EFFECT OF SPRAY IRRIGATION OF TREATED WASTEWATER ON WATER QUALITY OF THE SURFICIAL AQUIFER SYSTEM, REEDY CREEK IMPROVEMENT DISTRICT, CENTRAL FLORIDA

By Edward R. German

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 88-4174

Prepared in cooperation with the
REEDY CREEK IMPROVEMENT DISTRICT

Tallahassee, Florida
1990

U.S. DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR. Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Suite 3015
227 North Bronough Street
Tallahassee, Florida 32301

Copies of this report
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CONVERSION FACTORS AND ABBREVIATIONS

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

Multiply inch-pound unit	By	To obtain metric unit
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow	
gallon per minute (gal/min)	0.06308	cubic meters per minute (m^3/min)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)
million gallons per month (Mgal/mo)	3.785	cubic meter per month (m3/mo)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
inch per month (in/mo)	25.4	millimeter per month (mm/mo)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Transmissivity	
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

Additional abbreviations

meq/L	milliequivalents per liter
mg/L	milligrams per liter
μS/cm	microsiemens per centimeter at 25 degrees Celsius

Effect of Spray Irrigation of Treated Wastewater on Water Quality of the Surficial Aquifer System, Reedy Creek Improvement District, Central Florida

By Edward R. German

Abtract

Spray irrigation of ornamental plant stock is used to dispose of part of the treated wastes from the Walt Disney World complex. The irrigation quantities for October 1980 through September 1984 were equivalent to about 41 inches of rainfall per year.

A 2.7-million-square-foot area (62 acres) of the spray-irrigation system bounded on three sides by canals or impounded wetlands was selected for study. Objectives were to determine rates and direction of wastewater movement, the effect of the wastewater application on water quality in the underlying aquifer system, assessment of processes associated with the wastewater assimilation, and a determination of hydraulic characteristics of the aquifer system.

During the water-quality, data-collection phase of the study (1983-84), rainfall was near the long-term (1931-80) mean of 52.4 inches. Recharge to the surficial aquifer system, estimated from records of rainfall and water-level changes, averaged about 34 percent of the annual rainfall for a 6-year period.

Vertical movement of water in the study area is hindered by a small downward vertical hydraulic gradient, a relatively low vertical permeability of the surficial aquifer system (compared to horizontal permeability), and a confining unit (the Hawthorn Formation) between the surficial aquifer system and the Floridan aquifer system. Within the studied wastewater application area, most of the rainfall and wastewater not returned to the atmosphere probably moves laterally into surrounding canals, particularly Canal L-410, which received an estimated 0.18 cubic foot per second during the study.

Most of the nitrogen in the water of the surficial aquifer system is in the organic and ammonia forms. A significant part of the nitrogen is apparently being converted to the nitrate form beneath the wastewater application areas where water levels are at least 8 feet below land surface.

Phosphorus concentrations along one end of the study area exceeded that in the wastewater (0.55 milligrams per liter). A sludge-spreading field and a wastewater holding pond are also located beyond that end of the area. However, some of the wells with the highest phosphorus concentrations (1.5 milligrams per liter or greater) had low chloride concentrations, which seems to preclude contribution of the phosphorus from waste disposal operations. The reason for the high phosphorus concentrations is not known.

Analysis of water-quality data from a nest of four wells with sampling depths ranging from 19 to 62 feet indicate that vertical movement of wastewater in the surficial aquifer system is slow or is not occurring. Chloride concentration in the shallower two wells (23 feet or less beneath land surface) was 40 milligrams per liter or greater, and in the deeper wells (39 feet or more) was 6.5 milligrams per liter.

One-dimensional solute transport modeling indicates that equilibrium concentrations for conservative constituents such as chloride are established within about 7 years along Canal L-410. At points farther from the application areas, such as at the impounded wetland boundary about 2,400 feet from the nearest application area, equilibrium concentrations may not be reached for about 140 years.

Background

The Reedy Creek Improvement District, a State chartered organization controlling most of the upper Reedy Creek basin, is an area of about 43 mi^2 (square miles) in southwestern Orange and northwestern Osceola Counties (fig. 1). Construction of the Walt Disney World complex, which includes the Magic Kingdom, EPCOT (Experimental Prototype Community of Tomorrow), and other attractions in the district, has resulted in a rapid change from uninhabited swampland and piney flatwoods to urbanized, recreational, and commercial land. Commensurate with this change has been a need for disposal of wastes generated as a result of operation of the facilities.

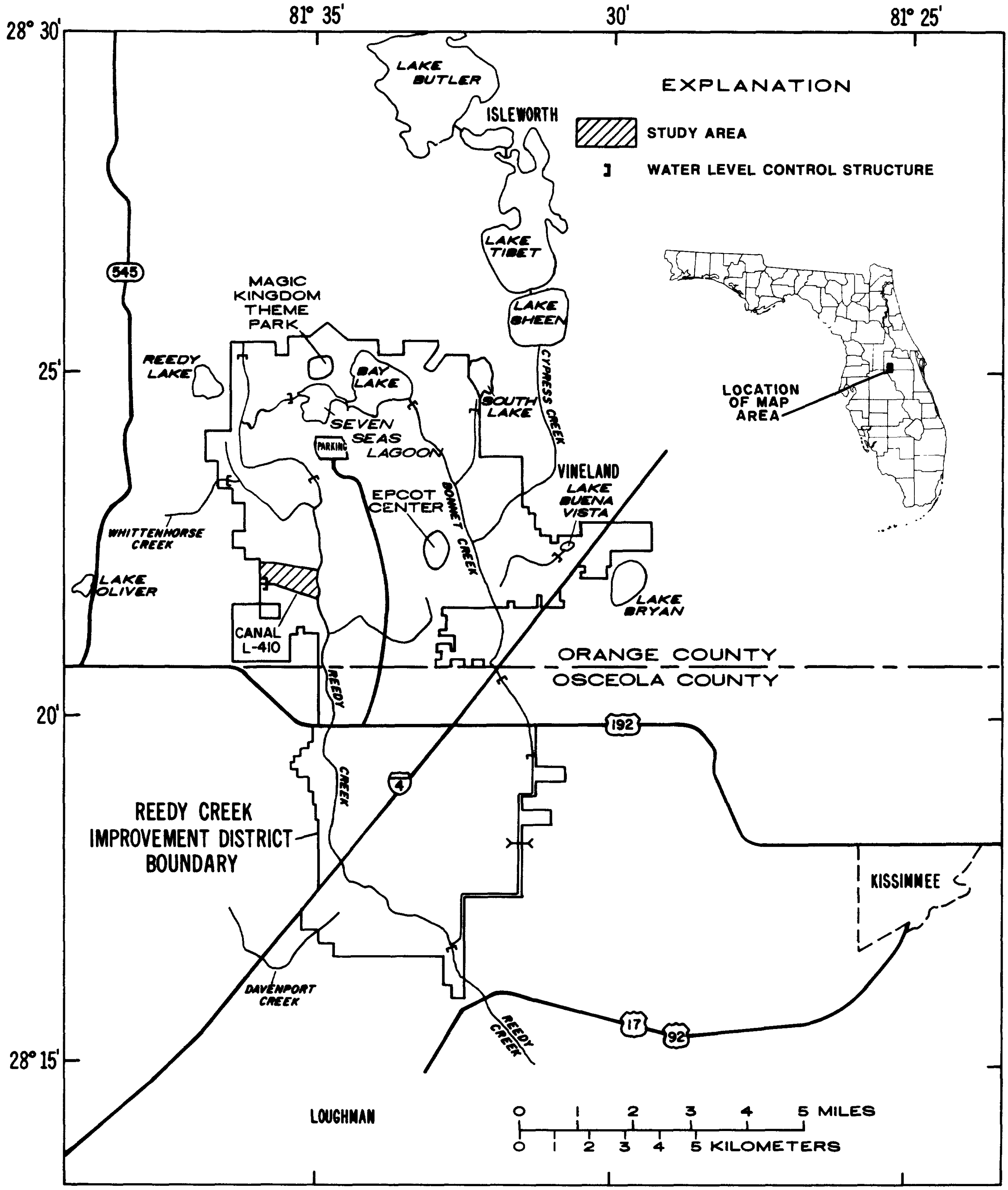


Figure 1. The Reedy Creek Improvement District, and location of the study area.

Purpose and Scope

This report describes results of a study of the hydrology of the Reedy Creek Improvement District tree farm area where treated wastewater is used for irrigation. Included in this report are descriptions of:

- Direction of movement and destination of the wastewater and constituents in the surficial aquifer system underlying the tree farm area.

- Rate of movement of the wastewater front.

- Effect of the wastewater application on water quality of the underlying aquifer and the areal extent of the wastewater plume in the surficial aquifer system.

- The nature of the processes affecting assimilation of the wastewater-related constituents in the ground-water system.

- Hydraulic characteristics of the surficial aquifer system.

The area studied includes the entire tree farm area located to the north of Canal L-410 (fig. 2). A similar area south of the canal was not included in the study so that the study resources could be concentrated to provide better sampling coverage. The areas north and south of L-410 are assumed to be hydrologically identical, so both systems should react in the same way to the wastewater application, and conclusions related to wastewater movement and assimilation in the study area (north of the canal) will also be valid for the unstudied area.

This investigation was conducted from October 1981 through September 1985. The work included installation of a monitoring well network in the surficial aquifer system, determination of lithology of the aquifer material, determination of transmissivity of the surficial aquifer system and sampling of the well network to characterize water quality of the surficial aquifer system underlying the tree farm and the surrounding area. The water-quality sampling was done four times between May 1983 and October 1984.

Method of Study

A network of surficial aquifer wells was constructed for the purposes of measuring water levels and sampling for water quality. Well locations and site numbers are shown in figure 2, and well depths and water levels are given in table 1. Two wells were constructed at most of the sites—a shallow well cased about 3 feet into the water table, and a deeper well cased to a depth of about 18 to 25 feet, followed by a 3-foot screened interval. The well and screen were 2-inch PVC (polyvinylchloride). The screen slot width was 0.015 inch. Well numbers used throughout this report are the site numbers followed with "S" to indicate the shallower (near water table) well and "D" to indicate the deeper well. Wells 4-D, 8-D, 10- D, and 17-D are deeper than 25 feet because these holes were used to determine the lithology of the surficial aquifer system underlying the study area; samples of aquifer material were taken every 5 feet. Two additional wells (14-42 and 14-62), cased to 42 feet and 62 feet, respectively, were constructed at the site of 14-S and 14-D to determine water quality at deeper points in the surficial aquifer system in the immediate vicinity of the wastewater application.

The surficial-aquifer wells were developed by pumping, using a centrifugal pump and drop pipe lowered to the bottom of the well. In this way, solids which had moved through the well screen were effectively removed from the wells. The wells were pumped until the water was no longer turbid, or until continued pumping resulted in no visible decrease in turbidity. Some of the wells produced clear water within 5 to 10 minutes from the beginning of pumping, while others failed to clear up even after more than 2 hours of pumping. Turbidity in the well water probably is caused by clay or silt particles, or, in some wells, by organic materials leached from plant debris in the soils and on the land surface. The particulate matter causing the turbidity probably is not transported through the aquifer with the water movement, and therefore, is not representative of the water. Therefore, all water samples from the surficial aquifer system were filtered through a 0.45-micrometer membrane filter. This ensured that water-quality determinations were unaffected by the chemical nature of the turbidity-causing particles.

Most of the wells were sampled four times for dissolved nitrogen and phosphorus species, and for dissolved major inorganic constituents. The sampling dates were in May and December 1983, and June and October 1984. These dates were selected to represent water quality following dry conditions (May and June) and wet conditions (October and December). Water levels in the wells were measured at the time of sample collection.

Water samples were collected using a centrifugal pump. The wells were pumped until specific conductance was stable before samples were taken. This generally occurred within about 5 minutes. During this time, several casing volumes of water were removed. Specific conductance, pH, and water temperature were then determined, and samples were filtered for determination of major constituents and nutrients.

Samples for nutrient analyses were preserved with mercuric chloride and packed in ice until analyzed by the U.S. Geological Survey laboratory in Ocala, Fla. Major constituents were analyzed by the U.S. Geological Survey National Laboratory in Doraville, Ga. The laboratory procedures used are described in Skougstad and others (1979).

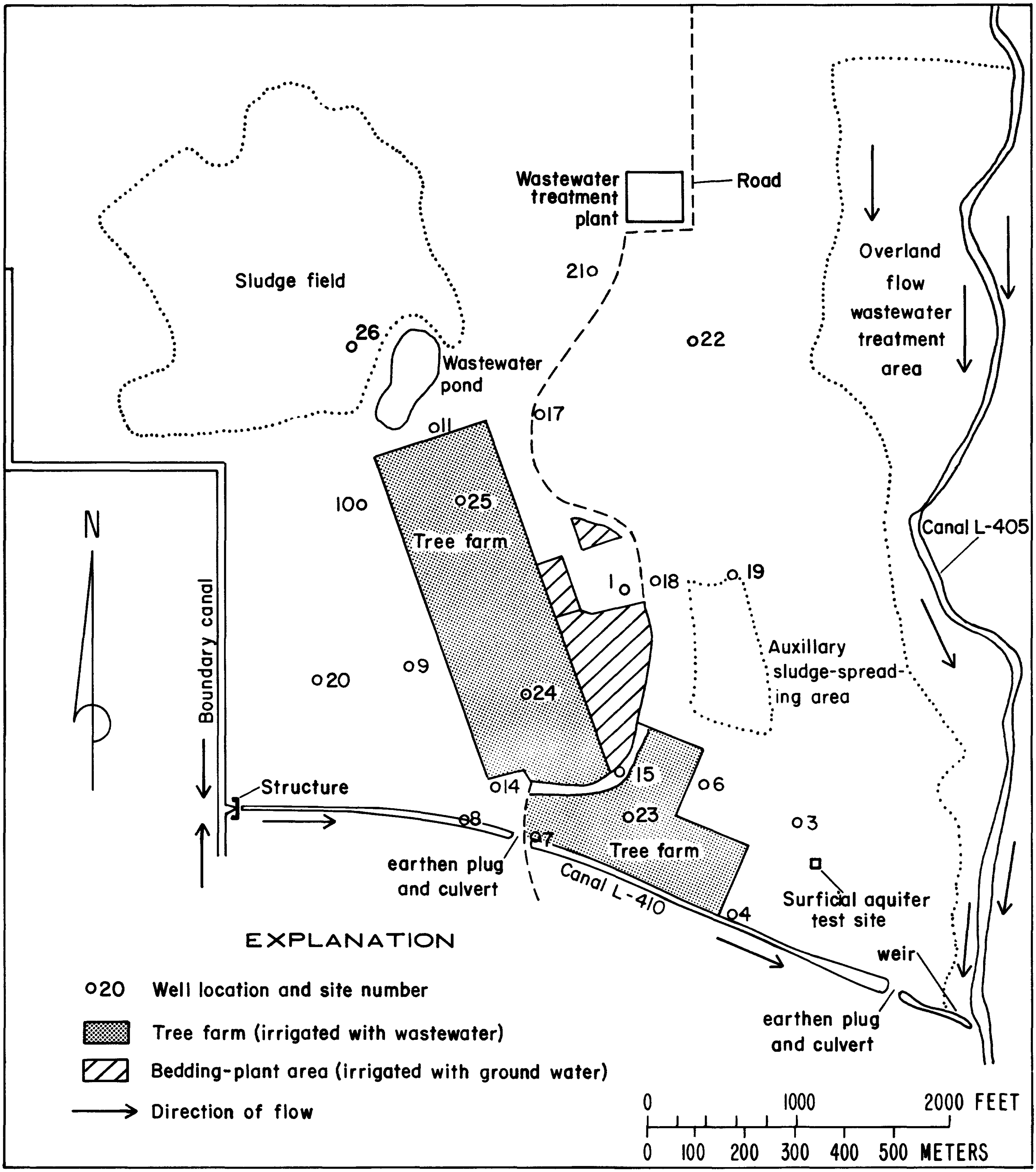


Figure 2. The study area, locations of wastewater application sites, and the monitoring well network.

Table 1. Monitoring-well depths and water levels

[Depth to water and water surface elevation are averages for the study period. Well depth includes 3- foot screen]

Well No.	Identification No.	Well depth (feet)	Water level depth below land surface (feet)	Water level altitude (feet)
1-S	282210081352601	18	5.23	96.96
3-D	282157081351702	26	6.07	90.53
3-S	282157081351701	12	4.81	92.42
4-D	282153081352002	41	8.89	90.01
4-S	282153081352001	14	9.39	89.24
6-D	282202081352202	26	7.50	92.15
6-S	282202081352201	12	5.31	94.39
7-D	282157081353402	25	12.17	88.55
7-S	282157081353401	16	12.57	88.55
8-D	282159081354002	51	9.58	92.51
8-S	282159081354001	20	15.76	88.35
9-D	282209081354402	28	8.02	95.33
9-S	282209081354401	10	4.35	98.74
10-D	282218081354802	30	4.91	96.74
10-S	282218081354801	10	4.16	97.26
11-D	282223081354302	26	5.94	96.21
11-S	282223081354301	12	4.29	97.09
14-D	282201081353702	23	11.34	91.65
14-S	282201081353701	18	11.98	91.73
[1]14-42	282201081353703	42	11.14	92.69
[1]14-62	282201081353704	62	11.90	91.73
15-D	282202081352802	26	4.54	94.65
15-S	282202081352801	13	4.02	96.00
17-D	282224081353402	57	7.04	91.80
17-S	282224081353401	12	4.56	94.29
18-D	282213081352402	26	3.36	96.38
18-S	282213081352401	12	3.52	96.20
19-D	282213081352102	26	5.20	91.71
19-S	282213081352101	12	2.82	93.58
20-D	282208081355102	23	6.37	95.50
20-S	282208081355101	12	5.20	96.69
21-D	282233081353002	22	5.57	89.15
21-S	282233081353001	12	4.86	90.34
22-D	282229081352302	22	4.50	88.04
22-S	282229081352301	12	3.86	88.94
23-S	282158081352501	13	8.91	92.32
24-S	282207081353501	8	2.70	99.97
25-S	282218081354001	8	4.06	99.04
26-S	282229081354901	8	3.55	95.72

[1]levels for June 27, 1985.

An aquifer test of the surficial aquifer system was done in the vicinity of the tree farm spray irrigation area (fig. 2). Drawdown data for a 24-hour pumping period were analyzed to determine aquifer transmissivity.

HYDROLOGIC SETTING

The study area is within the Reedy Creek Improvement District. Physiographically, the area is in the Osceola Plain between the Lake Wales Ridge to the west and the Mount Dora Ridge to the east (Puri and Vernon, 1964, fig. 6). The topography in the vicinity of the study area consists of relatively flat, swampy terrain interspersed with higher areas or "islands" of greater topographic relief. Altitudes range from 65 to 105 feet above sea level, but are mostly between 75 and 95 feet; the islands, including the study area itself, commonly are found at altitudes of about 100 feet. Land slopes are too slight to permit rapid runoff, even after heavy rainfall; to allow for development, a network of canals to facilitate runoff was constructed.

The climate is humid subtropical, characterized by long, warm summers and short, mild winters. Rainfall averages about 52 in/yr (inches per year), and the year can be divided into a rainy season and a relatively long dry season. Generally, more than half of the rainfall occurs during June through September.

Tree Farm Description

The study area (fig. 2) contains two tree farm areas (sprayfield) irrigated with treated wastewater, separated by an unnamed road. The area to the west of the road is about 41.3 acres. The area to the southeast of the road, along Canal L-410, contains about 20.7 acres. The wastewater, pumped from a holding pond north of the tree farm, is applied by rotating sprinklers on poles about 10 feet above land surface. These are spaced at intervals of about 30 feet within rows containing the plant stock. Rows with the sprinklers are alternated with rows with no sprinklers.

Each sprinkler can deliver water at a rate of about 10 gal/min (gallons per minute). The sprinklers, generally operated in evening and nighttime hours, are connected in several circuits, each circuit operated separately and for about 1 hour each day. This application procedure may be altered according to weather conditions; that is, certain circuits may be bypassed during periods of heavy rainfall if the ground becomes waterlogged, or the length of time each circuit is operated may be either increased or decreased as required to provide a suitable soil moisture content. Data furnished by the Reedy Creek Utility Company show that the amount of wastewater applied to the areas from October 1980 through September 1984 is equivalent to about 41 in/yr over the entire area.

The northern third of the western tree farm is underdrained by rows of perforated pipe buried in the clear rows. This underdrain system was installed to supplement the natural drainage which is sluggish in parts of the tree farm not adjacent to the canal. Water collected in the underdrain system is returned to the wastewater pond.

The effect of the underdrain system is to decrease the amount of recharge to the underlying surficial aquifer system. Data furnished by the Reedy Creek Utility Company show that, during a 48-month period from October 1980 through September 1984, a total of 120 Mgal (million gallons) were pumped from the underdrain system. This is equivalent to about 78 in/yr over the approximately 616,000 ft^2 (square feet) underdrained area.

Greenhouses and plots used for growing annuals and other bedding plants are located along the west side of the road traversing the study area. These areas are irrigated using water pumped from the Floridan aquifer system. Data furnished by the Reedy Creek Utility Company show that the amount of water pumped for irrigation from September 1981 to September 1984 is equivalent to about 85 in/yr over the irrigated areas.

Surface Drainage

Surface drainage at the study area is by canals, including a channelized section of Reedy Creek referred to as Canal L-405. Three sides of the study area are bordered by canals that serve to isolate the surficial aquifer system at the study area to the area within the canals.

The canal west of the study area (boundary canal in fig. 2) is part of a line of perimeter canals that receive drainage from outside the district and direct this drainage into other canals traversing the district. Ultimately, water draining from the area ends up in Reedy Creek, a tributary to the Kissimmee River chain of lakes.

Canal L-410 forms the southern boundary of the study area. This canal is separated from the west boundary canal by a gated structure. Because of this structure, water level in L-410 is about 7 feet lower than in the boundary canal. Water in L-410 flows eastward and through a culvert in an earthen plug near the east end of the canal. East of the culvert, Canal L-410 discharges into L-405, a channelized reach of Reedy Creek.

Canal L-405 discharges to the south and bounds an impounded wetland area between it and the study area. The wetland area is separated from the canal by a levee and is used as an overland-flow treatment process (fig. 2) for the excess wastewater not accommodated by the land-spraying operation. This overland flow area discharges through a weir into Canal L-410 just upstream from Canal L-405. Because of the levee and weir, water level in the impounded wetland is higher by about 4 feet than water in L-405, and lower by about 3 feet than water in L-410. Therefore, the impounded wetland forms the east boundary of the study area.

Surficial Aquifer System

The surficial aquifer system is the uppermost aquifer in the study area. This aquifer consists of generally fine-grained quartz sands with interbedded clays of irregular extent and distribution. Generally, fine-grained sand occurs near the land surface; the aquifer becomes finer grained and contains more clay with depth. Where the material becomes predominantly clay, it is considered part of the confining layer (the Hawthorn Formation) that separates the surficial aquifer system from the Floridan aquifer system.

Thickness of the surficial aquifer system in the study area varies according to the depth at which the clay material occurs. Samples of aquifer material were taken at 5-foot intervals using a split-spoon sampler driven through lengths of hollow-core augers while drilling wells 4-D, 8-D, 10-D, and 17-D (fig. 2). These locations were chosen because they represent the boundaries of the wastewater application area. Drilling at these sites proceeded until the split-spoon samples appeared distinctly clayey, indicating the top of the confining layer. Well 10-D was stopped short of the desired final depth and before clayey soil was encountered, because the borehole kept collapsing and locking the auger.

Lithologic descriptions, based on visual analysis of the split-spoon samples, are given in figure 3. These data indicate that the upper 30 to 60 feet of the surficial aquifer system is generally composed of sand, or sand with dark-brown silty material. Thin clayey layers were noticeable at depths less than 25 feet at sites 4-D and 8-D. The lithology for site 8-D demonstrates the variable nature of the aquifer material at some locations, and includes distinct layers of clear sand, sandy clay, and silty sand, some of which has a dark-brown color. The silt and the dark color occurring in these split-spoon samples is typical of the entire area, and probably is derived from humic material. Only at site 17-D was there a relatively thick layer of clear sand, from about 25 feet to about 60 feet below land surface. The clayey material beginning at depths of 40 to 60 feet below these sites is the top of the confining layer.

Samples were selected from site 4-D for analysis of particle size distribution through the range of sand to clay-sized particles. Samples selected for this analysis were from the surface and at depths of 10, 20, 30, and 45 feet.

The grain-size analyses (table 2) indicated the expected gradation from coarser to finer sized grains with depth. The surface sample contained only 2.5 percent silt and 0.3 percent clay by weight. The percentage of silt and clay increased with depth, with the deepest sample (45 feet) having a clay content of 15.7 percent.

A mineralogical analysis of the clay fraction at 45 feet indicated the clay consists of 60 percent well-crystallized kaolinite, 30 percent smectite, and 10 percent illite.

Additional data on soil type in the surficial aquifer system are available from Dames and Moore, a consulting engineering company, that performed numerous test borings at the Theme Park site for the purpose of foundation engineering. The Theme Park is located about 2 miles north- northeast of the study area. In all, 103 borings were completed, extending in depth from 51 feet to 180 feet below the land surface (Dames and Moore, written commun., 1968). Land surface in the Theme Park area at that time (1967) ranged from about 95 to about 100 feet above sea level.

The Dames and Moore borings showed that the lithology of the area was variable and consisted of layers of sand, silty sand, and silty and sandy clay overlying the Hawthorn Formation. In general, the Hawthorn Formation was encountered at 35 to 45 feet below land surface, and limestone was encountered at depths of 45 to 55 feet. In four locations, a much greater depth to limestone was noted, indicative of sinkhole formation.

None of the drilling in the wastewater application study area encountered limestone, even though three of the holes were more than 50 feet deep, and the deepest was 62 feet. This indicates that the depth to limestone probably is slightly greater in the study area than in the Theme Park area.

Floridan Aquifer System

The Floridan aquifer system is the principal water-supplying aquifer in the Reedy Creek Improvement District. This aquifer, which underlies all of Florida, consists of about 2,000 feet of limestone and dolomite or dolomitic limestone of mainly Eocene age. In some parts of the district, basal limestones in the Hawthorn Formation are in hydraulic contact with the Eocene limestones and are included as part of the Floridan aquifer system (Putnam, 1975). This aquifer system stores and transmits enormous quantities of water and is the source of potable water throughout the area. Additionally, water from the aquifer system is used for irrigation in parts of the Walt Disney World complex, including the tree farm.

HYDROLOGIC CONDITIONS

Hydrologic conditions are affected by natural factors as well as by man-related ones. Amount of rainfall has a direct effect on water levels in the canals and the surficial aquifer system, and can affect water quality, chiefly through dilution. It is important that rainfall amounts, which occurred shortly before and during the phase of data collection, be documented to indicate the conditions that the study represents. Also, generalized conclusions regarding ground-water levels and water movement are given in following sections of this report, based on average conditions that prevailed during the study.

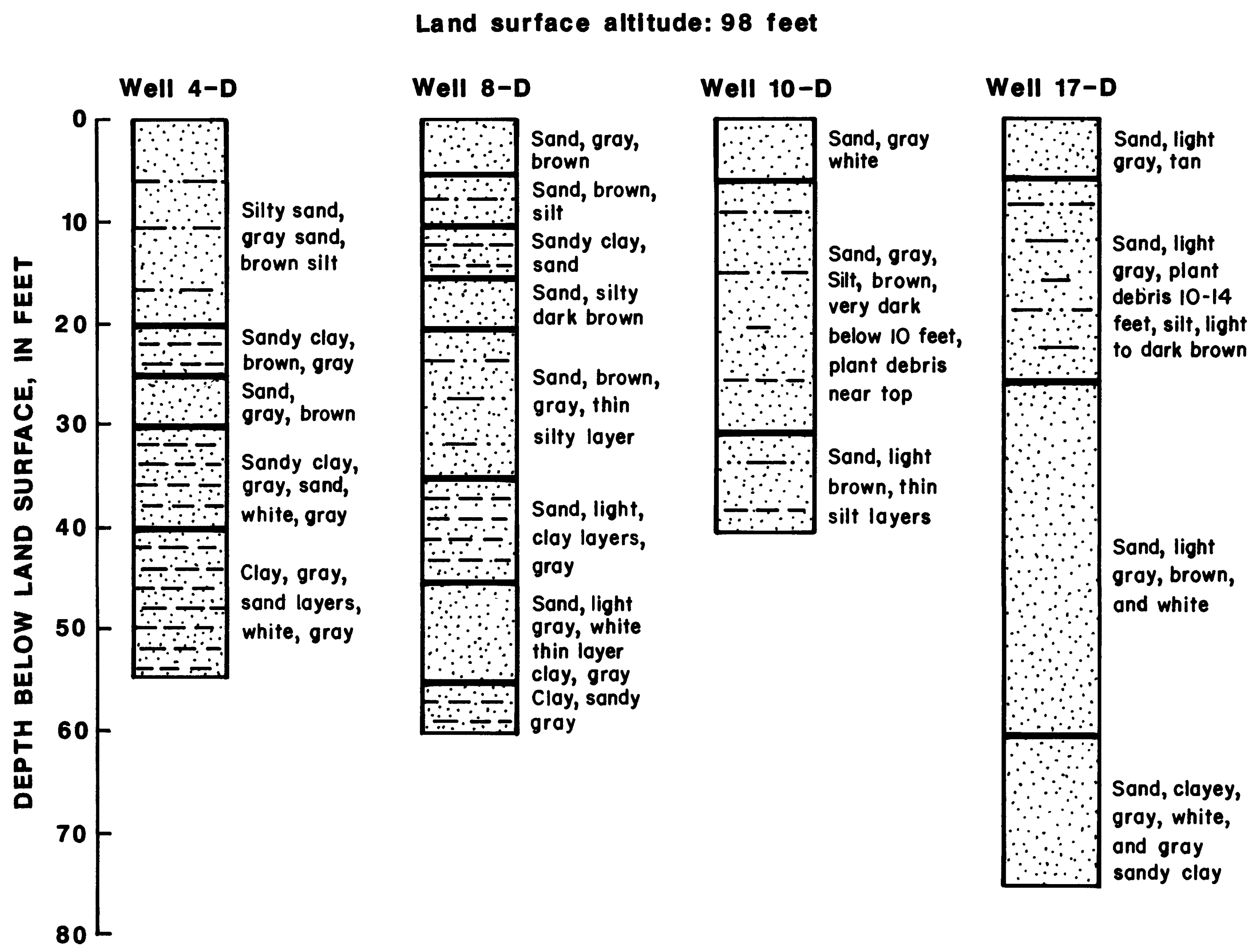


Figure 3. Lithology of the surficial aquifer system at four sites.

Table 2. Grain-size analyses of soil samples from site 4

[Analyses done by University of South Florida, Tampa, Fla., Department of Geology, under the direction of R.N. Strom]

Material	Size, in micrometers	Surface	10 feet	20 feet	30 feet	45 feet
		Cumulative percentage, by weight				
Sand	2,000	0.0	0.0	0.0	0.0	0.0
	1,000	.4	.3	.5	.8	.4
	500	7.8	8.0	10.0	9.4	3.6
	250	67.7	55.0	57.0	32.3	14.6
	125	96.7	89.7	89.5	87.3	53.4
	63	97.2	94.7	93.8	92.3	77.1
Silt	31	98.0	96.6	94.0	92.5	79.2
	15.6	98.8	97.7	96.0	92.7	80.4
	7.8	99.2	98.8	97.3	92.8	82.2
	3.9	99.7	99.5	98.1	92.8	84.3
		Total percentage, by weight				
	Sand	97.2	94.7	93.8	92.3	77.1
	Silt	2.5	4.8	4.3	.5	7.2
	Clay	.3	.5	1.9	7.2	15.7

Rainfall

Long-term annual rainfall totals are available for two stations near the study area. One station is located at Kissimmee, Fla., about 14 miles southeast of the study area. The other station is at Ilseworth, Fla., about 9 miles north of the study area (fig. 1). Both of these stations are operated by the National Oceanic and Atmospheric Administration (NOAA). Annual rainfall at these two stations for water years 1931 through 1980 are averaged and plotted in figure 4.

Average annual rainfall for this period is 52.4 inches. Recently (1981 through 1984), rainfall at a newly installed gage 1,000 feet south of the study area ranged from 39.6 inches (1981) to 57.6 inches (1982) and averaged 48.6 inches.

A cumulative frequency plot of the average annual rainfall at Kissimmee and Ilseworth (1931 through 1980) together with 1981-84 rainfall at the gage 1,000 feet south of the study area are shown in figure 4. Comparison of the 1981 through 1984 rainfall at the study area with the long-term frequency plot gives an indication of rainfall conditions (wet or dry) pertinent to this study. The plot indicates that 1981 was very dry (only 6 percent of the years had less rainfall), and 1982 was relatively wet (only 21 percent of the years had more rainfall), in comparison to long-term conditions. The data-collection years 1983 and 1984 are near the center of the frequency curve, indicating that these years were neither notably dry nor notably wet. Thus, data collected during this study should be representative of the usual range of rainfall conditions.

Wastewater and Irrigation Quantities

Monthly totals of wastewater applied to all tree farm areas during water years 1981 through 1984 ranged from 0 to 23.7 Mgal and averaged 7.56 Mgal. The total sprayed area is 3,581,000 ft^2. Over this area, the monthly wastewater application ranged from 0 to 10.6 inches, and averaged 3.39 inches (fig. 5). Annually, this average is 40.7 inches.

Water pumped from the Floridan aquifer system is used in areas totaling about 416,000 ft^2 for irrigation of bedding plants and other types of stock. Irrigation in these areas during water years 1981 through 1984 ranged from 0 to 3.8 Mgal/mo (million gallons per month) (fig. 5), and averaged 1.84 Mgal/mo. Converted to inches over the area of irrigation, the range was 0 in/mo (inch per month) to 14.6 in/mo, and the average was 7.10 in/mo, or 85 in/yr.

Water Level in the Canals

Water level in the west boundary canal is measured weekly at the structure (fig. 2) by personnel of the Reedy Creek Utilities Company. Monthly averages of the weekly data show that the monthly water level in the canal does not vary greatly, and for the period studied, was between 93 and 96 feet. The average water level in the canal was 95.0 feet.

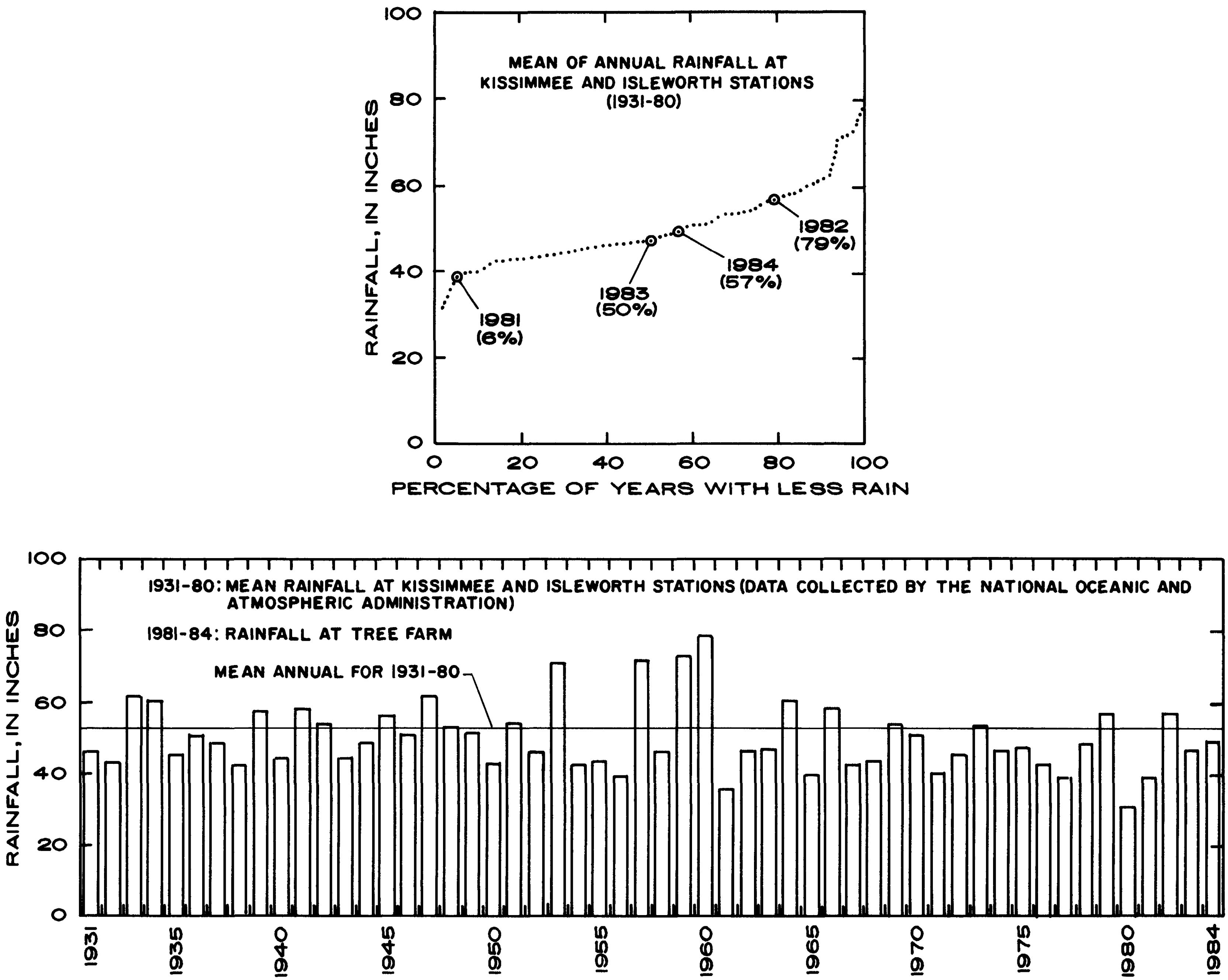


Figure 4. Annual rainfall near the study area, water years 1931 through 1984.

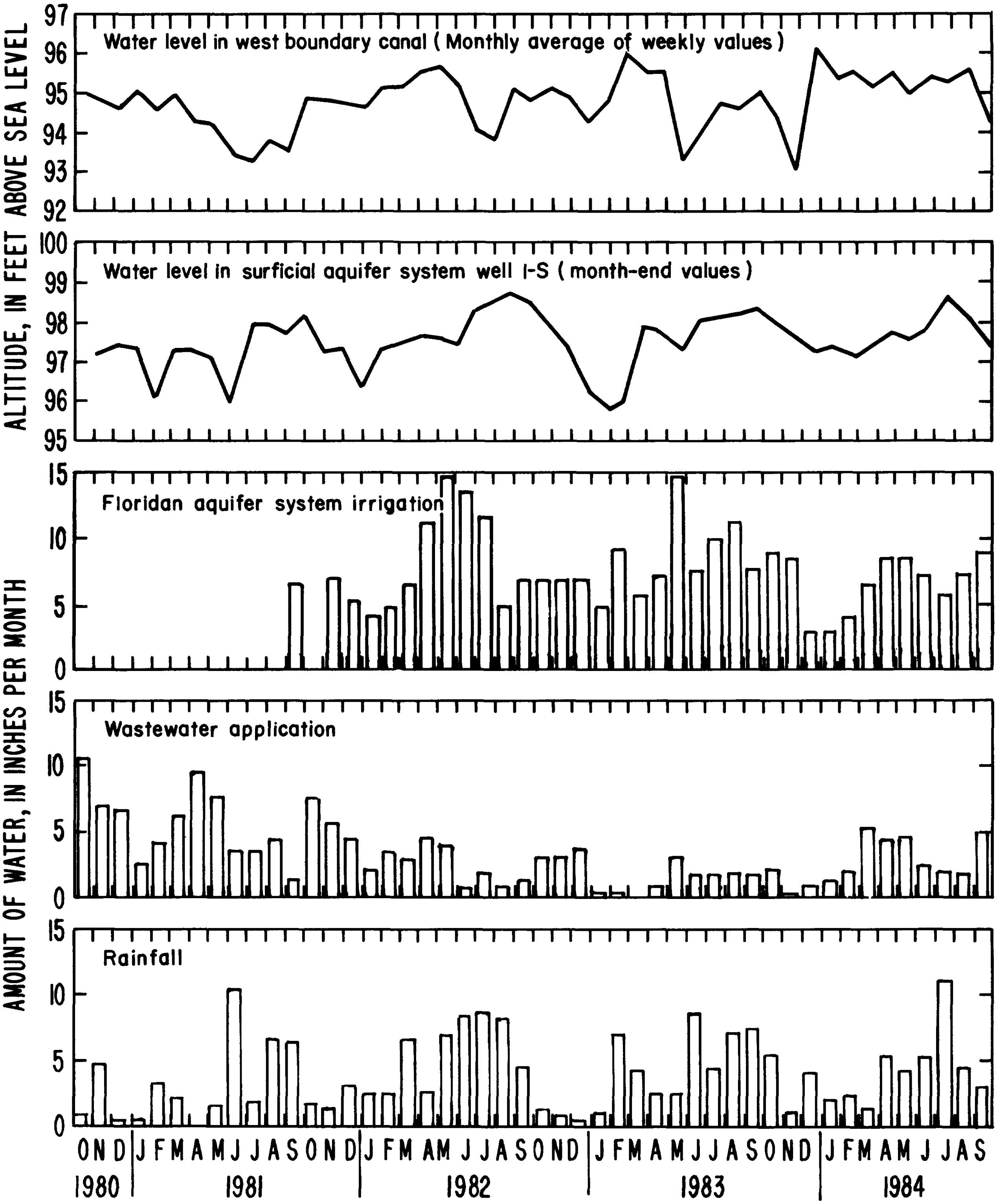


Figure 5. Water level in west boundary canal, water level in surficial aquifer system well 1-S, amounts of Floridan aquifer system water and wastewater used for irrigation, and rainfall, water years 1981 through 1984.

Water level in Canal L-410 was not measured regularly during the study, but casual observation indicated the water level in this canal does not fluctuate greatly. Five measurements made between March 1983 and October 1984 at the culvert near site 7 (fig. 2) show a variation in water level from 87.8 feet to 89.1 feet, and a mean of 88.2 feet.

The overland flow, wastewater treatment area is an impounded wetland forming the east side of the study area, along Canal L-405, and discharges through a broad-crested weir into Canal L-410. The water levels in this wetland vary only slightly (less than 0.5 foot) above the weir altitude of 84.9 feet (Ted McKim, Reedy Creek Utilities Company, oral commun., 1985).

Water Level in the Surficial Aquifer System

A summary of water levels for well 1-S in the surficial aquifer system near the center of the study site is given in figure 6 (see fig. 2 for well location). This summary, for the period of record (water years 1970 through 1984), is based on monthly maximum water levels in the well. Maximum water levels were near land surface altitude (101 feet) since waste application began in 1971, and the annual range in the monthly maximum water levels has generally been only 3 to 4 feet.

Daily maximum water levels for 1981 through 1984 are summarized in the cumulative frequency plot in the upper part of figure 6. This plot shows that the range in water surface altitude was small, and varied between 96.0 and 98.6 feet 90 percent of the days.

Potentiometric Surface of the Floridan Aquifer System

The Floridan aquifer system is tightly confined in the district vicinity, and Floridan aquifer wells located at lower altitudes may flow. For example, a well located about 3 miles south-southeast of the study area generally had a water level 10 to 15 feet above the land surface altitude of about 78 feet.

The potentiometric surface in the Floridan aquifer system is highest in the west-central part of the district, and slopes to the east at a gradient of about 4 feet per mile. The configuration of the potentiometric surface and its seasonal change in response to rainfall are shown in figure 7. The potentiometric surface configuration shown for May 1981 is representative of very dry conditions, which caused record low water levels in some wells in central Florida (George Schiner, U.S. Geological Survey, oral commun., 1985). The surface shown for September 1984 is typical of annual high water levels near the end of the normally wet summers.

Figure 7 shows that, at the study area, the potentiometric surface was at an altitude of between 90 and 95 feet in May 1981, and between 95 and 100 feet in September 1984. Thus, upward leakage from the Floridan is generally possible at the lower altitudes in the east side of the study area and to canals in the area, especially to Canal L-410 with a water-level altitude of about 88 feet. The water table in the surficial aquifer system in the areas of wastewater application is probably slightly higher than the Floridan aquifer system potentiometric surface (except near Canal L-410), so a vertical movement of water downward to the Floridan aquifer system could be possible at times. However, because of the presence of the confining layer and other factors to be discussed in more detail in a following section, the downward movement of large quantities of water is not likely.

Records of water levels in two Floridan aquifer wells (wells F-1 and F-2 in fig. 7) for water years 1967 through 1984 are summarized in figure 8. This summary, based on monthly maximum water levels, shows that annual fluctuation in water levels at these sites is generally within about 4 feet, and that over the 1967 through 1984 period, the range in monthly maximum water levels was from 97.9 feet to 85.4 feet at well F-1, and from 111.0 feet to 105.6 feet at well F-2. The greater fluctuation at well F-1 is probably due to nearby pumping of water from the Floridan aquifer system for water supply in and around the district.

HYDRAULIC CHARACTERISTICS OF THE SURFICIAL AQUIFER SYSTEM

Recharge to the Surficial Aquifer System

Various past studies have included estimates of evapotranspiration. These estimates are generally made through water-budget studies, in which runoff from a basin is compared to rainfall, the difference between the two quantities being the evapotranspiration. Lichtler and others (1968, p. 32) estimated that about 70 percent of the rain that falls on Orange County returns to the atmosphere. The actual amount doubtlessly varies from location to location; a swampy area with water standing on the land surface for extended periods probably loses more water to evaporation than higher areas with sandy soils and a thick, unsaturated zone.

Crain and others (1975, p. 24) made an estimate of recharge to the surficial aquifer system in Indian River County in southeast Florida. Their estimate was based on observations of water-level rises in a surficial aquifer well in response to rainfall, assuming that recharge is equal to the sum of water-level rises adjusted for porosity of the aquifer material. Their observations for water year 1970, when about 51 inches of rainfall fell, indicated a recharge of 16 inches, 31 percent of rainfall.

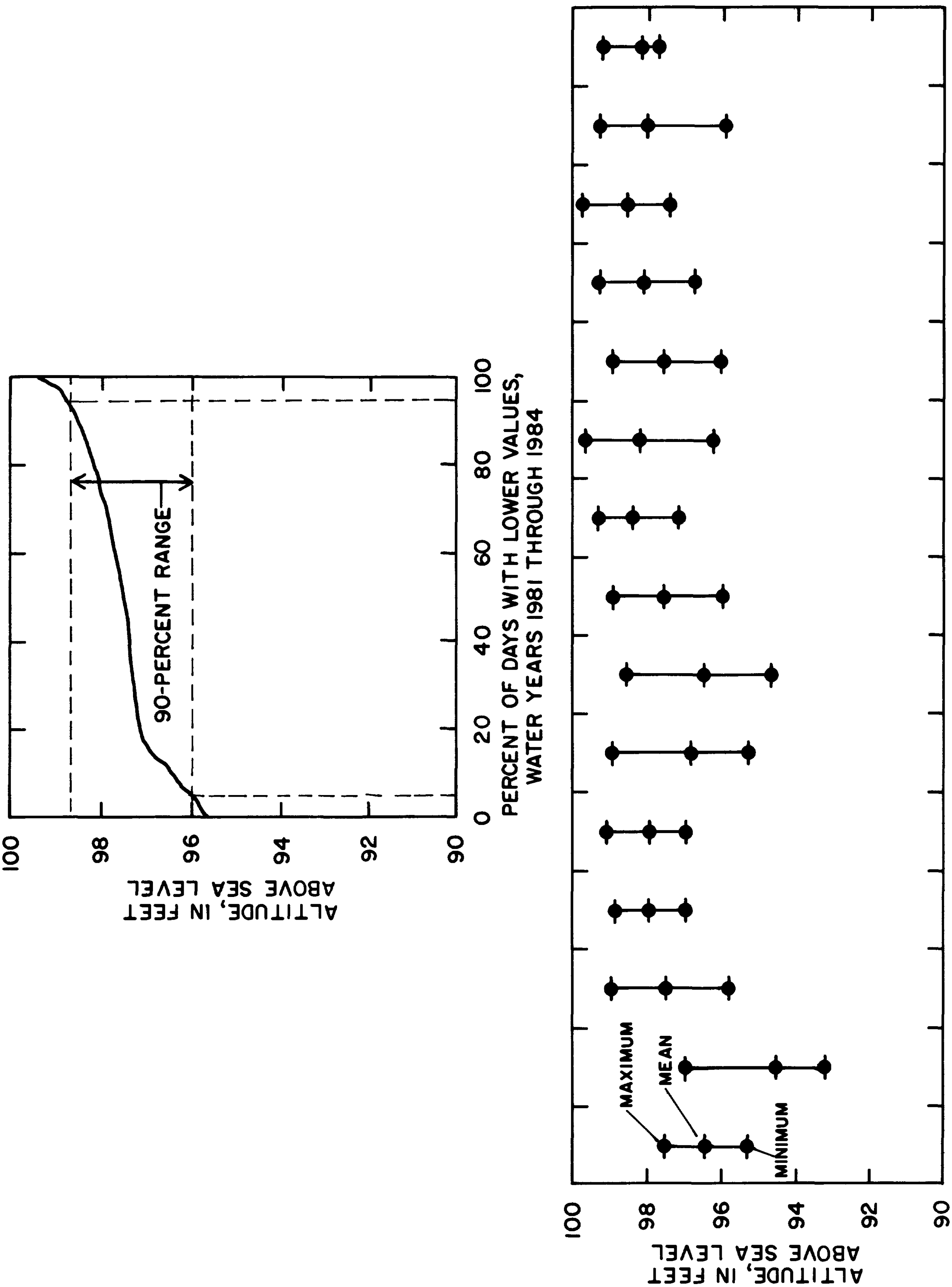


Figure 6. Summary of monthly maximum water level (water year 1970 through 1984) and frequency distribution of daily maximum water level (water years 1981 through 1984) in the surficial aquifer system at well 1-S.

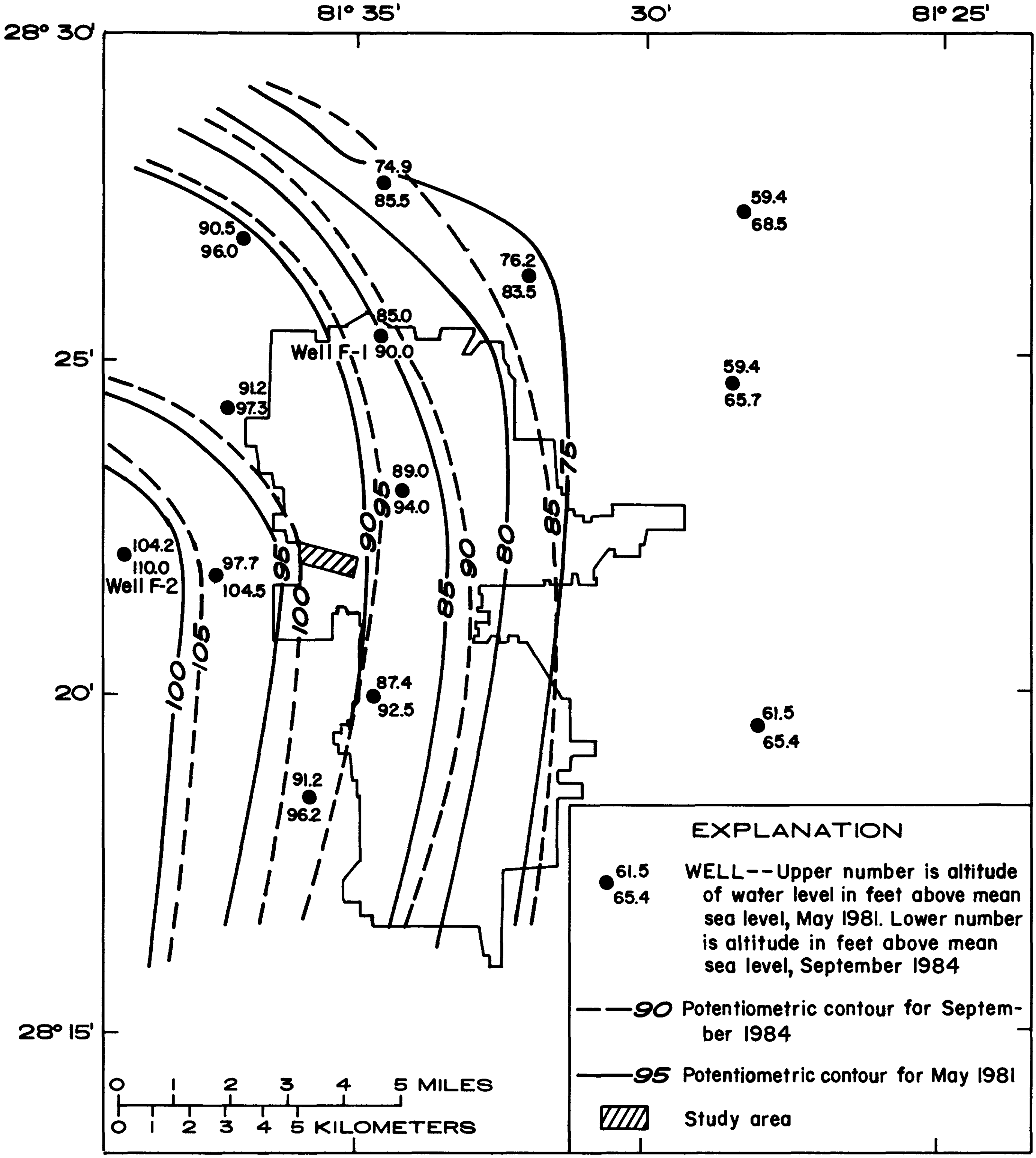


Figure 7. Configuration of the potentiometric surface in the Floridan aquifer system near the study area, May 1981 and September 1984.

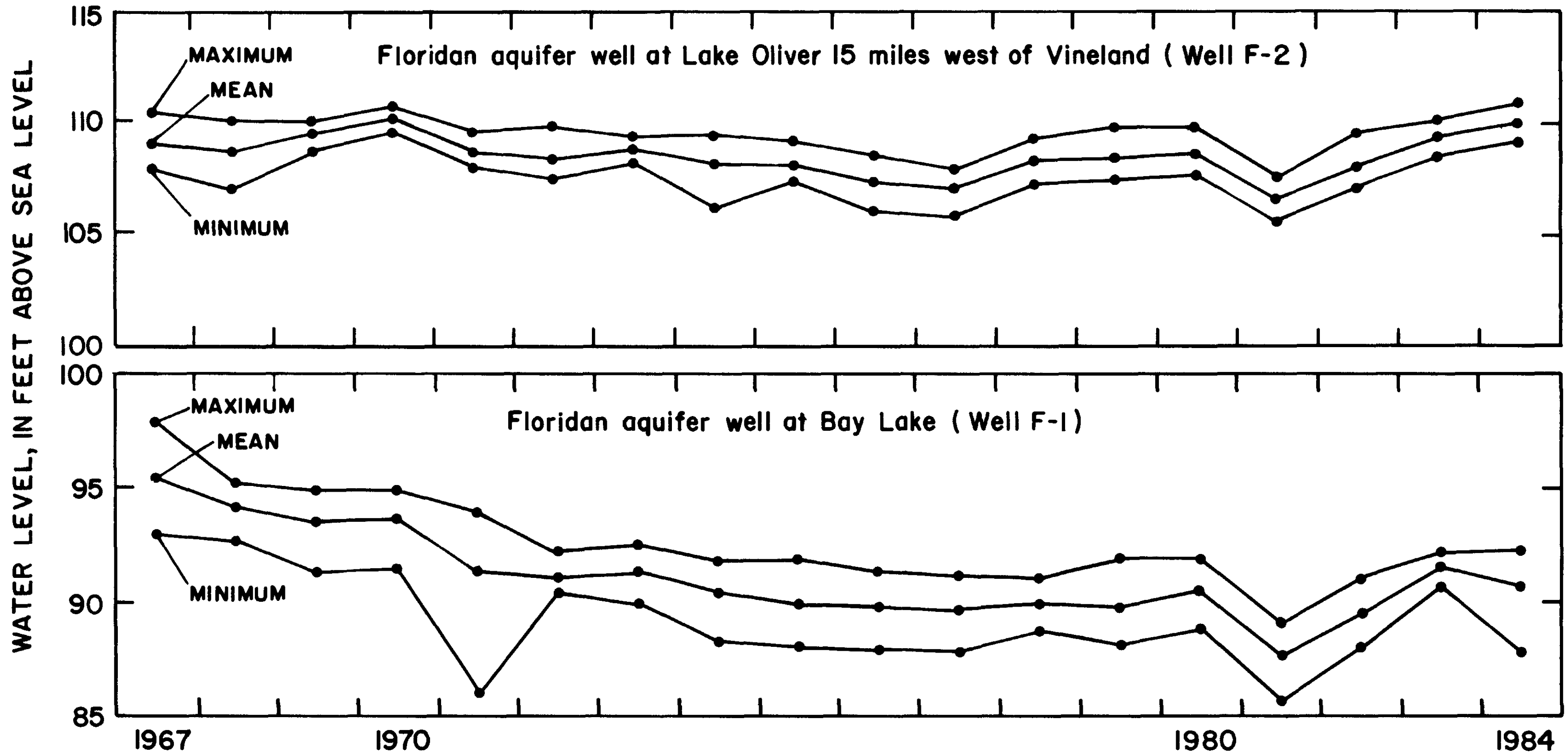


Figure 8. Summary of monthly maximum water level in two Floridan aquifer system wells, water years 1967 through 1984.

The technique used by Crain and others (1975) was applied to data from a surficial aquifer system well about 8 miles west of the study area in an area unaffected by irrigation or pumping. Records of daily water level at the well (station identification number 282202081384601 in U.S. Geological Survey files) were complete for 6 years during water years 1975 through 1984. Water-level rises were compared with rainfall record for the rain gage located 1,000 feet west of the study area, and about 8 miles east of the well. The water-level rises were first adjusted to the estimated specific yield of the aquifer, 27 percent. This estimate of specific yield was made using the grain-size distribution measured at site 4-D in the study area, and relations of specific yield to the maximum 10-percent grain size established by Eckis (1934). The maximum 10 percent grain size is the grain size in which the cumulative total weight, beginning with the coarsest material, reaches 10 percent of the total sample. At site 4, the maximum 10 percent grain size of the upper 30 feet of the aquifer is closest to 500 micrometers, or 0.5 millimeter (table 2).

The recharges estimated with this technique are given in table 3. Recharge fraction estimates for the 6 years ranged from 20 percent to 48 percent of the applied rainfall, and averaged 34 percent, in good agreement with the other estimates. The rather wide year-to-year variability, however, serves to indicate the imprecision of the method.

Recharge quantities probably vary over the study area, according to land cover and quantities of water applied. In the irrigated areas, the fraction of applied water available as recharge will likely be much greater than 30 percent. In other areas with dense vegetative cover, evapotranspiration may approach potential evaporation, the maximum possible evapotranspiration for the area. Recharge to the various parts of the study area was estimated so that quantities of water moving through the surficial aquifer system could be determined.

The bedding plant area and the nonunderdrained part of the tree farm are expected to have the greatest amount of recharge, and because the soils of these areas are wetted daily, the evapotranspiration may be limited by the potential evaporation of the area. Visher and Hughes (1969) estimated that potential evaporation in the area is about 4 in/yr less than rainfall. For the purposes of this verification process, rainfall is estimated to be a uniform 50 in/yr, so that the potential evaporation is 46 in/yr. If runoff is assumed to be negligible, the difference between the total incident water (rainfall plus irrigation) and the potential evaporation is the recharge. Based on this premise, recharge in the tree farm was about 45 in/yr, and recharge in the bedding-plant area was about 89 in/yr.

The underdrained part of the tree farm probably has the least amount of recharge. According to data furnished by the Reedy Creek Utilities Company, water was pumped from the underdrains at an average rate of 78 in/yr (October 1980 through September 1984). This is only 10 inches less than the total incident water. To obtain an estimated recharge fraction for this area, it is assumed that one-half of this difference, or 5 in/yr, reaches the aquifer. This amounts to about 6 percent of the incident water.

A heavily wooded part of the study area probably has a relatively low recharge rate, because part of the rainfall is intercepted by the dense leaf canopy, and the dense plant growths probably contribute to a higher evapotranspiration than in other areas. For the purposes of estimating quantities of water moving through the surficial aquifer system, a recharge of 5 in/yr, or 10 percent of rainfall, is assumed.

The remainder of the study area probably has a higher rate of recharge than the heavily wooded area, although lower than that in the tree farm. Because the water table is relatively close to land surface, evapotranspiration losses from the water table would tend to cause recharge to be lower than the areal estimate of 30 percent. For the purposes of this estimation, a recharge of 10 in/yr, or 20 percent of rainfall, is assumed for all areas other than the tree farm, the bedding plant area irrigated with Floridan aquifer water, and the heavily wooded area.

Transmissivity of the Surficial Aquifer System

An aquifer test of the surficial aquifer system was conducted on November 26 and 27, 1984, to determine the transmissivity of the aquifer. The transmissivity can be used to estimate rates of water movement in the aquifer in response to an observed hydraulic gradient.

Layout of the aquifer test is shown in figure 9. The pumped well, 38 feet deep, probably approaches full penetration of the aquifer in this part of the study area. Soil samples from site 4 (fig. 3) near the test site indicate the presence of a bed of dark-gray clay at 50 to 55 feet below land surface, and is probably indicative of the upper part of the Hawthorn Formation. Observation wells were placed to observe head in the upper part of the surficial aquifer system in the zone of water movement to the boundary canals.

The test was conducted by pumping and measuring drawdowns for 24 hours and measuring recovery for another 24 hours after pumping stopped. Pumping was done using an electric submersible pump and was regulated to provide 13 gal/min throughout the pumping period. Water from the pumped well was piped to a point about 300 feet downslope from the pumping well and then discharged to the land surface. Water levels were measured manually with steel tapes at intervals sufficient to construct plots appropriate for the analysis.

Hydraulically, the surficial aquifer system is vertically (and perhaps horizontally) anisotropic and is underlain by the leaky semiconfining Hawthorn Formation. The aquifer, when pumped, reacts somewhat like a semiconfined aquifer rather than a purely unconfined aquifer. That is, the

Table 3. Estimates of surficial aquifer system recharge from observations of water-level rises

[Water level rises are for surficial aquifer system well 282202081384601, located about 8 miles west of the study site. Rainfall is from a rain gage located 1,000 feet west of the study site. Estimated specific yield is 27 percent]

Water year	Total rises (inches)	Total rises, corrected for specific yield	Rainfall (inches)	Recharge percent, (ratio of corrected rises to rainfall)
1975	38.3	10.3	50.48	20
1978	56.3	15.2	44.90	34
1979	83.2	22.5	59.95	38
1980	31.6	8.5	34.65	24
1983	67.7	18.3	47.52	39
1984	87.4	23.6	49.60	48
Average	60.8	16.4	47.85	34

drawdown caused by pumping from the surficial aquifer system increases the upward head difference between the surficial aquifer system and the underlying Floridan aquifer system. At the time of the pumping test, the potentiometric surface of the Floridan aquifer system was about 5 feet above the surficial aquifer system water level.

The method of Jacob (1946) was used to compute the transmissivity of the surficial aquifer system. This method is customarily applied to an artesian, or confined aquifer, overlain by a leaky confining bed. It is applicable to the present situation, however, by turning the more usual situation upside down, and considering the upper part of the surficial aquifer system to be semi-isolated from the lower, less permeable part. The analysis is done using drawdowns after equilibrium has been reached. Analysis of the data plotted in figure 10 results in a transmissivity of 500 ft^2/d (feet squared per day).

Other studies of the surficial aquifer system in Orange County, Fla., also have determined transmissivities similar to that value. Bush (1979) determined a transmissivity of 595 ft^2/d at a site about 25 miles northeast of the present study site. Watkins (1977) determined a combined transmissivity of about 300 ft^2/d at a site about 15 miles northeast of the present study site for a two-layer surficial aquifer system in which the upper and lower layers were separated by a well-defined hardpan layer.

MOVEMENT OF WATER IN THE SURFICIAL AQUIFER SYSTEM

Ground water moves from areas of higher potential, or water level, to areas of lower potential, or water level, and from areas of recharge to areas of discharge. In the study area, surficial aquifer system water levels in the areas of wastewater application are higher than in surrounding canals and may at times be higher than the potentiometric surface in the underlying Floridan aquifer system. Therefore, the applied wastewater moves laterally through the surficial aquifer system to the canals and may move downward to the Floridan aquifer system.

Movement of water downward to the Floridan aquifer system is hindered by three factors: the small hydraulic gradient between the surficial and the Floridan aquifers, a relatively low vertical hydraulic conductivity (compared to horizontal hydraulic conductivity) in the surficial aquifer system, and the presence of a confining bed separating the two aquifer systems.

The gradient, or head difference between the surficial and the Floridan aquifer system is small; the surficial aquifer system water level in the area of wastewater application probably is less than about 100 feet above sea level, and the potentiometric surface in the Floridan aquifer system probably is above 90 feet. This indicates a head difference of less than 10 feet at most locations in the area.

Vertical hydraulic conductivity in the surficial aquifer system probably is much lower than horizontal hydraulic conductivity. Bush (1979) estimated a horizontal to vertical hydraulic conductivity ratio of 39 to 1 in an area about 25 miles northeast of the study area. According to Bush (1979, p. 34), this high ratio apparently is caused by either the arrangement or shape of the sand grains that comprise the shallow aquifer, and probably is common throughout east Orange County and perhaps central Florida.

The Hawthorn Formation, separating the surficial aquifer system from the underlying Floridan aquifer system, generally acts as a confining unit. According to Putnam (1975), the hydraulic conductivity of this formation varies throughout the Reedy Creek Improvement District, providing varying degrees of hydraulic contact between the surficial aquifer system and the Floridan aquifer system. An artesian flowing well located near Reedy Creek about 3 miles south-southeast of the study area and having a head of generally 10 to 15 feet above the land surface is a manifestation of the confining unit.

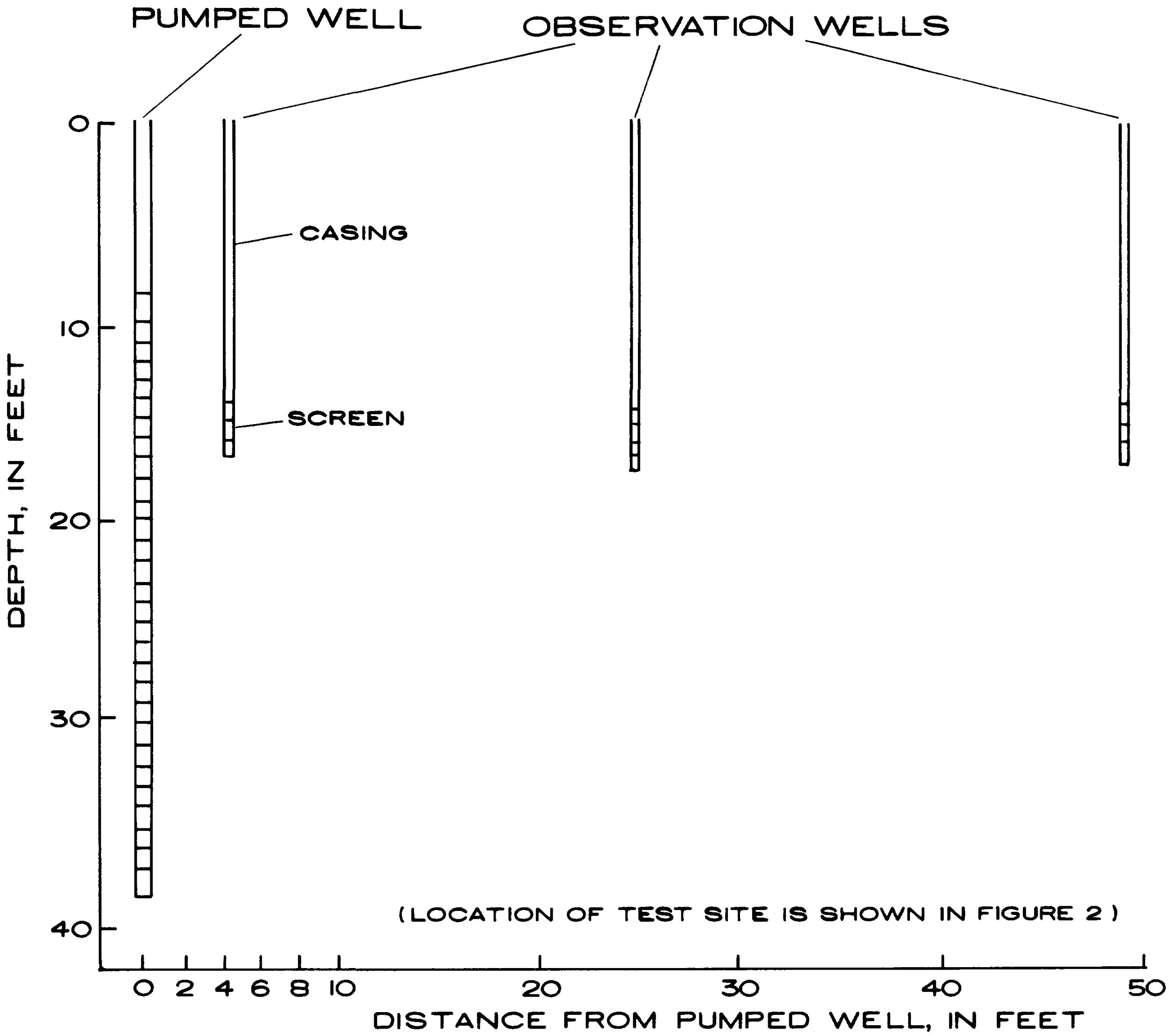


Figure 9. Layout of surficial aquifer system test.

The direction of lateral water movement can be inferred by analysis of the water-level contours. That direction, and also ground-water divides, can be determined using the principle that water flows in the direction of the maximum hydraulic gradient, that is, perpendicular to contour lines, if isotropy is assumed. Ground-water basins in the study area, determined in this manner, are delineated in figure 11. The configuration of the basins is somewhat subjective because of the number of ways in which contours can be drawn. The most uncertain part in delineating the basins is in placing the location of the ground-water divide within the west tree farm area. Control in this area is sparse, consisting of only two wells. Definition of the divide will determine the contributing recharge to each of the surrounding canals. The total amount of water from the area will be the recharge to the surficial aquifer system by rainfall, wastewater application, and Floridan aquifer system irrigation.

Figure 11 indicates that most or all of the recharge moving laterally in the tree farms discharges to the surrounding canals. Quantities of water flowing to the boundary canals can be estimated by measuring the areas within the ground-water divides and applying estimated recharge to these areas. This procedure requires estimation of the fraction of applied water that recharges the surficial aquifer system, and assumes that surface runoff and interchange of water between the surficial aquifer system and the Floridan aquifer system are insignificant. The estimates of ground- water discharge from a selected ground-water basin are very dependent on the estimated configuration of the surficial aquifer system water table, as defined by the contours in figure 11.

Quantities of water flowing to the boundary canals, given in table 4, are based on recharge rates of 45 in/yr in the nonunderdrained wastewater application areas, 89 in/yr in the Floridan aquifer water irrigation areas, 5 in/yr in the

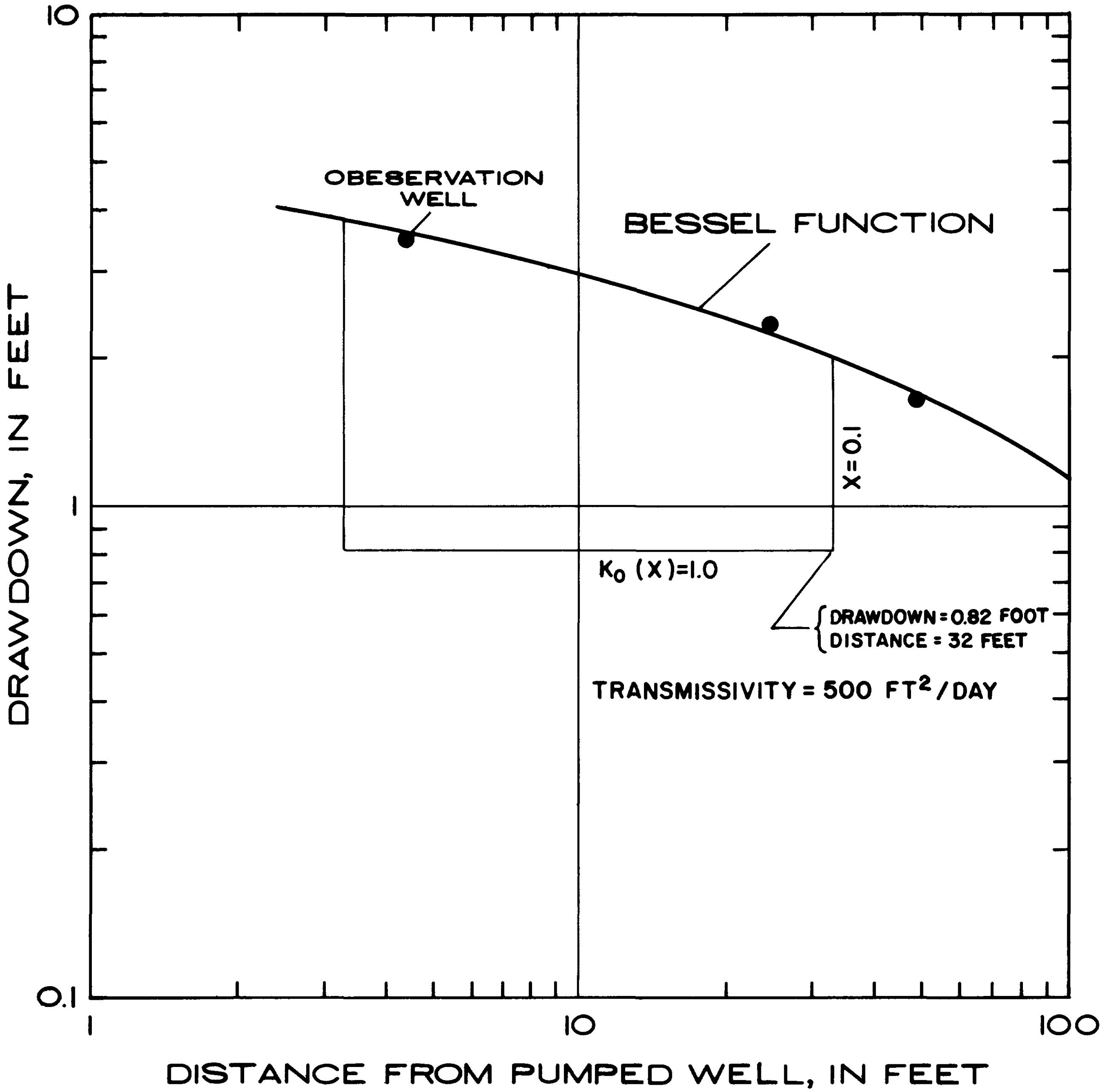


Figure 10. Analysis of the surficial aquifer system test using the method of Jacob.

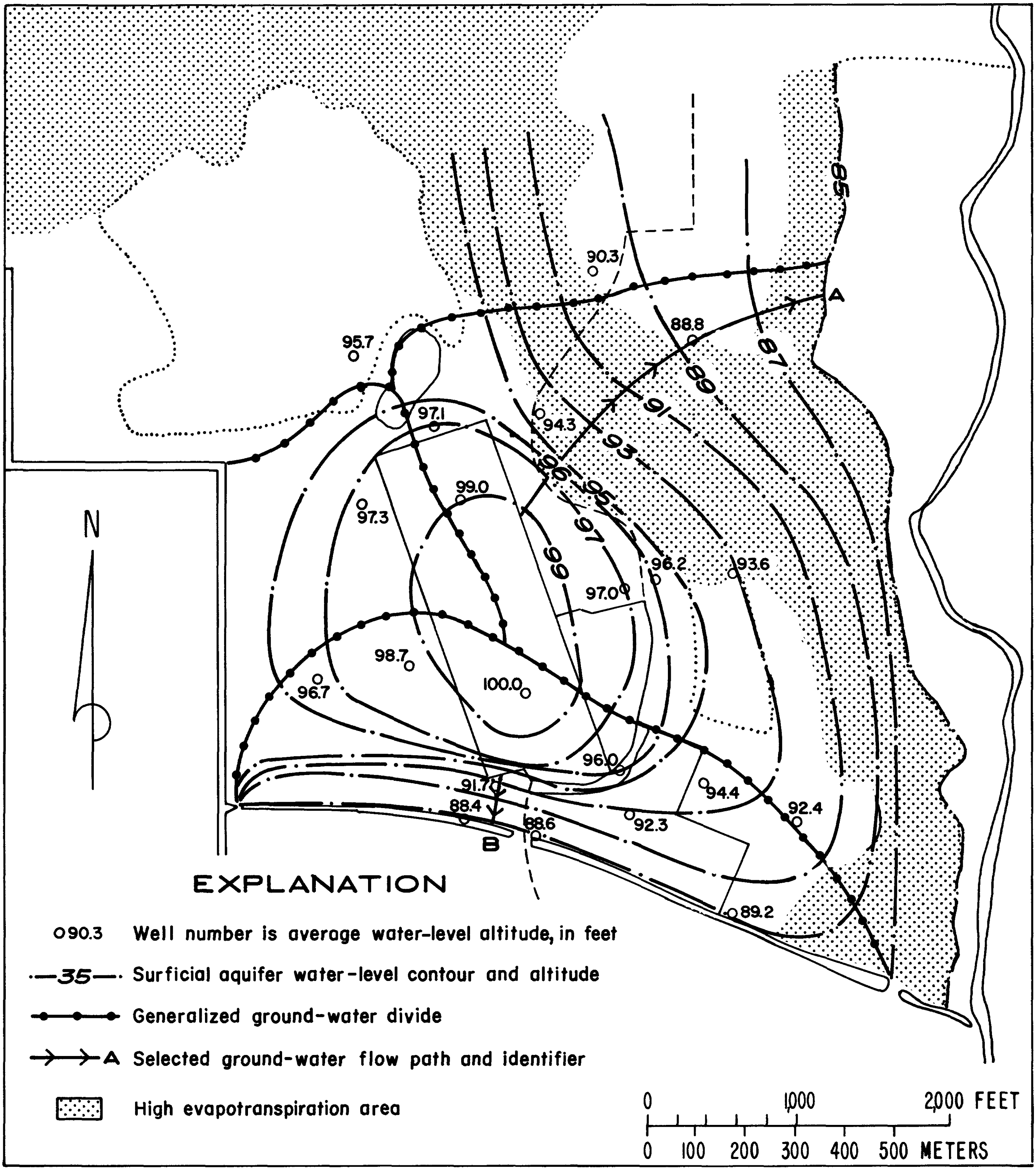


Figure 11. Generalized configuration of the surficial aquifer water table and direction of ground-water flow in the study area.

heavily wooded high-evapotranspiration area, 5 in/yr in the underdrained area, and 10 in/yr elsewhere.

Based on these assumptions, Canal L-410 receives most of the tree farm area recharge, or about 0.18 ft^3/s. This accounts for about 72 percent of the total recharge in the tree farm. About 0.045 ft^3/s (total discharge from non-underdrained and underdrained sections), or 18 percent of the total recharge in the tree farm areas, reaches the Canal L-405 overland flow area. The remaining 0.027 ft^3/s (10 percent) ends up in the west boundary canal.

Discharge measurements were made in Canal L-410 on May 27, 1983, upstream and downstream from the tree farm. This was done to determine the amount of gain in the canal flow due to ground-water discharge. The discharge measurements were preceded by nearly 4 weeks of less than 0.2 inch of rainfall, so that ground-water discharge was probably typical of relatively steady-state, dry-season conditions. A discharge of 1.64 ft^3/s was measured at the upstream (west) end of the canal, and 3.13 ft^3/s was measured near the downstream (east) end. Thus, a gain of 1.49 ft^3/s was observed in the canal from ground-water seepage. This is considerably more than the 0.25 ft^3/s of ground water estimated to reach Canal L-410 from the area north of the canal, and may indicate a relatively large ground-water contribution from the south, compared to the north side of the canal. The reason for this larger contribution from the south side of the canal is probably that the larger part of the canal's drainage area is in that direction. The ground-water drainage divide was not determined south of the canal, but inspection of topographic maps indicates that the southern divide could be several miles from the canal. Another possibility for the gain in Canal L-410 is upward leakage from the Floridan aquifer system.

Table 4. Quantities of water discharged from the surficial aquifer system to boundaries of study area
ET, evapotranspiration; ft^2, square feet; in/yr, inches per year; ft^3/s, cubic feet per second]

Source	Area (ft^2)	Estimate recharge (in/yr)	Contribution to boundary discharge (ft^3/s)	Per-cent
			Overland flow wastewater treatment area	
Tree farm	340,000	45	0.040	14
Tree farm, underdrained	375,000	5	.005	2
Floridan irrigation	346,000	89	.082	28
High-ET area	5,620,000	5	.074	25
Other	3,490,000	10	.092	31
Total	10,171,000		.293	
			Canal L-410	
Tree farm	1,545,000	45	0.184	69
Floridan irrigation	72,000	89	.017	6
High-ET area	280,0005		.004	1
Other	2,350,000	10	.062	23
Total	4,247,000		.267	
			West boundary canal	
Tree farm	200,000	45	0.024	30
Tree farm, underdrained	246,000	5	.003	4
Other	1,968,000	10	.052	66
Total	2,414,000		.079	

WATER QUALITY IN THE SURFICIAL AQUIFER SYSTEM

Processes Affecting Water Quality

Water applied to the land surface, either as rain or as spray irrigation, will change chemically as it moves through the material of the unsaturated zone and the media of the saturated zone. The types of change that take place are a function of the chemistry of the applied water, and the composition of soils and saturated zone materials. The interactions of the water with the soil and aquifer materials are, in most cases, complex with a number of possible processes and reactions. It is not intended that this report should be a complete text on the subject; however, some of the fundamental mechanisms of water-chemistry changes applicable to the tree farm operation are described as an aid in clarifying interpretation of data presented in this report.

Processes affecting water quality in the soil zone are of major importance in the study area. Freeze and Cherry (1979, p. 240) consider soil to be "the layer at the surface of the earth that has been sufficiently weathered by physical, chemical, and biological processes to provide for the growth of rooted plants." The most important changes in the chemistry of water penetrating the soil zone are probably those related to production of acid through respiration of plant roots and the decay of organic matter. These processes produce carbon dioxide which hydrolyzes to carbonic acid (H_2CO_3). Another process contributing to acidity of water in the soil zone is the production of humic and fulvic acids. The presence of these organic acids, produced by biochemical processes in the soil, is accompanied by a distinctive color in the water, as well as a lowered pH. Accompanying the production of acids in the soil is the consumption of dissolved oxygen. This consumption of dissolved oxygen then affects speciation of many constituents in the ground water, primarily metals, nitrogen, and sulfur compounds.

Conversion of the nitrogen compounds is of particular interest because these compounds are one of the distinguishing characteristics of wastewaters, and are of concern because they can affect potability of the water, or, if they reach a surface body of water, can contribute to eutrophication. Much of the nitrogen in the wastewater applied to the land surface is in the organic form. This may be converted to ammonia through the process of ammonification. The ammonia may then be converted to nitrate through the process of nitrification. Both of these processes normally occur in the presence of organic material and oxygen, and thus, are predominantly soil and unsaturated zone processes. The end result is nitrate, which is very mobile in ground water because it is not limited by solubility restrictions or a tendency to become sorbed.

In many sections of the study area the water table may reach the soil zone. The most visible manifestations of soil effects on water quality are the high amount of color and low pH of water encountered at many of the wells. Due to the closeness of the water table to the land surface, processes of ammonification and nitrification may not have time to occur before water percolating from the surface reaches the water table. This is described in more detail in a following section.

Beneath the soil zone, the more important processes affecting water quality probably are those involving precipitation reactions, oxidation-reduction reactions and cation exchange. The subject of oxidation-reduction is complex, and can affect the occurrence and movement of many constituents in ground water, particularly metals. A prime example is iron, which is not very soluble in oxygenated water, but can commonly reach concentrations of 1.0 to 10 mg/L (milligrams per liter) as the reduced (ferrous) species in ground waters (Hem, 1970). Reducing conditions can also affect nitrate through the process of denitrification, in which nitrate nitrogen is reduced to nitrogen oxide or free nitrogen gas.

Redox conditions in the study area were not evaluated during this study. According to Freeze and Cherry (1979, p. 245), shallow ground water in sandy recharge areas should contain detectable (>0.1 mg/L) dissolved oxygen. This would probably prevent the denitrification process, though further, more detailed study would be required to substantiate this.

Ion exchange could affect water chemistry, with respect to either the major cations (calcium, magnesium, sodium, and potassium) or trace constituents. According to Hem (1970), most mineral surfaces have some cation-exchange capacity. Cation exchange takes place on colloidal sized particles, or those with diameters in the 10^{-3} to 10^{-6} mm (millimeter) range (Freeze and Cherry, 1979, p. 127). In the surficial aquifer system, these colloidal particles are primarily the clay minerals. The most noticeable manifestation of cation exchange in the study area should be that involving replacement of the monovalent ions (sodium and potassium) held on the colloidal sized particles with the divalent ions (calcium and magnesium) in the wastewater.

Possibilities for cation exchange in the study area would appear to be somewhat limited due to the nature of the surficial aquifer system material. Though clay does exist in the area, it is spotty in occurrence and is most probably not common in the upper parts of the aquifer; the particle-size analyses for site 4-D indicated clay-size particles to comprise only about 2 percent or less of the material at depths of 20 feet or less (table 2). Based on this analysis, water percolating from the surface would likely discharge into one of the boundary canals before reaching the depths at which clay sized particles are more apt to be encountered.

Overview of Water Quality

Water quality is highly variable within the study area, as demonstrated by the cumulative frequency plots of mean values (by well) for selected variables shown in figure 12. These plots show the percentage of wells having water with a lower mean value. For example, mean specific conductance was less than 67 µS/cm (microsiemens per centimeter) in 50 percent of the 16 deep wells, and less than 95 µS/cm in about 50 percent of the 19 shallow wells. General conclusions suggested by figure 12 are:

- Water quality is highly variable throughout the area. For example, mean values of specific conductance in the shallow wells ranged from 50 µS/cm to 330 µS/cm, and mean chloride concentrations ranged from 4.0 to 62 mg/L. Lower values of most constituents are probably indicative of natural water-quality conditions, and the higher values probably indicate effects of the wastewater application. Color and turbidity, however, probably are not related to presence of wastewater. Rather, they are probably related to naturally occurring silt and clay beds, and organic material leached from plant debris in the soil and on the land surface.

- The shallow wells generally contain higher concentrations of most dissolved constituents. This is especially true of phosphorus, for which the median concentration was 0.23 mg/L in the shallow wells and 0.04 mg/L in the deep wells.

- Color values are much greater in the shallow wells. This is because the shallow wells were screened in the zone of organic leaching, and thus, were open to that part of the surficial aquifer system containing organic matter.

- Although median turbidity in shallow and deep wells was about the same (10 units), several deep wells had highly turbid water, compared to the shallow wells. The higher turbidity in some deep wells probably is caused by fine silt and clay size particles, which are less likely to be encountered at shallower depths.

Within-Site Consistency in Water Quality

The four samples per site, taken within a 2-year period, are not adequate to accurately define water-quality variations that might occur over a longer timespan and wider range of meteorological conditions. However, these data provide some indication of ranges in water quality in the study area. Also, these data give some idea of the reliability of the mean concentration, which is used to relate ground-water quality to wastewater application and other activities on the land surface.

Variation in specific conductance, depth to water, color, and turbidity are shown in figure 13. For most wells, the among-samples variation in specific conductance was low; the specific conductance range was less than 50 µS/cm at 75 percent of the sites. Ranges of over 100 µS/cm were observed at three sites—the pond, well 14-S, and well 23-S. These were also the sites with the highest maximum specific conductance. Variation in the specific conductance at these three sites is probably the result of varying dilution of the wastewater by rainfall.

Depth to water at sampling time varied from less than 3 feet to nearly 16 feet, but in most of the wells the variation in depth to water was low. This variation was less than 1 foot in 68 percent of the wells.

Color variation was low at some sites and extremely high in others. About 86 percent of the sites had a range in color of 300 platinum cobalt units or less. In one well (10-D), color varied from 500 to 1,300 units. This variation in color is probably related to the amount of rainfall, but color is apparently affected more by the rainfall (or other factors) than are other water-quality variables.

Like color, turbidity was also highly variable in some wells. The range in turbidity was less than 60 units at about 72 percent of the sites. In five wells (14 percent of the sites), the range in turbidity was greater than 200 units. Because turbidity is generally caused by aquifer material passing through the well screen, it is probably not related to rainfall or other factors on the land surface. Rather, it may vary in response to processes associated with well development. After a sufficiently long period of pumping, during which fine materials around the well screen are removed by the pumping action, turbidity should decrease, reaching some value which is constant with time.

Variation in calcium, sodium, chloride, and sulfate are shown in figure 14. Calcium concentrations were low in most wells (maximum 1.8 mg/L or less in 78 percent of the wells). The range in calcium concentration at each well was low, less than 7 mg/L, except at one well (11-S). Variation in concentration of the other ions was higher than for calcium, with sulfate having the most variation. About 50 percent of the sites had a variation in sulfate of 10 mg/L or more. This variation in sulfate could be related to varying redox conditions in the area. In oxidizing conditions, most sulfur will be in the sulfate form. In reducing conditions, sulfides will predominate.

Variation in nitrogen species concentrations are shown in figure 15. Dissolved nitrogen (all species) variation was less than 0.9 mg/L for about 78 percent of the sites. In some wells, the variation in nitrogen was extreme: For example, well 6-D had a dissolved nitrogen concentration ranging from 7.6 mg/L to 19 mg/L (as nitrogen), and the range in dissolved nitrogen at well 23-S was from 4.1 to 7.6. Organic nitrogen was the most variable of the nitrogen species, and nitrate plus nitrite was the least variable species.

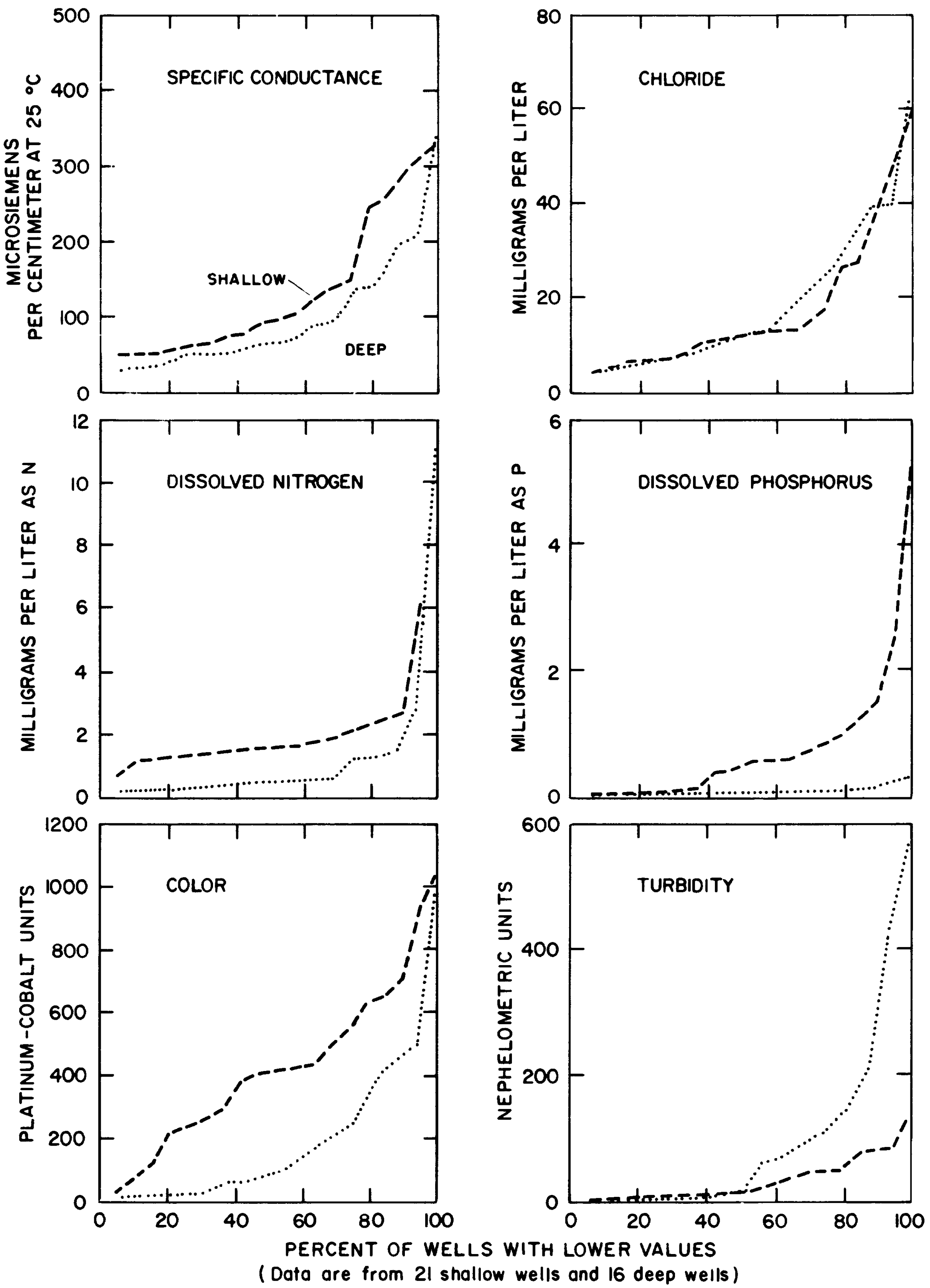


Figure 12. Frequency distribution of specific conductance, chloride, dissolved nitrogen, dissolved phosphorus, color, and turbidity in the surficial aquifer system.

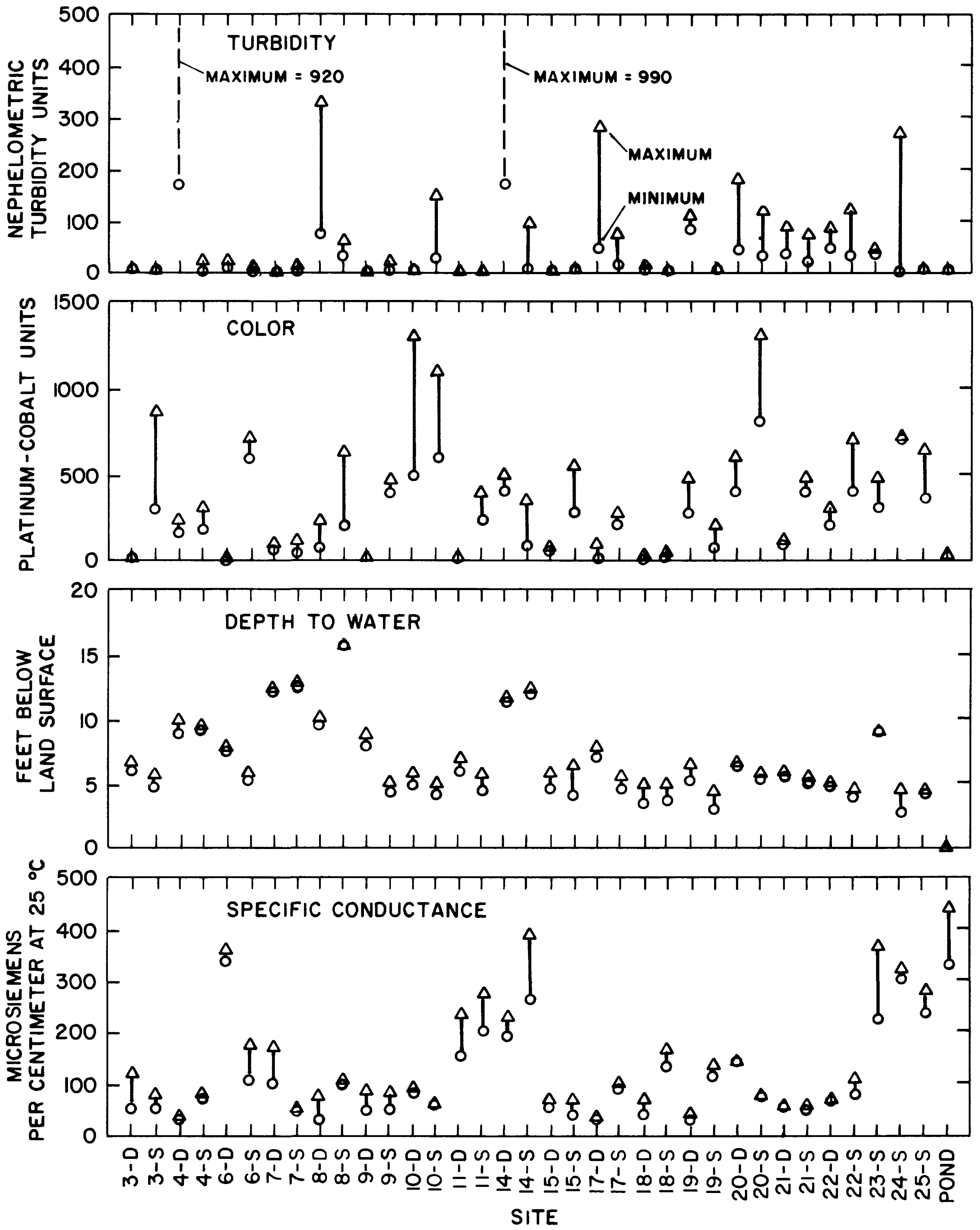


Figure 13. Variation in turbidity, color, depth to water, and specific conductance in surficial aquifer sytem monitoring wells.

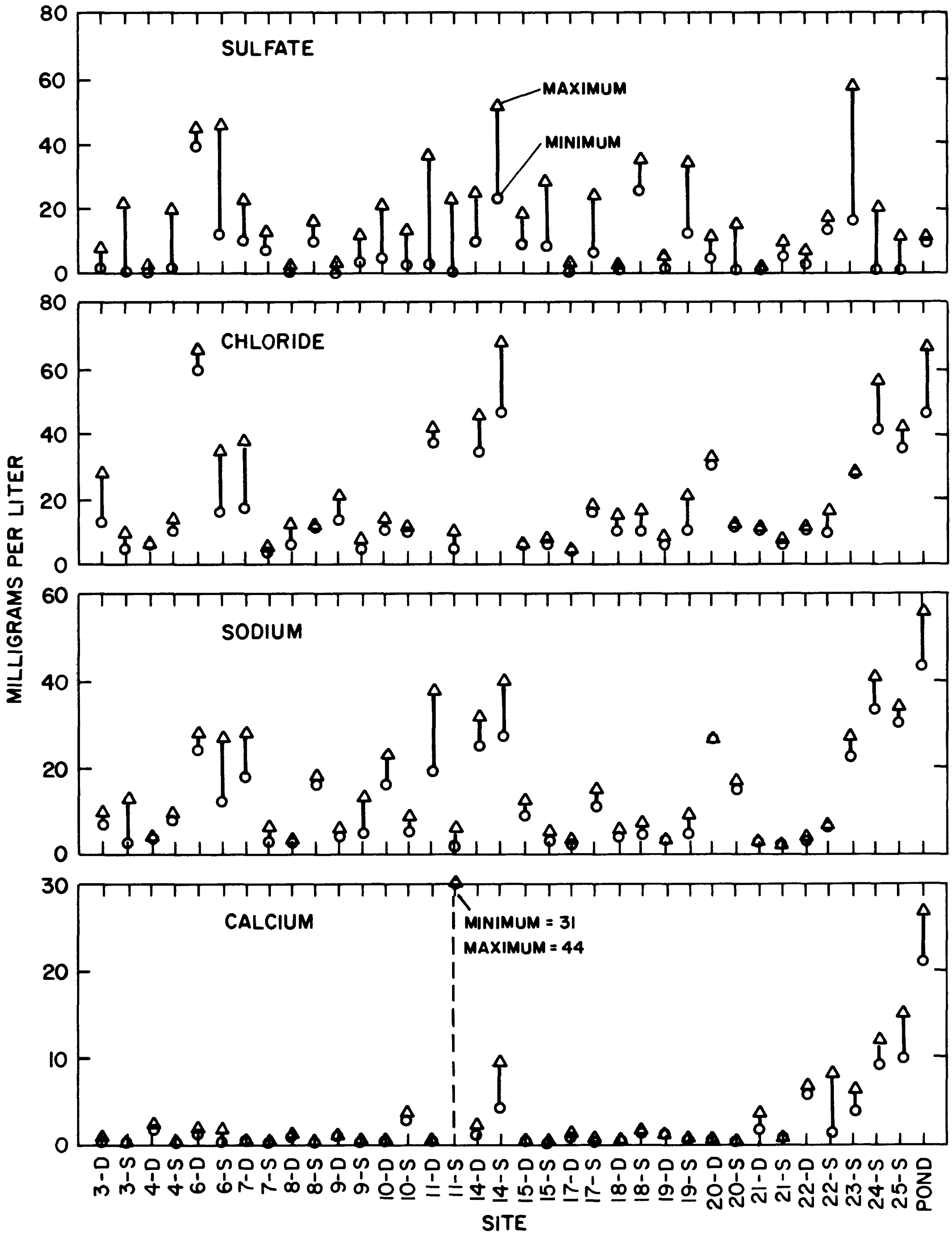


Figure 14. Variation in sulfate, chloride, sodium, and calcium in surficial aquifer system monitoring wells.

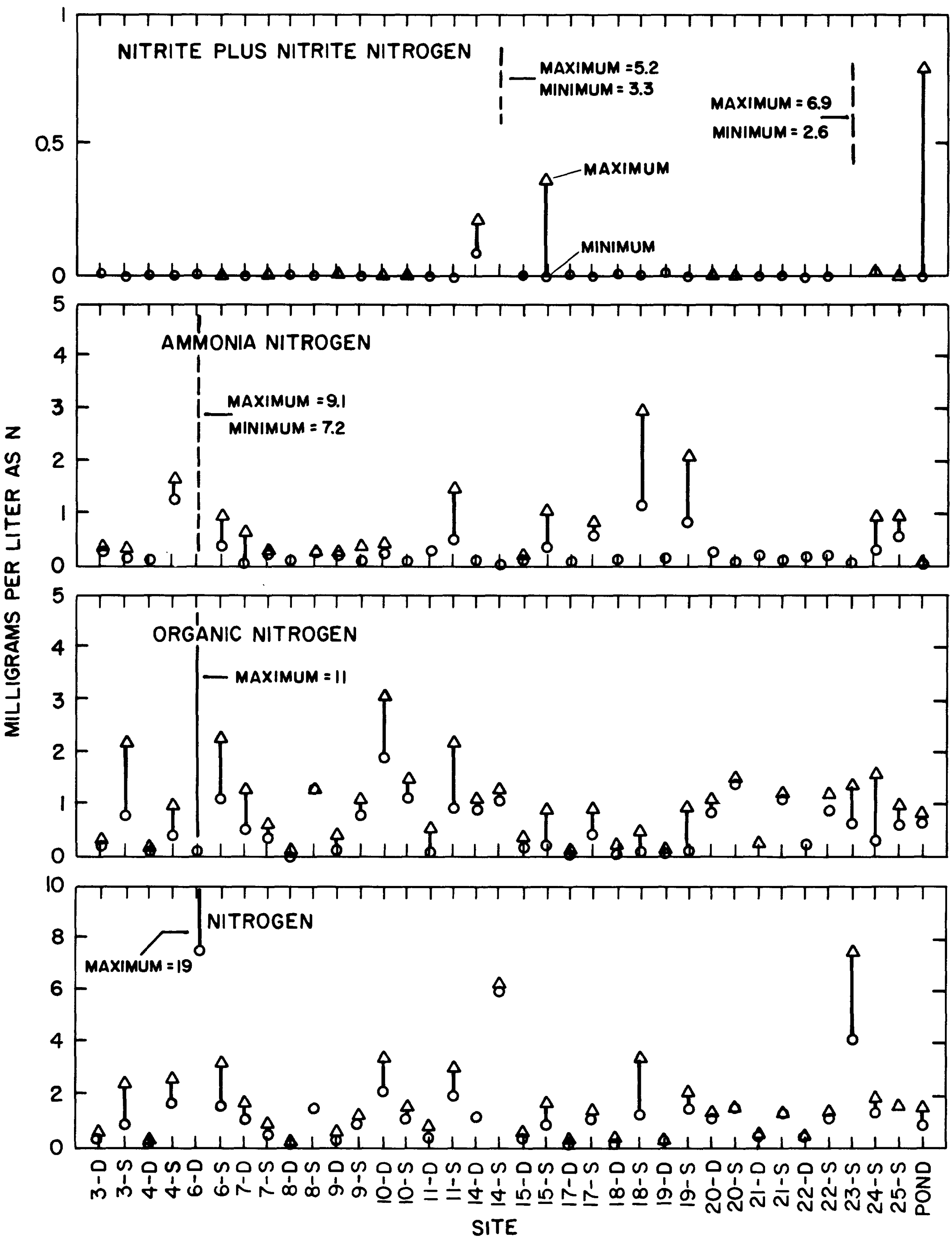


Figure 15. Variation in dissolved nitrite plus nitrate, dissolved ammonia, dissolved organic nitrogen, and total dissolved nitrogen in surficial aquifer system monitoring wells.

Variation in dissolved phosphorus, orthophosphate, and pH is shown in figure 16. Dissolved phosphorus variation was less than 0.1 mg/L in 75 percent of the sites. This is also true of orthophosphate. Variation in pH was 0.6 units or less at 72 percent of the sites.

In summary, figures 13 through 16 indicate that, while some water-quality characteristics are variable, the data are probably consistent enough to allow mean concentrations at the sites to be used for interpreting water-quality effects of the land application of wastewater.

EFFECT OF WASTEWATER APPLICATION ON WATER QUALITY

Water-Quality Type as Related to Wastewater Application

The quality of water in the surficial aquifer system is determined by the quality of the recharge water and the processes, discussed previously, taking place in the soil zone and the aquifer. In the study area, recharge to the surficial aquifer system is from three sources: (1) rainfall, (2) wastewater, and (3) Floridan aquifer system water used for irrigation. If the soils and the aquifer material were chemically and physically inert, and if other sources of materials (such as fertilizer application) are insignificant, water quality in the aquifer would be that of a mixture of the recharge waters. The extent to which various processes or materials input are affecting water quality can be assessed by comparing samples of water quality from the surficial aquifer system with hypothetical mixtures of the recharge waters.

Rainfall quality was not sampled as part of the study. Irwin and Kirkland (1980, p. 63-64) report summaries of analyses of composited samples of bulk precipitation at Lake Hope at Maitland, about 20 miles northeast of the study area. Lake Hope is in an urbanized area, and precipitation quality at the study area may be different than at Lake Hope. However, the Lake Hope data provide at least an indication of precipitation quality in central Florida. Summaries for selected variables, in milligrams per liter unless indicated, for July 1972 through September 1978, follow:

Variable	Mean	Range
Specific conductance (μS/cm at 25 °C)	23	13 - 58
pH units	—	5.0 - 7.5
Chloride	1.6	.6 - 2.7
Total nitrogen	1.6	.19 - 6.8
Total phosphorus	.18	.01 -. 89

This summary indicates that specific conductance and chloride concentration of precipitation are likely to be very low in comparison to surficial aquifer system water in the study area (figs. 13 and 14). The nitrogen and phosphorus content of precipitation, however, may be comparable to, or even greater than, nitrogen and phosphorus content of the surficial aquifer system water.

Some surficial-aquifer water samples are thought to represent background, or ambient, water quality and are probably representative of the surficial aquifer system where precipitation is the only input of materials. Wells with a chloride concentration of less than 10 mg/L and a specific conductance of less than 70 are probably unaffected, or only minimally affected by man-caused input of materials. Using this criteria, five shallow wells and five deep wells are probably representative of background, or near background conditions.

The five wells thought to represent background conditions in the shallow part of the surficial aquifer system are 3-S, 7-S, 9-S, 15-S, and 21-S. Waters from all of the shallow wells represent a wide variety of chemical types, but most of the waters are within or near the area that represents mixing of Floridan aquifer system water, wastewater, and the background water (polygon in fig. 17).

Wells 8-S and 20-S plot relatively far from the mixture polygon, having water with almost no calcium or magnesium. This may be an indication that both wells are in an area where ion-exchange processes are removing calcium and magnesium from the waters, replacing them with sodium and potassium.

Well 11-S is the only site where water has a strong resemblance to Floridan aquifer system water type. This well is located between the tree farm and the wastewater pond, and thus, would be expected to resemble wastewater. The reason for the type resemblance of water from well 11-S to Floridan aquifer system water is not known.

Wells 23-S, 24-S, and 25-S resemble the wastewater in chemical type as expected, because these wells are within the tree farm. Two other wells (6-S and 14-S) that are immediately adjacent to the tree farm are in the flow path of the wastewater application, as indicated by relatively high chloride concentrations. The mean chloride concentration is 26 mg/L in water from well 6-S and 56 mg/L in water from well 14-S. The mean chloride concentration in the wastewater is about 60 mg/L, indicating that water sampled at well 14-S is nearly undiluted wastewater. Bicarbonate concentration in both wells is relatively low, indicating neutralization of the alkalinity in the wastewater by humic and fulvic acids leached from the soils as the wastewater flows away from the tree farm.

Water from well 9-S, thought to represent background conditions because of the low chloride concentration, has a chemical type similar to that of wastewater. This is an indication that background water can resemble wastewater in type if not in concentration of the dissolved constituents.

The five wells thought to represent background conditions in the deeper part of the surficial aquifer system are: 4-D, 8-D, 15-D, 17-D, and 19-D. These wells, together with the wastewater and Floridan aquifer system water, define a wide range of chemical types (fig. 18). Waters from many of the deeper wells, however, are outside the mixing polygon.

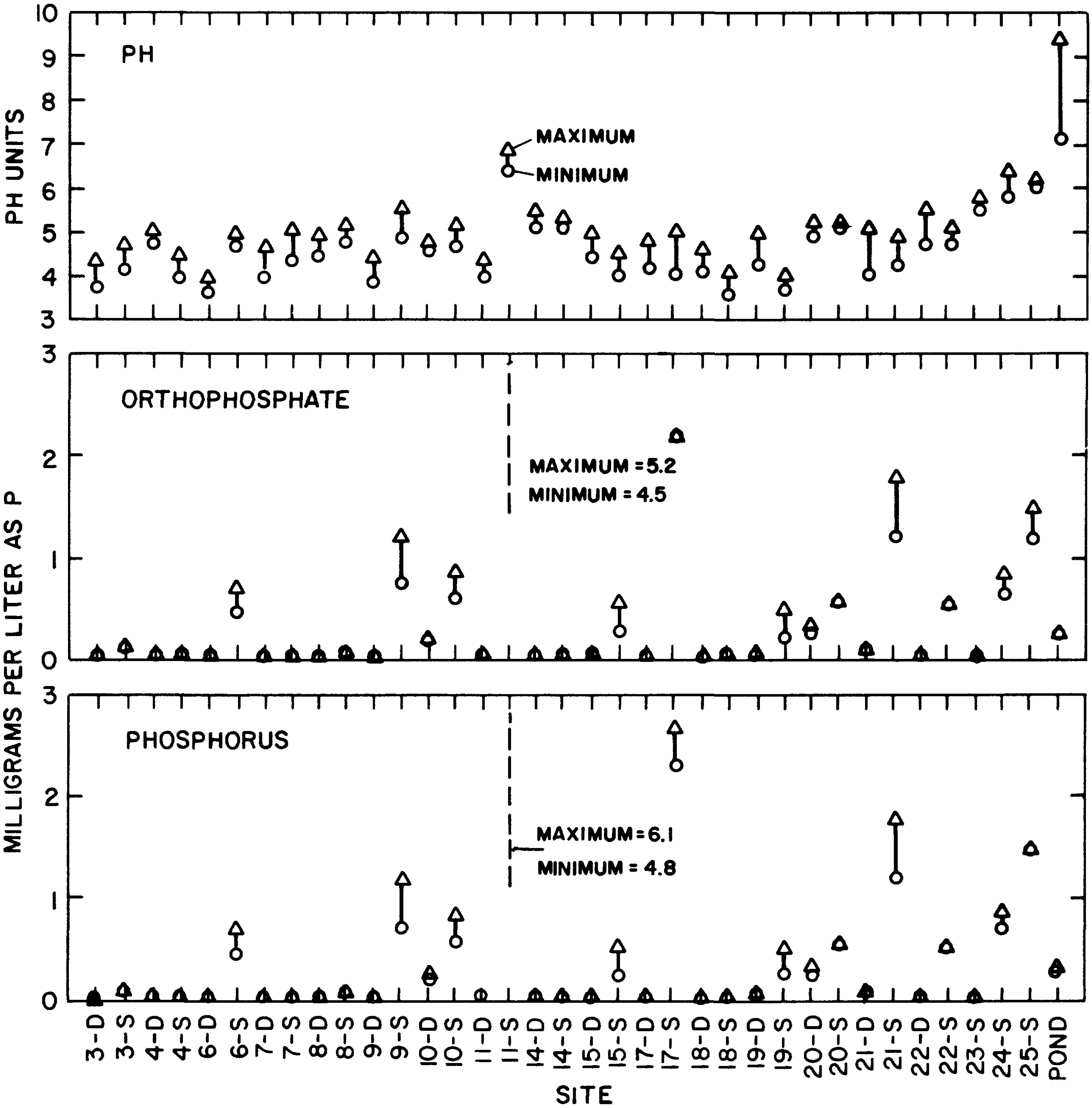
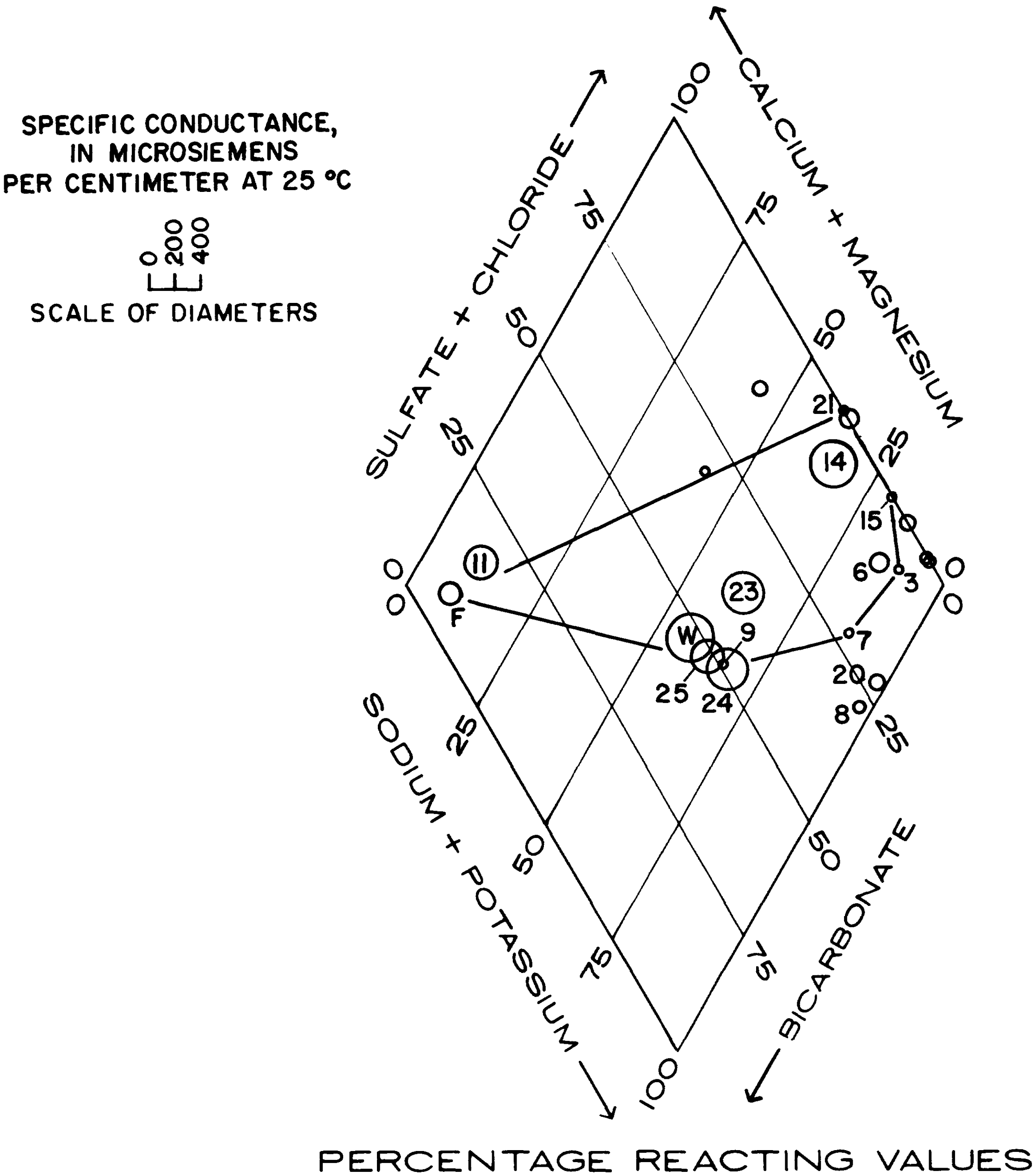


Figure 16. Variation in pH, dissolved orthophosphate, and dissolved phosphorus in surficial aquifer system monitoring wells.



EXPLANATION: CENTER OF CIRCLE INDICATES PLOTTING LOCATION. NUMBERS IDENTIFY WELLS MENTIONED IN TEXT. F INDICATES FLORIDAN AQUIFER WATER. W INDICATES WASTEWATER

Figure 17. Major ion ratios in shallow surficial aquifer system monitoring wells.

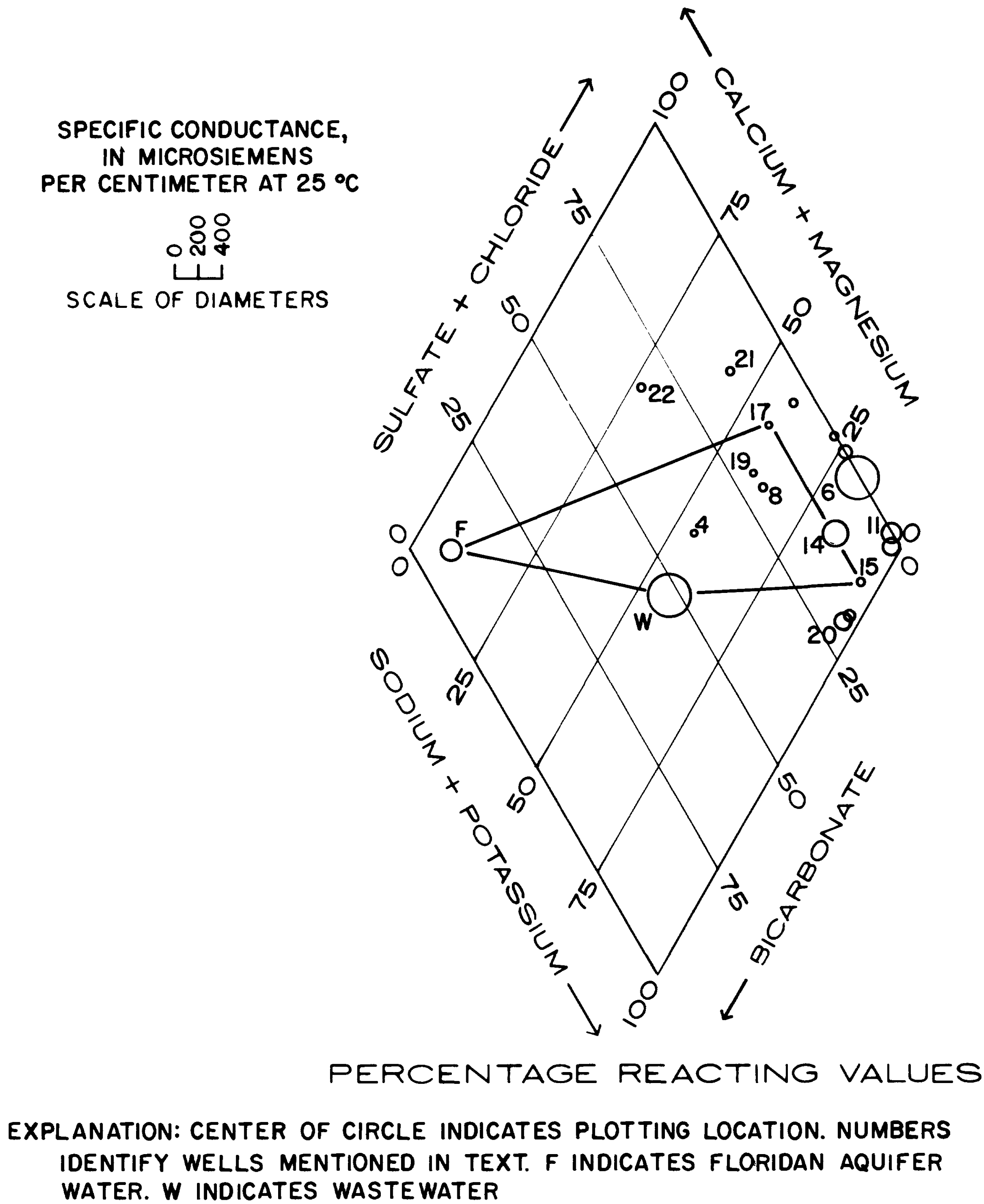


Figure 18. Major ion ratios in deep surficial aquifer system monitoring wells.

Many of the waters outside the mixing polygon are characterized by low bicarbonate concentrations, even those containing relatively high chloride concentrations indicating they are affected by wastewater. For example, water from wells 6-D, 11-D, 14-D, and 20-D contained an average chloride concentration ranging from 31 mg/L to 63 mg/L, but unlike the wastewater, little or no bicarbonate. The low bicarbonate concentrations are probably the result of neutralization by the humic and fulvic acids leached from soils.

Waters from wells 21-D and 22-D have a greater calcium plus magnesium percentage than waters from other wells. This is perhaps an indication of leakage of water from the Floridan aquifer system, with reduction of the bicarbonate concentrations because of neutralization.

Nitrogen Speciation

Nitrogen speciation can be depicted on triangular plots by ratios of average organic nitrogen, ammonia nitrogen, and nitrite plus nitrate nitrogen to the total nitrogen. The wastewater nitrogen is mostly in the organic form, about 60 percent, as shown in figure 19. Nitrate accounts for about 34 percent, and ammonia for the remaining 6 percent of the total nitrogen. The high percentage of organic nitrogen in the wastewater is probably due to the high levels of algae in the wastewater pond. These organisms store nitrogen in their cellular structure and also produce high oxygen levels in the pond through photosynthesis. The latter process keeps ammonia concentrations low by oxidizing ammonia to nitrate.

Figure 19 shows that all but two of the shallow wells have nitrogen highly dominated by the organic and ammonia species. Only three wells contained more than 2 percent nitrite plus nitrate nitrogen. These are wells 15-S (about 15 percent nitrite plus nitrate), and wells 14-S and 23- S,each with about 80 percent nitrite plus nitrate. The high nitrite plus nitrate in wells 14-S and 23-S is perhaps not surprising because these wells are either in (well 23-S), or very near (well 14-S), wastewater application areas. The typical high level of nitrite plus nitrate in well 15-S is probably not related to wastewater because the low chloride concentration in the well water (7 mg/L) is an indication that the well is not affected by the wastewater application. Because well 15-S is near the area where bedding plants are cultivated and irrigated with water from the Floridan aquifer system (which is low in nitrogen), it seems likely that the nitrite plus nitrate originates from use of fertilizers in the bedding-plant area.

Wells 24-S and 25-S, both located within the wastewater application areas, have small amounts of nitrogen in the nitrite plus nitrate form. This is in contrast to wells 23-S and 14-S, in or adjacent to the wastewater application area where most of the nitrogen is nitrite plus nitrate. The major difference in the environment around these wells is the thickness of the unsaturated zone, which is related to the proximity of the wells to the boundary canal. At well 23-S, the water table is about 9 feet beneath the land surface, and at well 14-S, the water table is about 12 feet beneath the land surface, because the wells are located relatively close to the canal. This is in contrast to wells 24-S and 25-S, not near a canal, and where the water table is therefore only about 3 feet beneath the land surface. The depth to water could be significant; the deeper water table at wells 14-S and 23-S allows the wastewater to percolate out of the shallow root zone before plants can utilize the very soluble and mobile nitrate nitrogen which is produced by oxidation of organic and ammonia forms on and near the land surface. Another possibility is that oxidation to nitrate is more likely in a thick unsaturated layer than in a thin one.

Distribution of nitrogen species in the deep wells (fig. 20) is similar to that in the shallow wells, except that only one of the deep wells (well 14-D) contained more than about 2 percent nitrite plus nitrate nitrogen. Well 14-D, which contains about 11 percent nitrite plus nitrate, is at the same site as the shallow well 14-S which has a nitrite plus nitrate of about 80 percent. The change in nitrogen speciation with depth at this site is accompanied by a change in dissolved nitrogen concentration, from 6.2 mg/L in the shallow well to 1.2 mg/L in the deep well. This change in concentration may be the result of denitrification, which is the reduction of nitrate to nitrite, nitrous oxide, and nitrogen gas.

The process of denitrification is suggested by the fact that the decrease in the concentration of chloride, which moves conservatively through the aquifer, is relatively small compared to the decrease in nitrate. This is an indication that processes other than dilution are contributing to reduction in nitrogen concentration. Also, nitrate accounted for most of the difference in dissolved nitrogen between wells 14-S and 14-D, as indicated by the following comparison in average concentrations:

	Well 14-S (mg/L)	Well 14-D (mg/L)	Difference (percent)
Ammonia nitrogen	0.04	0.10	150
Chloride	58	40	-31
Nitrate nitrogen	4.4	.10	-98
Nitrite nitrogen	.005	.005	0
Organic nitrogen	1.1	1.0	-9

The difference in average chloride concentration was about 31 percent, compared to a difference in nitrate of about 98 percent. Ammonia also showed a large percentage difference, but the concentrations of ammonia were relatively low, so that small differences in concentration resulted in a large percentage change.

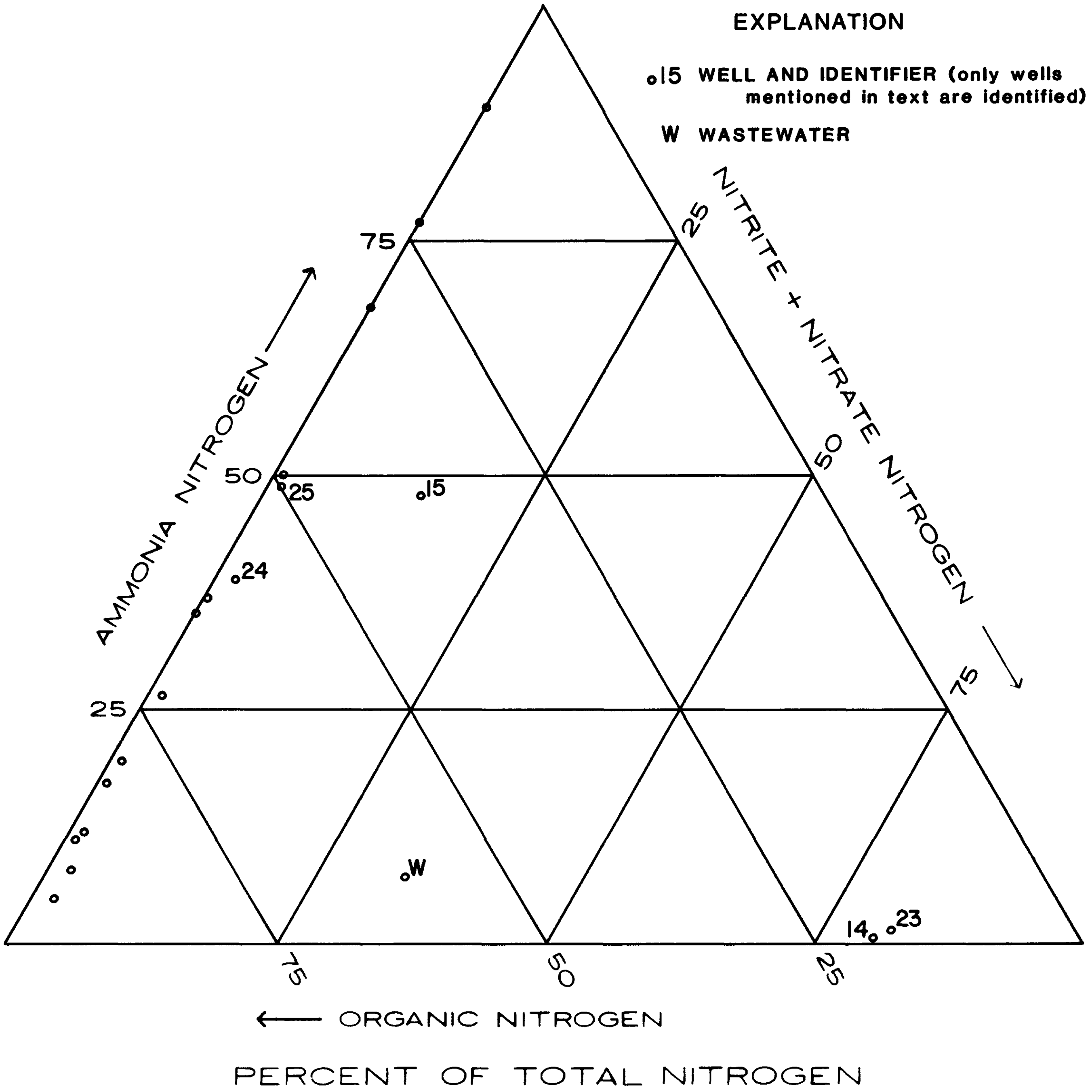


Figure 19. Dissolved nitrogen species distribution in shallow surficial aquifer system wells.

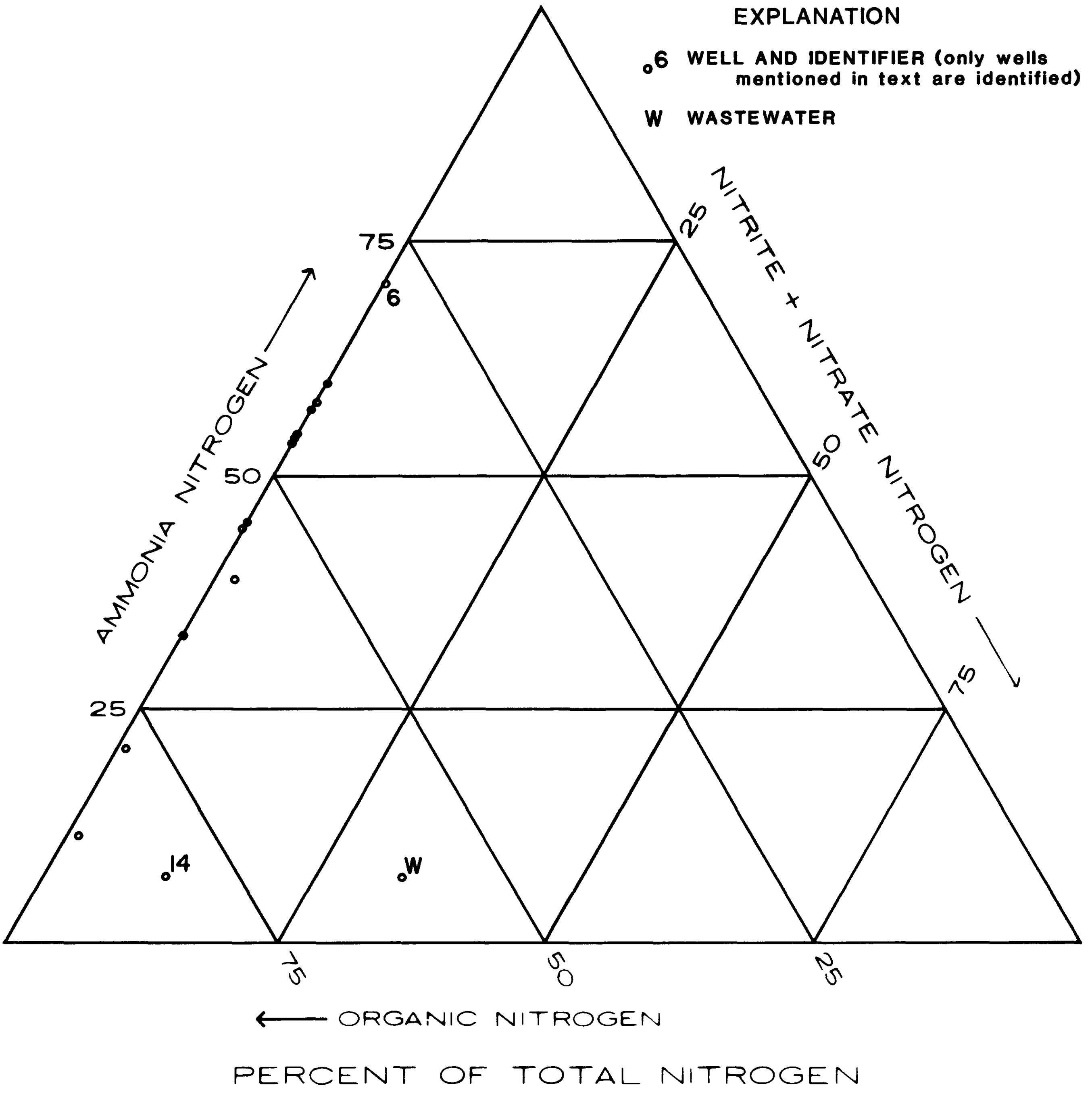


Figure 20. Dissolved nitrogen species distribution in deep surficial aquifer system wells.

Areal Patterns in Water Quality

Chloride

Chloride is probably the best tracer of wastewater movement because it is present in relatively high concentrations in the wastewater and moves conservatively through the aquifer. Chloride concentration in the wastewater pond on the dates of well sampling ranged from 46 to 67 mg/L (fig. 14). Additional data furnished by the Reedy Creek Improvement District laboratory for October 1984 through July 1985 showed a range of 38 mg/L to 91 mg/L in 38 samples for the wastewater pond and a mean chloride concentration of 61 mg/L.

The highest chloride concentrations in the shallow wells occur at or near the points of wastewater application, as would be expected (fig. 21). The five shallow wells with the highest average chloride (25 mg/L or greater) are 6-S (26 mg/L), 23-S (27 mg/L), 25-S (38 mg/L), 24-S (48 mg/L), and 14-S (58 mg/L). However, some shallow wells located near the tree farm areas have low chloride concentrations and apparently are not located within ground-water flow paths from the tree farm. For example, wells 7-S, 9-S, 11-S, and 15-S all have a mean chloride of less than 7 mg/L.

The highest chloride concentrations in the deeper part of the surficial aquifer system (wells deeper than 18 feet) are at or near the tree farm boundaries. Wells 11-D, 14-D, and 6-D had a mean chloride concentration ranging from 39 to 63 mg/L (fig. 21). Another deep well (20-D), located 900 feet west of the application area, had a mean chloride concentration of 31 mg/L. The high chloride in this well is probably a result of previous wastewater application in the area west of the present tree farm. Wastewater was applied there in the early 1970's, prior to completion of the existing tree farms.

The rather large difference in chloride concentration between shallow and deep wells at some sites indicates that water quality in the surficial aquifer system differs vertically as well as areally in response to wastewater application, at least in the upper 20 or 30 feet of the surficial aquifer system. In some locations (particularly wells 6, 7, and 11), water from the shallow wells was considerably lower in chloride than water from the deep wells. This is an indication that the water near the land surface in these locations is a mixture of rainfall and wastewater.

The vertical extent of the wastewater travel was examined by drilling two additional wells at the site of wells 14-S and 14-D, one 42-feet deep and one 62-feet deep. Data from these wells, presented in a following section, indicated that chloride concentration at 42 and 62 feet were at background levels and, therefore, that wastewater was probably not affecting deeper parts of the surficial aquifer system.

Nitrogen

The highest dissolved nitrogen concentrations were in wells in, or near, the tree farm and generally occurred in the shallow wells (fig. 22). Wells 6-S, 18-S, 11-S, 23-S, and 14-S, with the highest dissolved nitrogen concentration, all contained more than 2.3 mg/L of dissolved nitrogen. Of these, only well 18-S is not within or on the boundary of the tree farm. However, well 18-S is near the bedding-plant area and, therefore, could be affected by fertilizer application.

Dissolved nitrogen concentrations in the deep wells were highest near the tree farm (wells 6-D, 7-D, and 14-D) and in the original application areas (wells 10-D and 20-D). The deep wells generally had lower nitrogen concentrations than the shallow wells, with a particularly notable exception. This is at the site of wells 6-S and 6-D, where dissolved nitrogen concentration in 6-D (11.44 mg/L) was nearly five times greater than in 6-S. Most of the nitrogen at well 6-D is in the ammonia form (fig. 20). The reason for the high nitrogen concentration in well 6-D (nearly four times higher than in any other well) is not known. This anomalously high concentration may be the result of a fertilizer spill or some other event, perhaps localized within a clay lens where mixing of the water with surrounding water is slow.

Phosphorus

Unlike chloride and nitrogen, the phosphorus concentration in many of the shallow wells exceeded that in the wastewater. The phosphorus concentration of the wastewater averaged 0.55 mg/L, based on data for 179 samples furnished by the Reedy Creek Improvement District laboratory for October 1984 through July 1985. Nine of the nineteen shallow wells had amean phosphorus concentration higher than 0.55 mg/L. Four of the wells (11-S, 17-S, 21-S, and 25-S) had a mean phosphorus concentration of 1.5 mg/L or more. These four wells have little in common, except that all are located near the north end of the study area and in the general vicinity of the sludge-spreading field and the wastewater pond (fig. 23). Water seeping from these areas could be high in phosphorus, but should also contain high concentrations of chloride. Wells 17-S and 21-S do not contain high concentrations of chloride (fig. 21), an indication that the relatively high phosphorus concentrations are not related directly to wastewater. The reasons for the high phosphorus concentrations remain unknown.

Phosphorus concentrations in two shallow wells in or near the tree farm (wells 14-S and 23-S) were less than 0.05 mg/L, among the lowest of any of the wells. The low phosphorus in these wells, both of which are in the flow path of the wastewater, may be due to the thickness of the unsaturated layer, in which precipitation of phosphorus complexes could be occurring, thus removing the phosphorus before it can reach the water table.

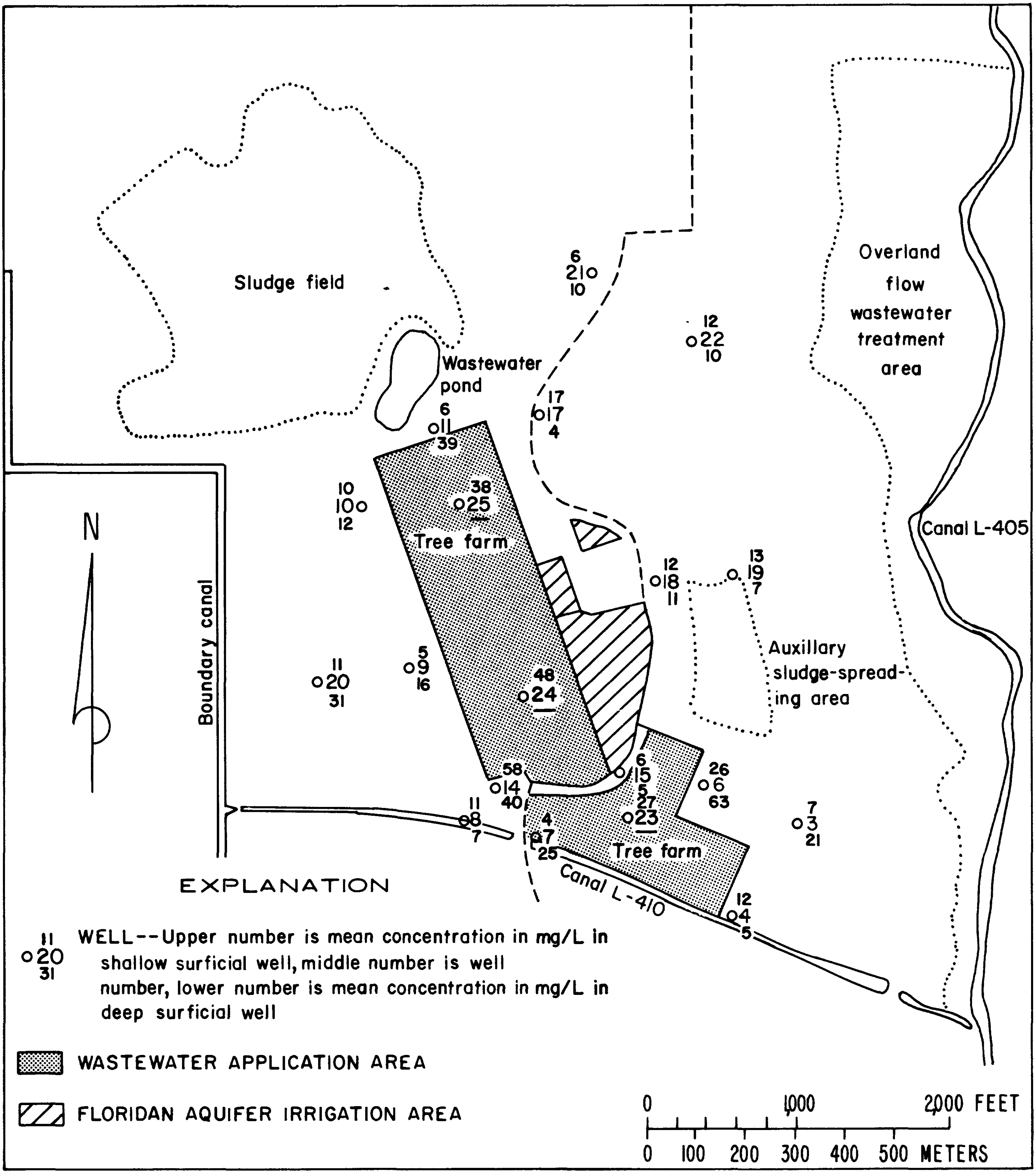


Figure 21. Areal distribution of mean dissolved chloride concentrations in the surficial aquifer system.

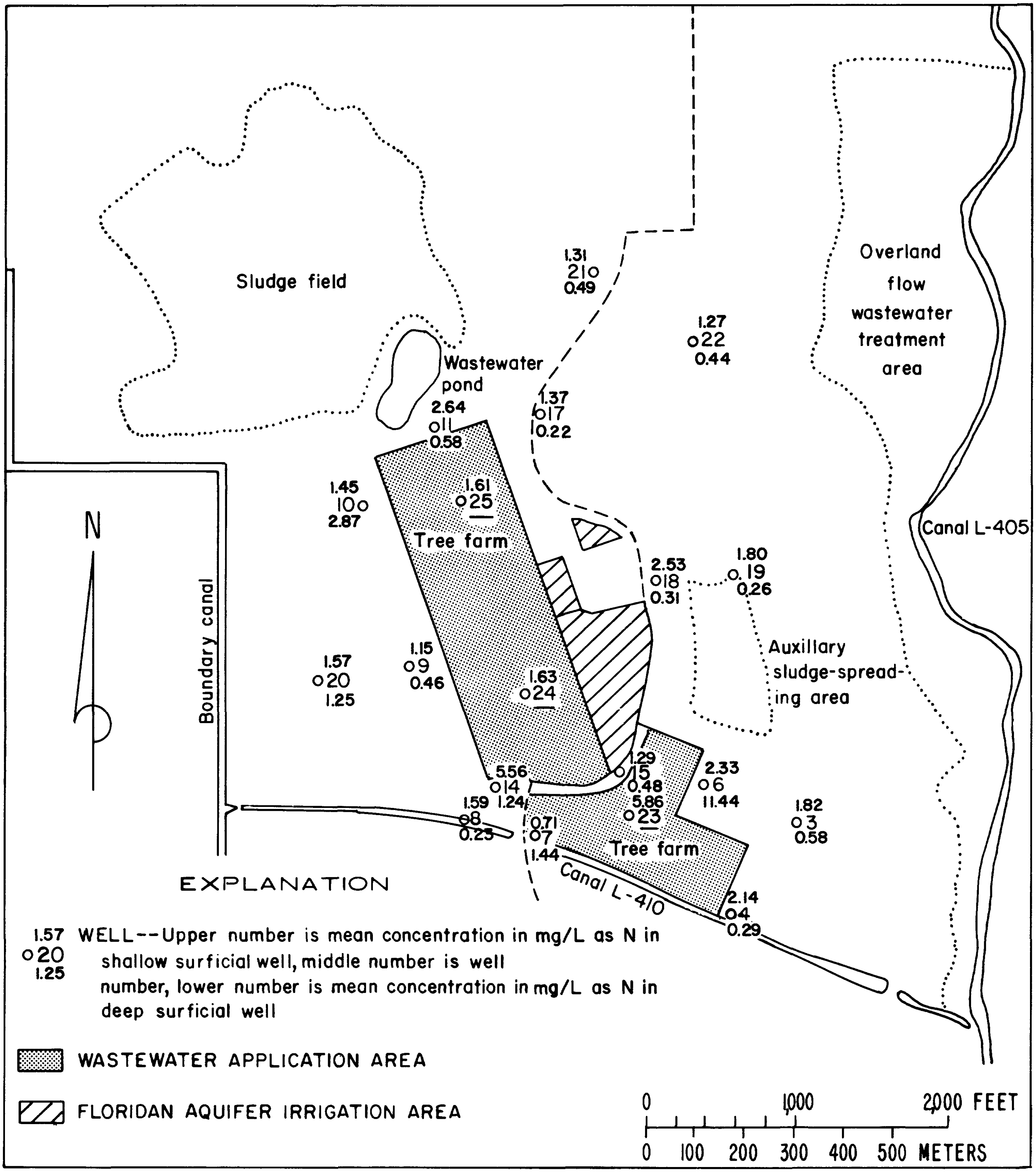


Figure 22. Areal distribution of mean dissolved nitrogen concentrations in the surficial aquifer system.

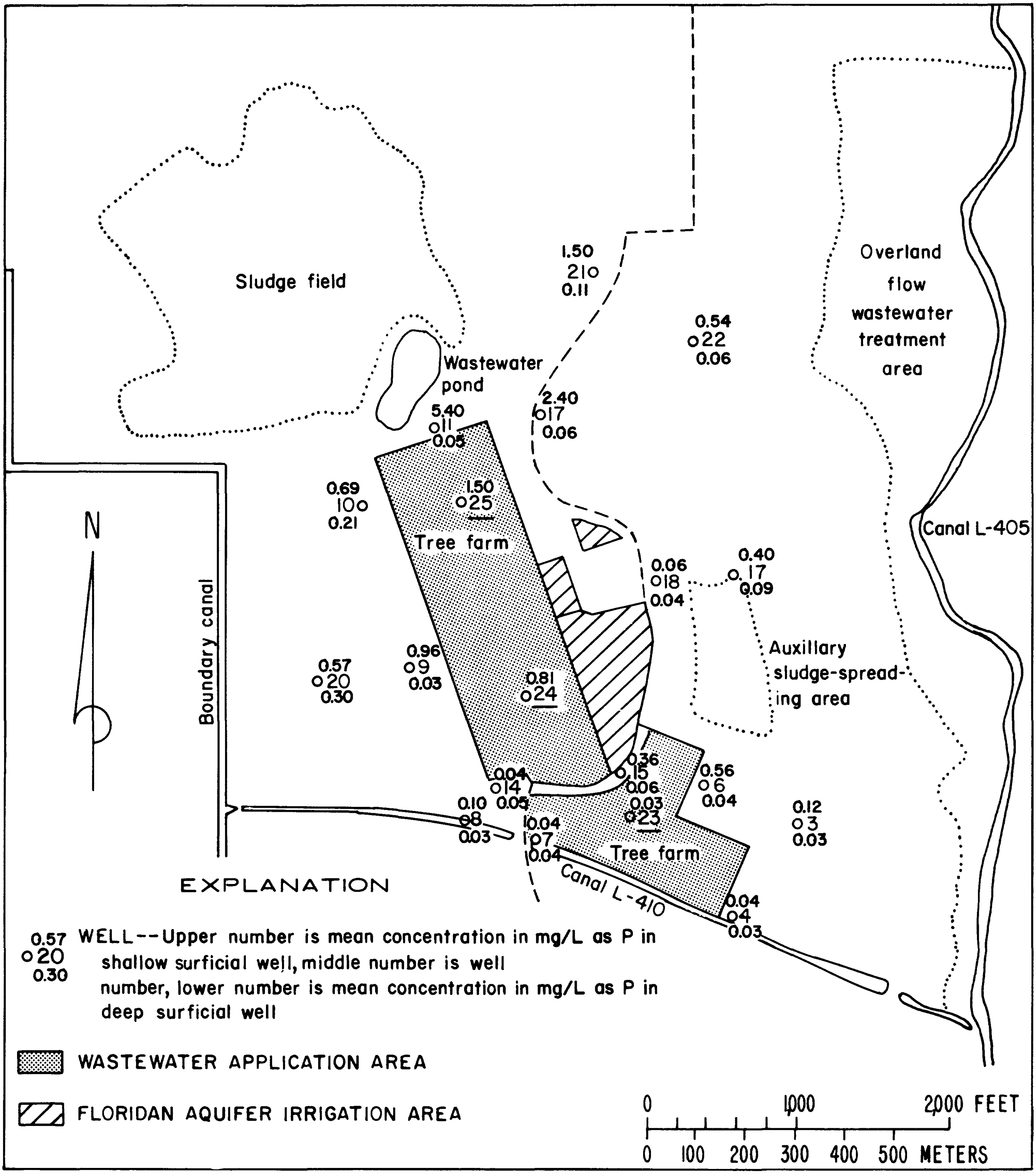


Figure 23. Areal distribution of mean dissolved phosphorus concentrations in the surficial aquifer system.

Phosphorus concentrations in the deep wells were generally much lower than in the shallow wells. The maximum mean phosphorus concentration in a deep well was only 0.3 mg/L, a value that was exceeded in 12 of the 19 shallow wells. The highest mean phosphorus concentrations, greater than 0.2 mg/L, were in the original wastewater application area (wells 10-D and 20-D), east of the boundary canal. However, well 9-D, in that area, had a very low phosphorus concentration.

Vertical Pattern in Water Quality

Changes in water quality with depth have been discussed in previous sections in which the set of shallow surficial-aquifer monitoring wells has been compared with the deeper wells. These comparisons have indicated that, in general, the deeper part of the surficial aquifer system is characterized by lower concentrations of most dissolved constituents (fig. 12). This is an indication that vertical movement of the wastewater constituents is insignificant or is very slow in comparison with horizontal movement.

One site was selected for additional study of the variation in water quality with depth. This was at the site of wells 14-S and 14-D. These wells both contain relatively high concentrations of chloride (averaging 58 mg/L for 14-S and 40 mg/L for 14-D), indicating the presence of wastewater. Two additional wells were constructed at this site, one screened from 39 to 42 feet below the land surface, and the other screened from 59 to 62 feet below the land surface. These additional wells, together with wells 14-S and 14-D, were sampled once, in June 1985. Selected dissolved constituent concentrations in milligrams per liter, are listed below:

Well No.	Screen depth, (feet)	Chlo- ride	Total nitro- gen	Ammon- ia (N)	Ni- trate (N)	Phos- phorus
14-S	15-18	68	4.3	0.06	3.3	0.03
14-D	20-23	40	1.1	.24	.01	.03
14-42	39-42	6.5	.24	.12	.01	.02
14-62	59-62	6.5	.62	.13	.01	.02

These data (especially the low chloride concentrations in deeper wells) indicate that the vertical migration of wastewater is presently confined to the upper 30 feet of aquifer or less. Some vertical migration of wastewater constituents undoubtedly does occur, because of the process of molecular diffusion, but the rate of migration by this mechanism is probably slow enough that wastewater has not had enough time since initial application to migrate to the deeper parts of the aquifer.

SOLUTE TRANSPORT IN THE SURFICIAL AQUIFER SYSTEM

A one-dimensional solute transport model was used to determine rate of chloride movement from the tree farm to boundary canals along three selected flow paths. This was done to gain a better understanding of rates of constituent movement. Use of chloride, which is a conservative constituent, represents a maximum rate of movement. Other constituents which interact with the soil or aquifer materials will move more slowly than chloride, and at a rate dependent on the degree of interaction. This model cannot be used to compute actual concentrations at a selected point and time, because it does not consider the effect of natural recharge along the flow path. However, it can be used to estimate how long the wastewater front will take to reach a selected point. This information may be useful in studies of water quality in the canals which may now or in some future time be affected by wastewater infiltration. Also, it may aid in planning of future studies of surficial aquifer system water quality in the tree farm area. The model is described by the following equation:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x} - K_d C$$

where

C = solution concentration (mg/L),
D = dispersion coefficient (ft^2/d),
V = interstitial pore-water velocity (ft/d),
K_d = degradation rate coefficient (1/d),
x = existance from application ppint (feet), and
t = time since beginning of application (days).

Transport of the chloride ion along two selected flow paths from the application area to the study area boundaries was modeled. To do this, it was necessary to determine values for the model coefficients listed above.

Because chloride is relatively inert with respect to the aquifer substrate, the degradation rate (K_d) was assumed to be zero (no degradation). Interstitial pore-water velocity was estimated from Darcy's equation:

$$V = (K/n) * dH/dL$$

where

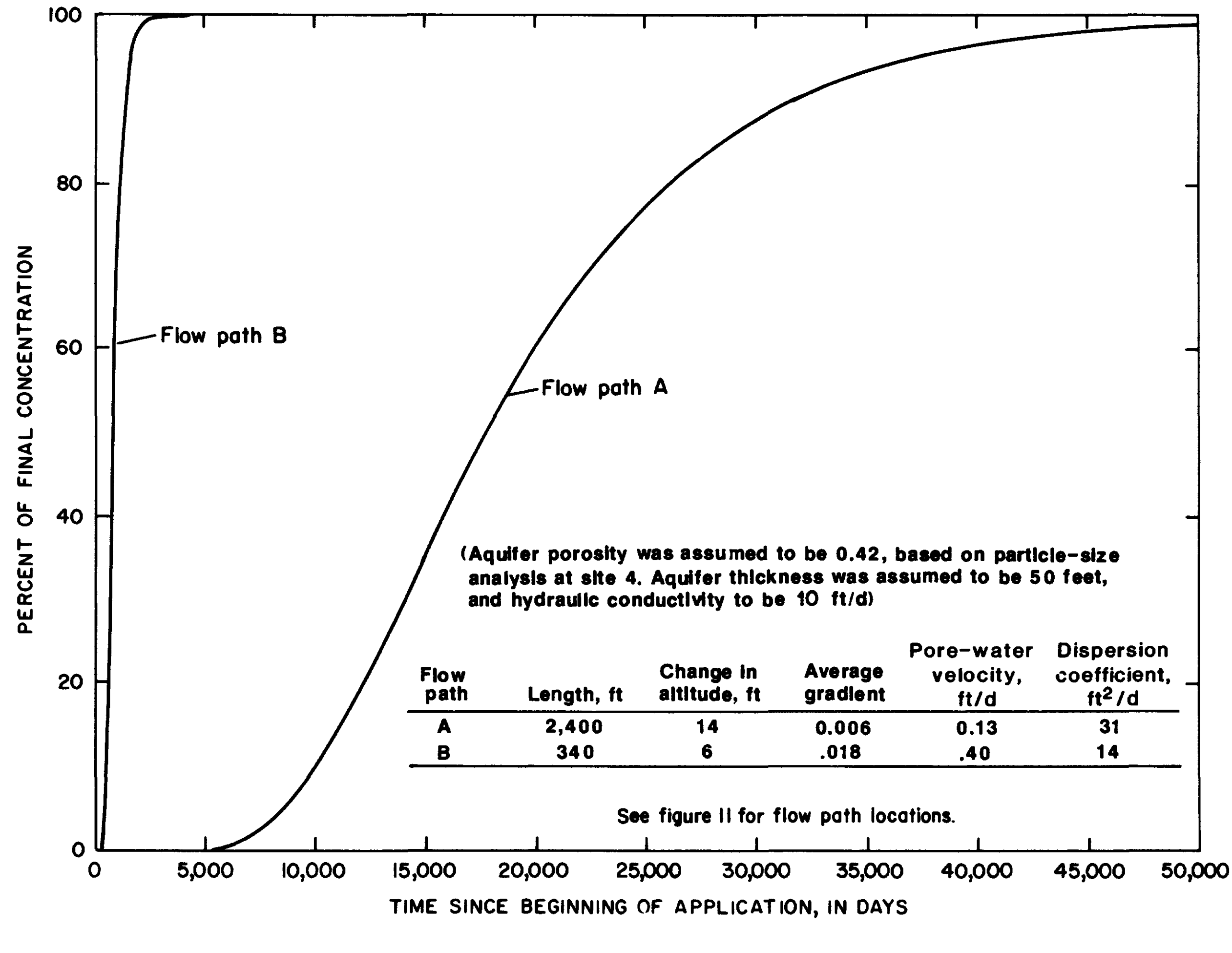
V = interstitial pore-water velocity (ft/d),
K = hydraulic conductivity (ft/d),
n = porosity (dimensionless), and
dH/dL = ground-water gradient, or vertical change horizontal distance (dimensionless).

The mathematical solution to this model is described in several publications dealing with solute transport, for example, Novotny and Chesters (1981), Javandel and others (1984), and Donigian and others (1983).

Hydraulic conductivity is calculated by dividing transmissivity (500 ft^2/d) by aquifer thickness (assumed to be 50 feet in the study area), and is 10 ft/d. Porosity is estimated to be 0.42, based on particle-size analysis of samples at the site of well 4-D. The average ground-water gradient was determined from the estimated water levels at the beginning and end of the flow paths (fig. 11).

The dispersion coefficient is more difficult to estimate; it is the sum of two terms, which are the dynamic dispersion due to the water movement through the aquifer, and the molecular diffusion, due to movement of the ions or molecules in solution. Dynamic dispersion is far more significant than ionic (molecular) diffusion except when ground-water velocities are very low (Freeze and Cherry, 1979). Therefore, dynamic dispersion probably accounts for nearly all of the horizontal dispersion in the study area. Molecular diffusion could be the dominant factor in vertical migration of solutes, due to the presumed slow, vertical movement of the water. Dispersion is difficult to measure directly, and results obtained in field or laboratory experiments may not be representative of the entire study area. Evidence indicates that a general rule for estimating dispersion is to set dispersivity (not dispersion) to 10 percent of the distance of the flow path (Gelhar and Axness, 1981), and then multiply this estimated dispersivity by pore-water velocity to get the dispersion coefficient. This was the method used in this study, resulting in a different value of the dispersion coefficient for each flow path considered.

The change in concentration with time at the end of two flow paths is shown in figure 24, along with the physical characteristics of the flow paths (length, gradient, pore-water velocity, and estimated dispersion coefficient). The location of the two flow paths is shown in figure 11. Figure 24 shows that for the relatively short flow path B, equilibrium or near-equilibrium concentrations of the chloride ion were probably established within about 2,500 days (7 years) at Canal L-410. At the end of the flow path A, or about 2,360 feet from the tree farm, there should be no increase in chloride due to migration of the wastewater for about 5,000 days (14 years), according to this analysis.



Flow path	Length, ft	Change in altitude, ft	Average gradient	Pore-water velocity, ft/d	Dispersion coefficient, ft^2/d
A	2,400	14	0.006	0.13	31
B	340	6	.018	.40	14

Figure 24. Predicted chloride concentration at ends of two selected flow paths.

Furthermore, the model shows that concentrations of chloride at the end of flow path A are near maximum but are still increasing slowly in response to wastewater application 50,000 days (137 years) after beginning of application.

The importance of dispersion in solute transport can be realized by considering that, if dispersion is zero and travel of the wastewater front is a function only of advection, the front would arrive abruptly at the end of flow path A after about 17,800 days (49 years), after which there would be no further concentration increase. Using the estimated dispersion of 31 ft^2/d, the chloride concentration would begin to increase significantly after about 5,000 days (14 years), and at 17,800 days would have increased to little more than half the final value (fig. 24). Thus, the effect of dispersion is to hasten the arrival of the wastewater front, and to delay the rise to peak concentration.

SUMMARY AND CONCLUSIONS

Spray irrigation is used to dispose of a part of the treated wastes from the Reedy Creek Utility Company serving the Walt Disney World complex. The irrigated area is used to grow ornamental plant stock for use in landscaping throughout the complex. Not all of the wastewater treatment plant effluent is utilized in the sprayfield operation. The quantities that are used amount to about 41 in/yr.

The wastewater being applied is high in nutrients and has an effect on the ground-water quality near the application area. To evaluate the effect, about 2.7 million square feet (62 acres) of the spray irrigation system was selected for study, with emphasis being placed on the quality of the ground water in the surficial aquifer system beneath the application area. The study area is bounded on three sides by canals or impounded wetlands. The objectives of the study were to determine direction of movement and destination of the wastewater and its constituents, to determine rate of movement of the wastewater front, to determine effect of the wastewater application on the water quality in the underlying aquifers, to determine nature of the processes affecting wastewater assimilation, and to determine the hydraulic characteristics of the surficial aquifer system.

A network of surficial aquifer system wells was constructed and sampled for nitrogen and phosphorus species, and major dissolved inorganic constituents. This network was also used to determine hydraulic gradients and, therefore, rates and direction of water movement. Core samples were collected from four sites to determine aquifer lithology, and selected samples were used to determine particle-size distribution. An aquifer test was conducted to determine surficial aquifer system transmissivity.

Some of the major findings of this study are as follows:

- Analysis of core samples at four surficial aquifer system sites indicated that the upper 30 to 60 feet is generally composed of sand, or sand with dark-brown silty material. Analysis of the samples from one of the wells indicated that the proportion of clay sized particles increased from 0.3 percent at the land surface to 15.7 percent at 40 feet below land surface. This increase in clay content with depth is characteristic of the transition from the surficial aquifer system to the confining Hawthorn Formation which separates the surficial aquifer system from the Floridan aquifer system.

- Average annual rainfall for the area is 52.4 inches based on records from NOAA stations at Kissimmee, Fla., and Ilseworth, Fla., for 1931-80. A rain gage near the study site showed annual rainfall for 1981-84 to range from 39.6 inches in 1981 to 57.6 inches in 1982. Water-quality samples were collected during 1983-84, and during these years rainfall was more typical of long-term conditions.

- Recharge was estimated from records of water level in the surficial aquifer system, in combination with rainfall records. Recharge estimates for 6 years ranged from 20 to 48 percent of rainfall, and averaged 34 percent. This method of estimation is imprecise, but the results indicate the relative magnitude of recharge. Actual recharge in the study area is thought to vary from place to place according to type of land cover and other factors.

- An aquifer test of the surficial aquifer system in the vicinity of the study area indicated that transmissivity is about 500 ft^2/d.

- Most of the recharge (rainfall, and wastewater not returned to the atmosphere) in the tree farm and bedding-plant areas probably moves laterally into the surrounding canals. Canal L-410 receives most of this recharge, estimated to average about 0.18 ft^3/s during the study.

- Water-quality type in the surficial aquifer system (with respect to the major dissolved inorganic constituents) is variable and does not always resemble a mixture of wastewater, Floridan aquifer system water, and background surficial aquifer system water, except in the immediate vicinity of the tree farm. Shallow wells within the wastewater application area yield water similar in type to the wastewater. Processes affecting the water types probably include cation exchange between wastewater and clay sized soil particles, and leaching of humic and fulvic acids from the soil.

- Most of the nitrogen in the surficial aquifer system water is in the organic and ammonia form. Exceptions are at a well near an area of bedding plant cultivation, probably affected by fertilizer usage, and two wells in or on the edge of the tree farm where the water table was at least 8 feet below land surface. Water from these wells had at least 15 percent of the nitrogen in the nitrate form. Other wells within the tree farm and where the water table was near the land surface did not have a significant nitrate proportion. Based on these data, it seems possible that depth to water has an effect on nitrogen speciation, perhaps because oxidation is more likely in a thick unsaturated layer, or because the nitrate form can be utilized by plants in areas where the water table is near the land surface.

- Chloride, probably the best tracer of wastewater movement, is present in highest concentrations in water from wells within or near the tree farm. However, some wells near the tree farm had low chloride concentrations, probably because of their location with respect to the principle ground-water flow paths from the application areas.

- Phosphorus concentration in nine wells exceeded 0.55 mg/L, the average concentration in the wastewater for October 1984 through July 1985, and in four wells was 1.5 mg/L or higher. The four wells with the highest concentration had little in common except that they are on the north side of the study area and in the general vicinity of a sludge-spreading field and the wastewater holding pond. The four wells did not all contain high concentrations of chloride, indicating they are not all affected by the wastewater. The reasons for the high phosphorus concentrations in some wells is unknown.

- The vertical pattern of water quality in the surficial aquifer system is indicated by comparison of samples taken at pairs of shallow and deep surficial aquifer system wells. In general, the deeper part of the surficial aquifer system (>30 feet) is characterized by lower concentrations of most constituents. A nest of four wells with sampling depths ranging from 15 to 62 feet, located at the edge of the tree farm, indicated that there is no evidence for deep vertical penetration of the wastewater-derived constituents at this time and location. Chloride concentrations ranged from 68 mg/L in the shallowest well (screened from 15 through 18 feet) to 6.5 mg/L in the two deepest wells (screened from 39 through 42 feet and 59 through 62 feet).

- One-dimensional solute transport was modeled along two selected flow paths from wastewater application areas to study area boundaries. The modeling results indicate that equilibrium concentrations of conservative constituents, such as chloride, are probably established within about 7 years along the Canal L-410 boundary. A much longer time is needed to reach equilibrium along longer flow paths, such as those toward the impounded wetlands bordering Canal L-405. According to the transport calculations, chloride concentrations could be near the maximum but still be increasing at the end of a 2,360-foot flow path toward the impounded wetland 50,000 days (137 years) after beginning of wastewater application.

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