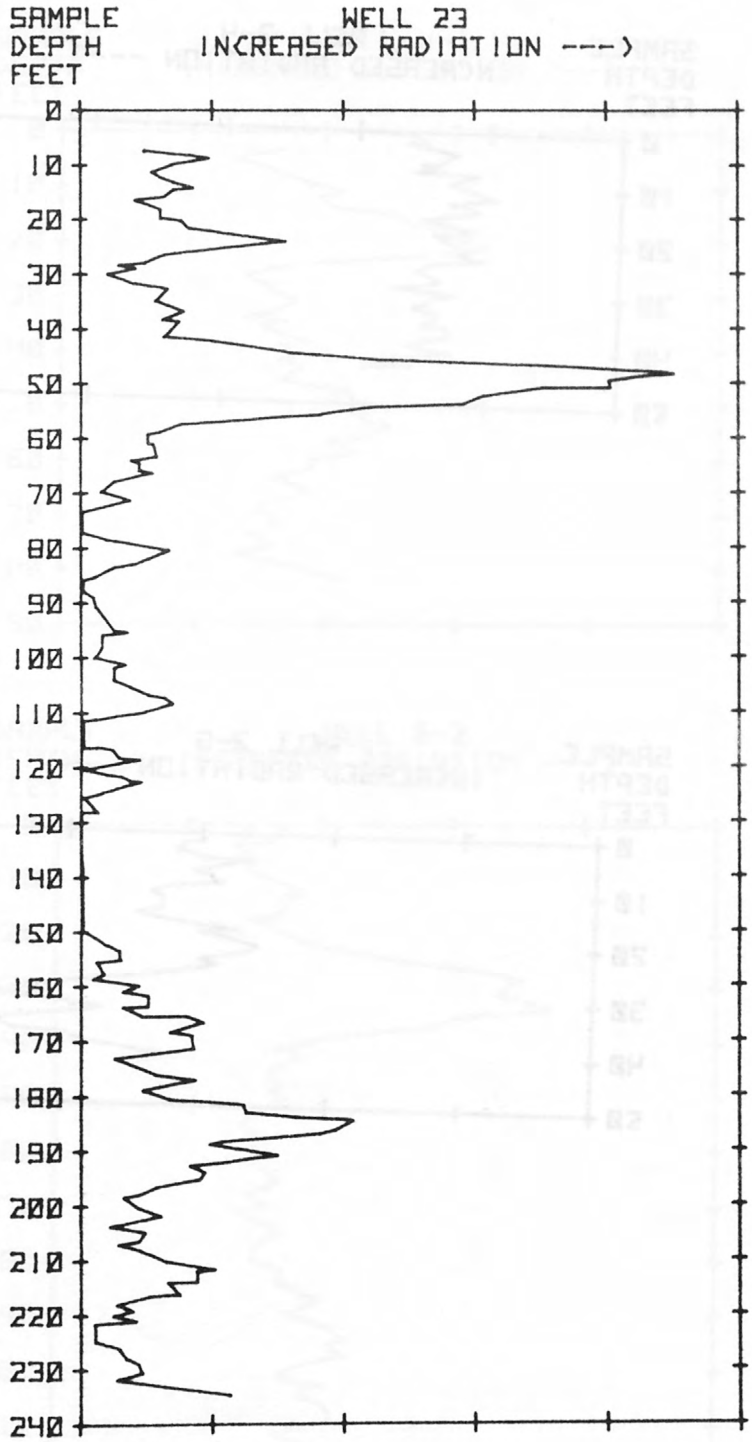

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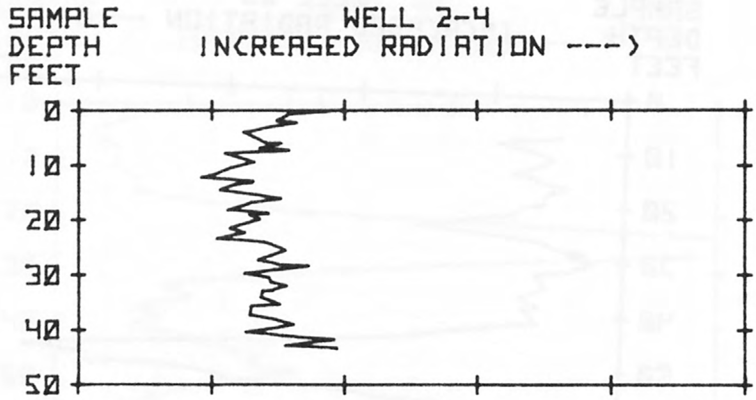
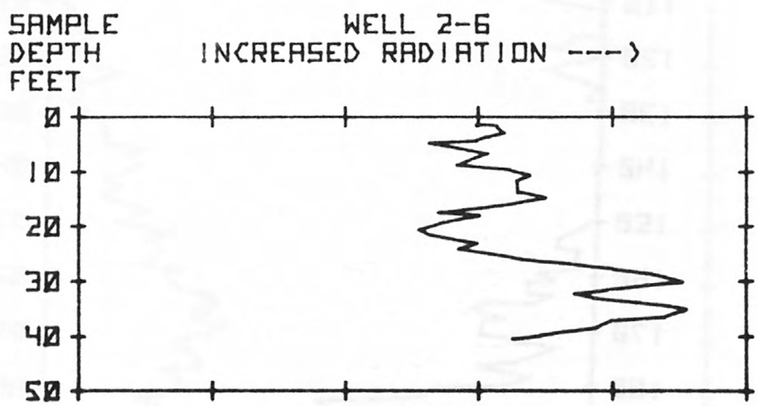
230
240


SAMPLE
DEPTH
FEET
WELL 2-4
INCREASED RADIATION --->
0
10
20
30
40
50


SAMPLE
DEPTH
FEET
WELL 2-6
INCREASED RADIATION --->
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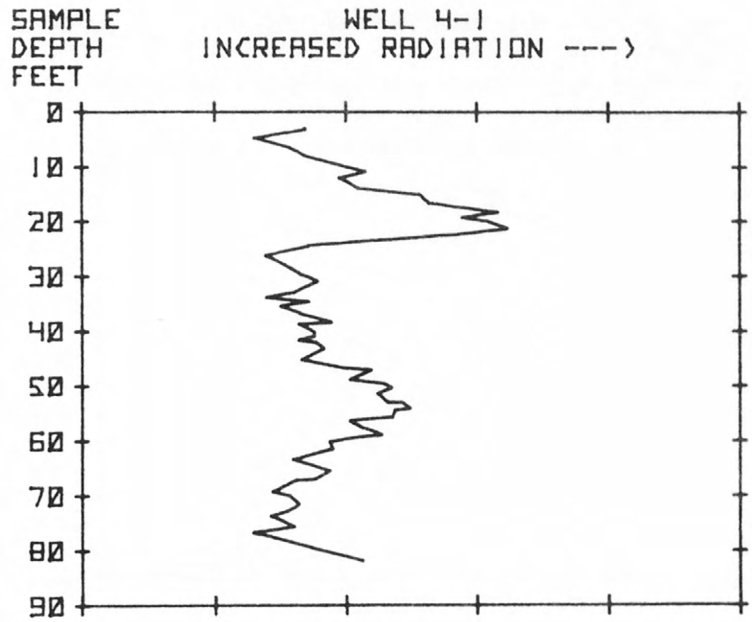
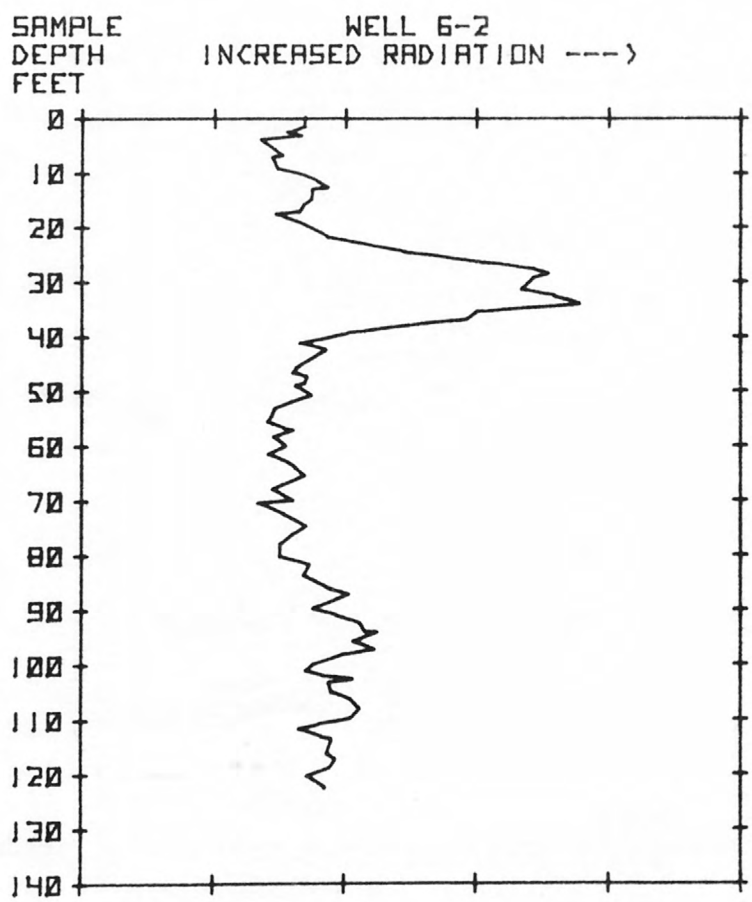
10
20
30
40
50


SAMPLE
DEPTH
FEET
WELL 4-1
INCREASED RADIATION --->
0
10
20
30
40
50
60
70
80
90


SAMPLE
DEPTH
FEET
WELL 6-2
INCREASED RADIATION --->
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140

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