STATE OF LOUISIANA

DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

PUBLIC WORKS AND FLOOD CONTROL DIRECTORATE

WATER RESOURCES SECTION

WATER RESOURCES

TECHNICAL REPORT

NO. 56

MOVEMENT AND FATE OF FECAL-COLIFORM BACTERIA THROUGH A SHALLOW AQUIFER SYSTEM IN SOUTHEASTERN LOUISIANA, 1991

Prepared by
U.S. DEPARTMENT OF THE INTERIOR
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In cooperation with
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U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, Director

For additional information write to:

Edward H. Martin
District Chief
U.S. Geological Survey, WRD
3535 S. Sherwood Forest Blvd., Suite 120
Baton Rouge, LA 70816

Telephone: (504) 389-0281

Zahir "Bo" Bolourchi, P.E.
Chief, Water Resources Section
Louisiana Department of
Transportation and Development
P.O. Box 94245
Baton Rouge, LA 70804-9245
Telephone: (504) 379-1434

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Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	4,047	square meter
square foot (ft^2)	0.09290	square meter
gallon (gal)	0.003785	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
foot per day (ft/d)	0.3048	meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
foot per foot (ft/ft)	0.3048	meter per meter

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows: °F = 1.8 (°C) + 32.

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum 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.

Abbreviated water-quality units:

colonies per 100 milliliters (cols/100 mL)

liter (L)

microsiemens per centimeter at 25 degrees Celsius (µS/cm)

milligrams per liter (mg/L)

milliliter (mL)

MOVEMENT AND FATE OF FECAL-COLIFORM BACTERIA THROUGH A SHALLOW AQUIFER SYSTEM IN SOUTHEASTERN LOUISIANA, 1991

By Keith J. Halford, Otha L. Benton, *and* Dennis K. Demcheck

Abstract

In 1991, two experiments were conducted to determine the rate and direction of movement and fate of viable fecal-coliform bacteria in a shallow aquifer system in an area of dairy-farm pastureland in southeastern Louisiana. A ground-water recharge pit was constructed and filled with an effluent containing high concentrations of fecal-coliform bacteria and chloride and rhodamine-WT tracers. Two 30-gallon control tanks were placed next to the recharge pit, to determine fecal-coliform half-lives and assess the potential effects of chloride and rhodamine-WT tracers on bacterial viability. The movement of this effluent through the shallow aquifer system was monitored by collecting water samples from observation wells, remote wells, and nearby Bonner Creek, and samples of field runoff.

In spring 1991, during a period of maximum ground-water flow in the shallow aquifer system, concentrations of fecal-coliform bacteria in the initial effluent in the recharge pit and a separate control tank decreased from 12,000,000 cols/100 mL (colonies per 100 milliliters) in the control tank to less than 200 cols/100 mL in 34 days as a result of the combined effects of dilution, sorption, and filtration. The maximum concentration of fecal-coliform bacteria, 2,100 cols/100 mL, measured in an observation well near the recharge pit was only 0.04 percent of the concentration of 5,900,000 cols/100 mL measured in the control tank at the same time. No concentrations of fecal-coliform bacteria greater than the State's standard of 200 cols/100 mL for primary contact were detected beyond a distance of 40 feet from the recharge pit, although concentrations of bacteria greater than 50 cols/100 mL were detected more than 50 feet from the recharge pit.

In fall 1991, during a period of minimum ground-water flow in the shallow aquifer system, concentrations of fecal-coliform bacteria in the initial effluent decreased in the control tank from 700,000 cols/100 mL to less than 200 cols/100 mL in 42 days. The maximum concentration of bacteria, 95 cols/100 mL, was detected in an observation well 7 days after the pit was filled. No concentrations of fecal-coliform bacteria greater than 95 cols/100 mL were detected in the shallow aquifer system during the fall experiment.

The effect of fecal-coliform bacteria on ground-water quality decreases as the distance of the source above the water table increases. In the shallow aquifer system, filtration and adsorption of fecal-coliform bacteria was greater in the unsaturated zone than in the saturated zone because the effluent was dispersed over a larger volume of the aquifer and was exposed to more surface area. The rapid decrease in fecal-coliform bacteria concentrations compared to the relatively slow rate of ground-water movement substantially limited the extent of contamination of water in the shallow aquifer system.

INTRODUCTION

Bacteria in shallow aquifer systems can pose a health threat to humans through the direct consumption of ground water and contact with surface water contaminated through ground-water seepage. Bacteria can survive long enough to move through shallow aquifer systems that recharge surface waters, and bacteria have been traced more than 1.5 mi from a contaminant source (Harvey and others, 1987). Previous studies (Nyman and Fayard, 1978; Childers and others, 1984; Janes, 1987; Louisiana Department of Environmental Quality, 1988, p. 20-21; 1989, p. 268-276) have shown contamination of surface water with fecal-coliform bacteria to be a persistent problem in southeastern Louisiana, where dairy cattle are the primary agricultural source of fecal-coliform bacteria.

Discharge of agricultural waste to local rivers and streams is being abated by encouraging farmers to install and use no-discharge lagoons that capture waste runoff from milking pens (William Branch, Louisiana State University Agricultural Extension Service, oral commun., 1990). Although the farmers prevent the lagoons from discharging by applying excess effluent to nearby fields, the lagoons may be ground-water-recharge sites. Because little is known about the effect of effluent contaminated with bacteria on ground-water quality in southeastern Louisiana, the U.S. Geological Survey (USGS), in cooperation with the Louisiana Department of Transportation and Development, began a study in 1990 to monitor the movement of fecal-coliform bacteria through a shallow aquifer system in that area.

Purpose and Scope

This report presents the results of a study to determine the rate and direction of movement and fate of viable fecal-coliform bacteria moving through a typical shallow aquifer system in southeastern Louisiana. The study was limited to one 20-acre site on which a recharge pit was constructed and filled twice (spring and fall 1991) with effluent containing high concentrations of fecal-coliform bacteria. Two 30-gallon control tanks were placed next to the recharge pit, to determine fecal-coliform half-lives and assess the potential effects of chloride and rhodamine-WT tracers on bacterial viability. Water-quality data from 35 shallow observation wells in the area around the recharge pit are presented.

Due to the different rates at which effluent moves from the pit into the unsaturated zone, a cross-sectional computer model of the unsaturated zone was constructed using the VS2D (Lappala and others, 1987) computer program. This model will aid in understanding how effluent moves through the unsaturated zone.

Description of Study Area

The study area consists of 20 acres on the Louisiana State University Southeast Agricultural Research Station in Washington Parish (fig.1). The topography consists of gently rolling hills, with altitudes ranging from 170 to 220 ft above sea level. Topographic troughs and the creek valley are forested. The area near the pit is pastureland (fig. 1). A fence restricts cattle to an area at least 100 ft from Bonner Creek.

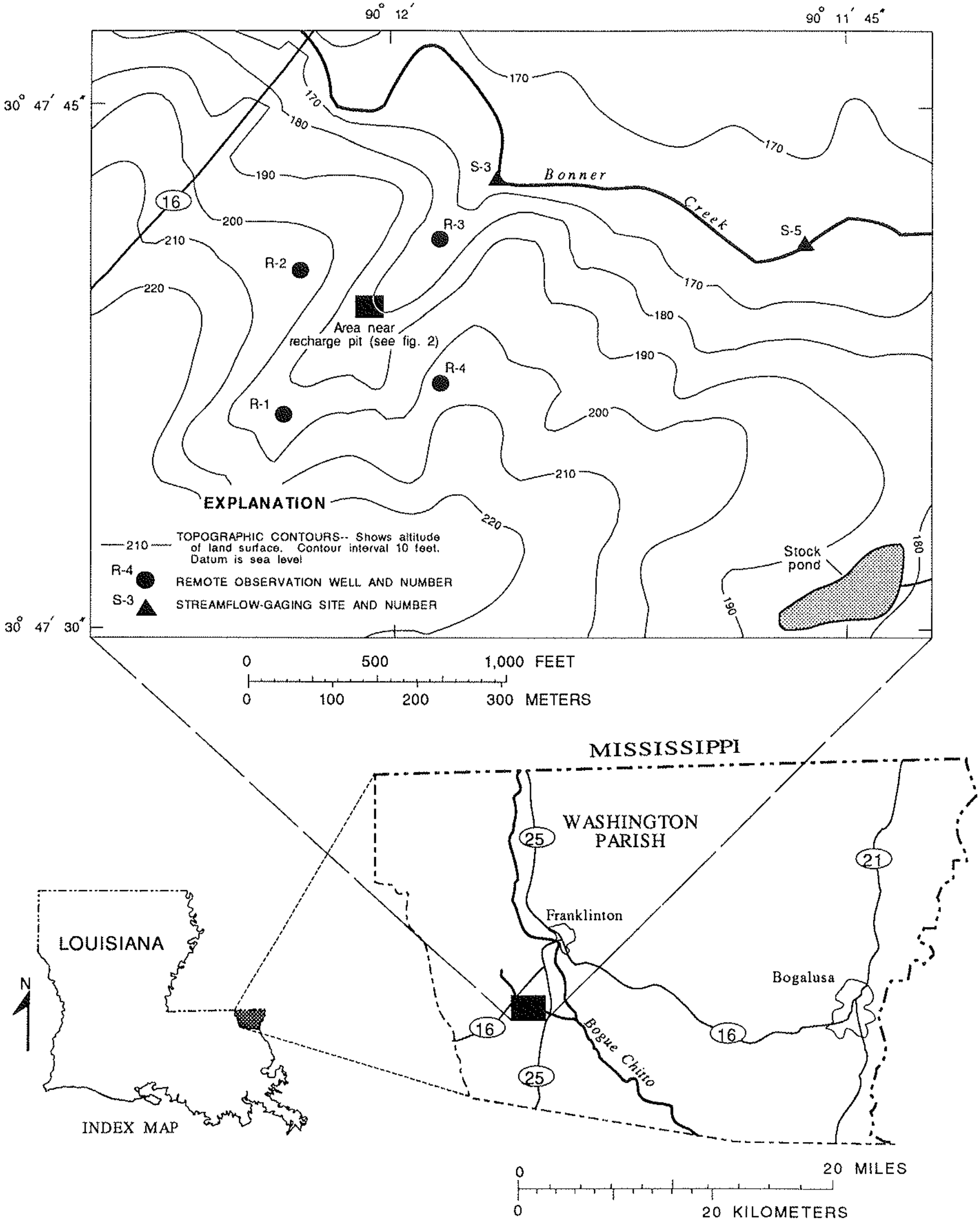


Figure 1. Location of the study area in Washington Parish, southeastern Louisiana.

The study area encompasses four remote wells (R-1, R-2, R-3, and R-4), two streamflow-gaging sites (S-3 and S-5), and the recharge-pit area (fig. 1). Water in the recharge pit and in 31 wells was sampled to monitor effluent movement in the immediate vicinity of the pit (fig. 2). The effluent used in the experiment was placed in the recharge pit and two control tanks simultaneously (fig. 2).

Acknowledgments

The authors thank James Baittey and his staff for their assistance and permission to drill test wells and conduct the study at the Louisiana State University Southeast Research Station. The authors also extend their appreciation to Mark Walthall of the Louisiana State University Agricultural Engineering Laboratory for supplemental analytical work and Zahir "Bo" Bolourchi, Chief, Water Resources Section, Louisiana Department of Transportation and Development, for guidance and assistance provided during this study.

APPROACH AND METHOD OF STUDY

The general approach followed in this study is described below:

1. A representative dairy-farm pasture in southeastern Louisiana was selected as the study site.
2. A recharge pit (hereafter referred to as "the pit") was constructed on the study site so that effluent in the pit would be discharged into the underlying shallow aquifer system.
3. Observation wells (hereafter referred to as "the wells") were installed around the pit to monitor ground-water movement from the pit through the shallow aquifer system.
4. Two 30-gallon plastic control tanks were installed adjacent to the recharge pit to determine fecal-coliform (FC) bacteria half-lives under field conditions and assess the potential effects of the chloride and rhodamine-WT tracers on fecal-bacterial viability. One tank contained the same effluent that was added to the recharge pit. The other tank contained effluent, chloride, and rhodamine WT.
5. Two experiments were conducted during spring and fall by filling the pit with effluent containing high concentrations of FC bacteria and other tracers and sampling the wells to monitor the rate and direction of movement and fate of viable FC bacteria in the shallow aquifer system.
6. A cross-sectional computer model was constructed to determine how and at what rate effluent moved from the pit into the unsaturated zone.

The study was designed to examine movement of FC bacteria under periods of wet and dry weather conditions. The pit was built in a topographic trough (fig. 1) to minimize the distance the effluent would travel through the unsaturated zone and, therefore, the dispersive effects of the unsaturated zone on effluent movement. The pit was located near Bonner Creek to achieve rapid movement within the saturated zone, as hydraulic gradients in unconfined aquifers generally become steeper as one approaches a stream.

Effluent from a no-discharge lagoon that contained high concentrations of bacteria and low concentrations of dissolved solids was used as the source of FC bacteria. Concentrations of FC bacteria from no-discharge lagoons typically range from 500,000 to 13,000,000 cols/100 mL (Allen and others, 1973, p. 21).

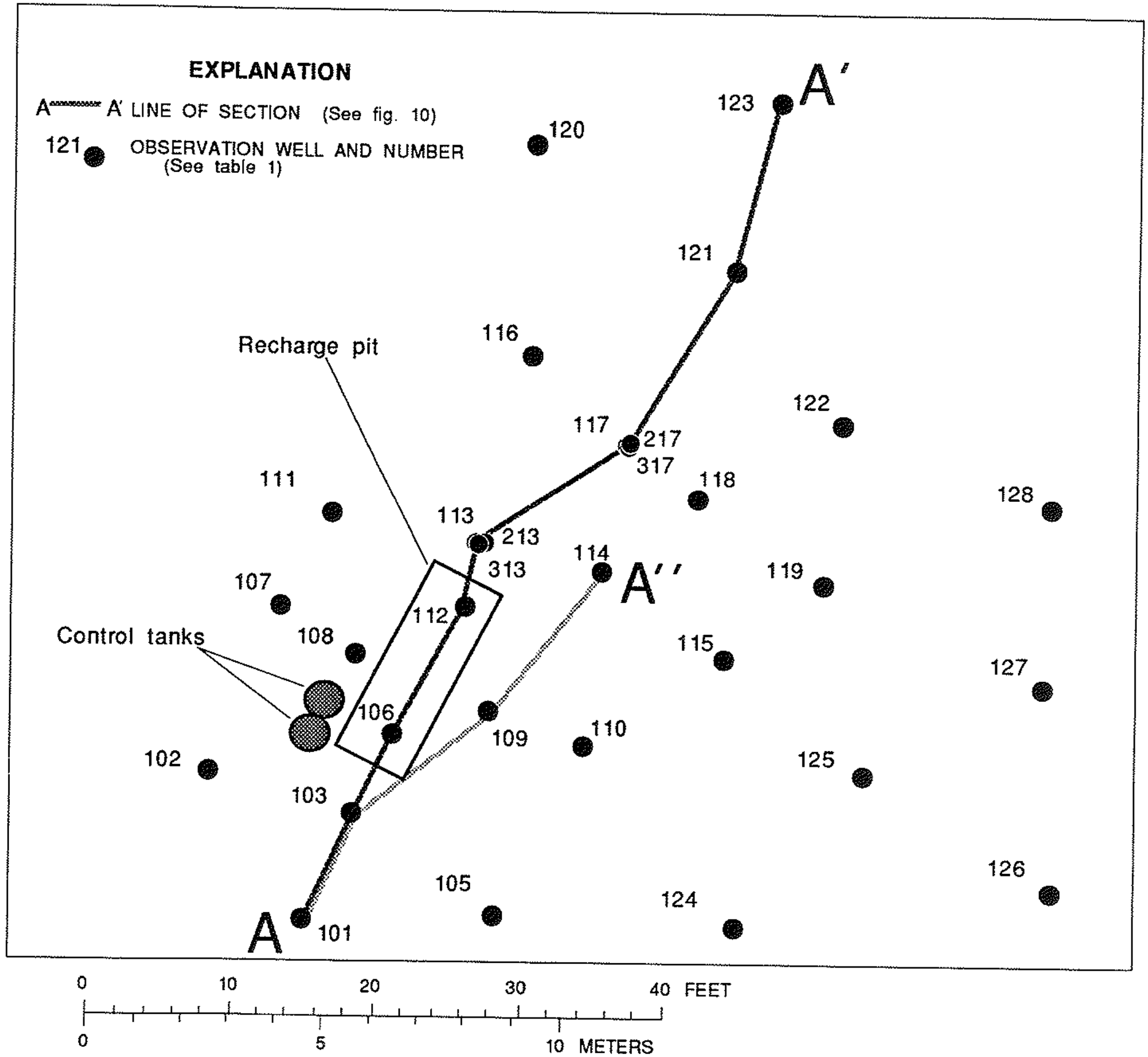


Figure 2. Immediate area near recharge pit.

Construction of Recharge Pit

The recharge pit was formed by excavating a trench 16 ft long, 6 ft wide, and 3 ft deep. In this trench, a 15-ft by 5-ft by 3-ft box, open on the top and bottom, was constructed of treated wooden planks to provide straight-sided retaining walls. The space between the trench sides and retaining walls was filled with a concrete slurry to reduce lateral migration of the effluent around the pit sides. The pit was covered with an elevated 20-ft by 8-ft tin roof to prevent dilution of the effluent with rainfall, and to reduce the effects of evaporation and exposure to sunlight. The interior of the pit measured 14.8 ft long, 4.6 ft wide, and 3.0 ft deep, with a floor area of 68 ft^2 and a total volume of 204 ft^3 (fig. 3). After construction, the pit was filled with about 200 ft^3 of effluent.

Installation of Observation Wells and Control Tanks

Thirty-one 2-in. diameter plastic wells with 0.01-in. slotted screens were completed in the shallow aquifer system near the pit. All wells were screened over 10-ft intervals except well 108, which, as a result of construction problems, was screened over a 5-ft interval. Near the pit, 27 wells were screened from the water table to 10 ft below the water table and were assigned three-digit numbers beginning with 1 (fig. 2). Two wells screened from 10 to 20 ft below the water table were assigned three-digit numbers beginning with 2, and two wells screened from 20 to 30 ft below the water table were assigned three-digit numbers beginning with 3 (fig. 2).

Four additional wells, referred to as remote wells, of similar construction to the wells described above, were installed about 250 to 460 ft from the pit. These wells were screened in the saturated zone to determine area-wide ground-water levels and gradients.

All wells were completed in 6-in. diameter, augered boreholes. After the 2-in. screen and pipe were assembled and inserted, the annulus was filled with coarse sand to a depth of 1 to 2 ft above the screened interval. The remaining annular space was cemented up to land surface. The conceptual diagram in figure 3 shows a typical well.

The observation-well network near the pit was designed on the basis of the following assumptions:

1. FC bacteria could persist for 90 days in an aquatic environment (Guthrie and others, 1986).
2. Lateral movement would be most rapid along shallow flow paths.
3. Ground-water flow would be accelerated locally by recharge from the pit.

Assuming that the FC bacteria persisted up to 90 days in an aquatic environment, the horizontal hydraulic conductivity was 10 ft/d, the porosity was 0.3, and the gradient was 0.015 ft/ft, the maximum lateral travel expected was 45 ft. Twenty-seven wells were located within 45 ft of the pit. Most wells were screened near the water table to intercept the shallowest flow paths. Four deeper wells were located downgradient from the pit to confirm the presence of FC bacteria if the movement of effluent was primarily vertical. Only four deep wells were used because the lateral component of flow was expected to decrease with depth.

Two control tanks were used to test the mortality rate of FC bacteria in separate effluents, one effluent containing sodium chloride and rhodamine WT and a second effluent without these additives. The effluent with sodium chloride and rhodamine WT was kept in one control tank (30-gal plastic trash can with lid) and the unaltered effluent was kept in the other control tank (fig. 4). The control tanks were partially buried to keep the effluent temperature close to the ground-water temperature. The lidded tanks were then covered with plywood to prevent changes in concentration due to rainfall, evaporation, and exposure to sunlight.

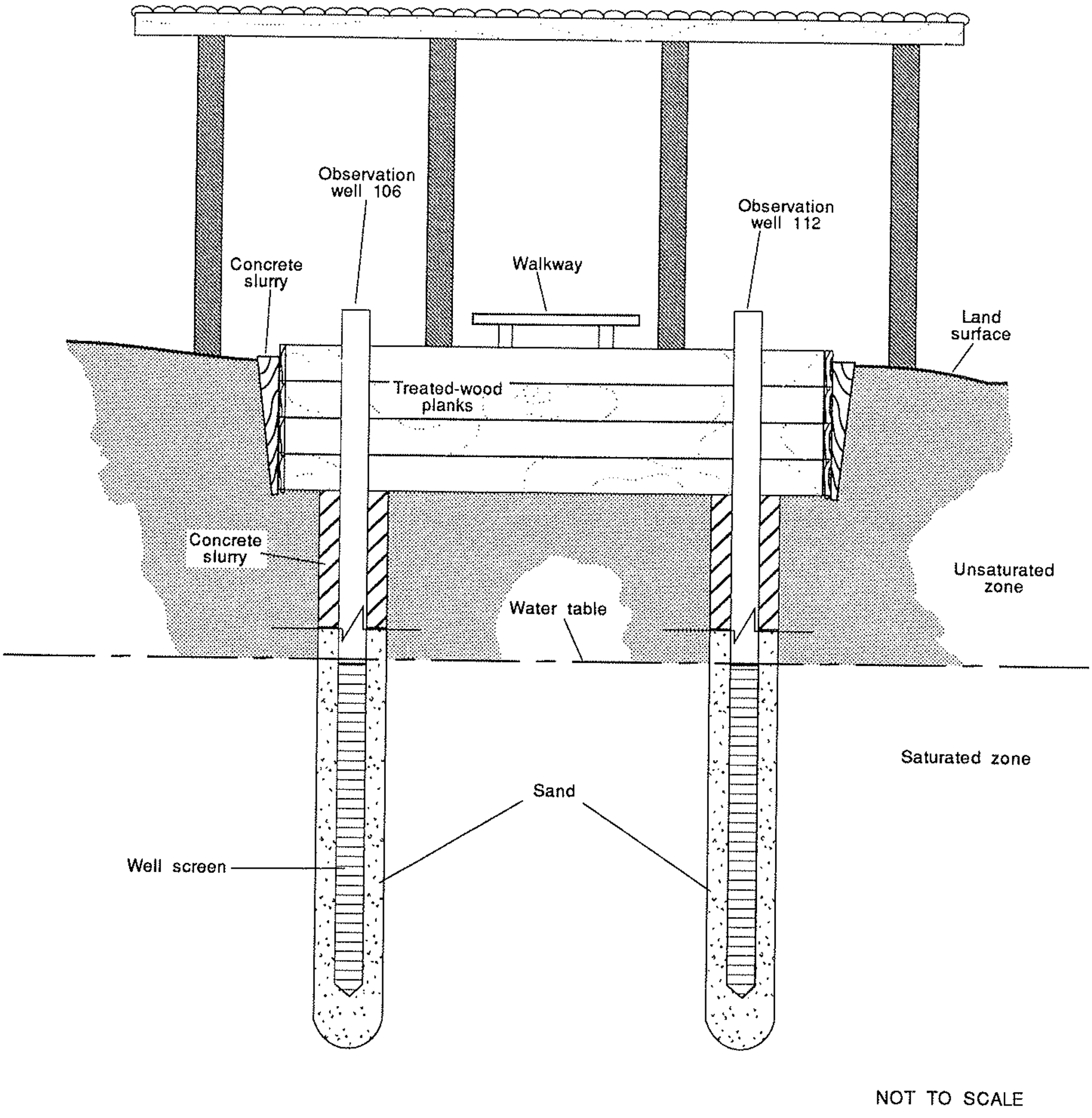


Figure 3. Construction characteristics of recharge pit along section A-A′ in figure 2.

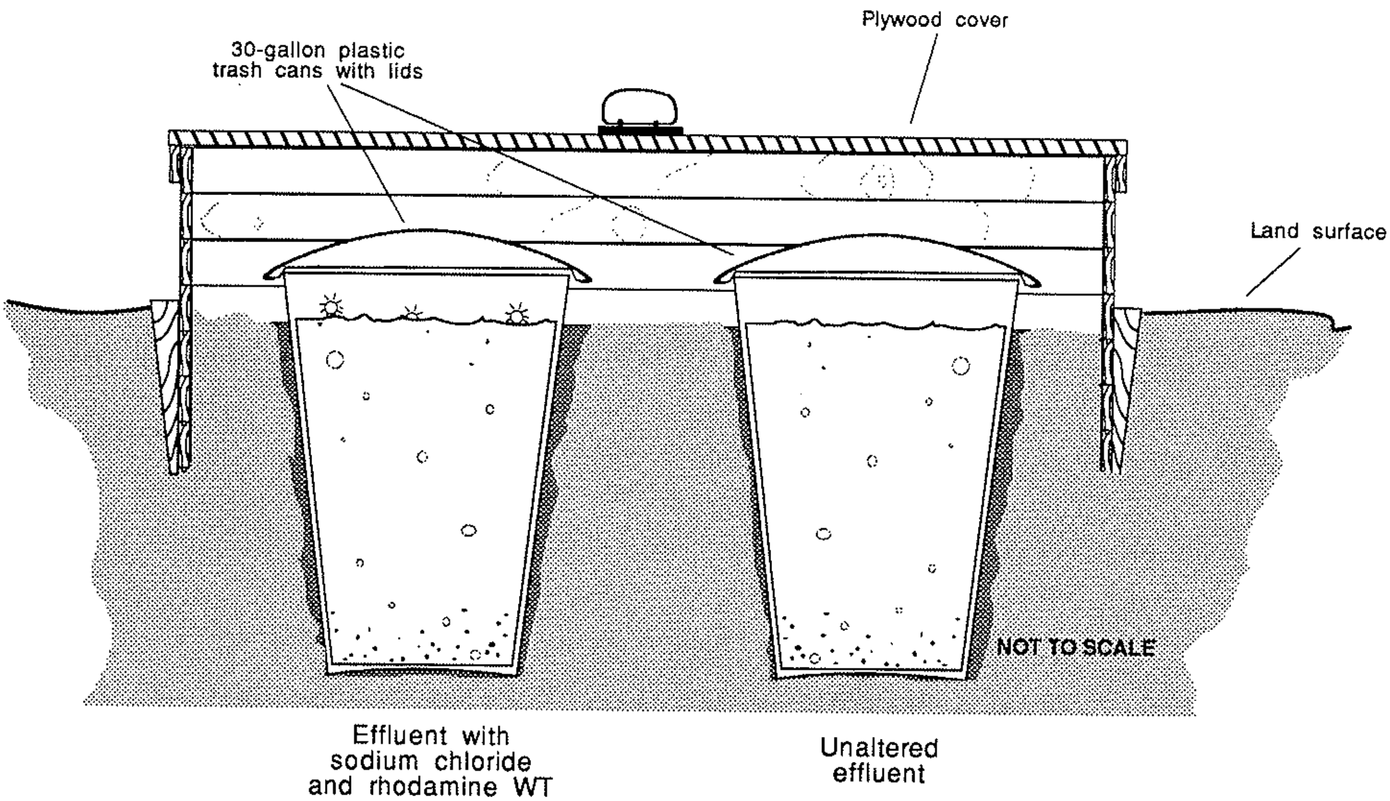


Figure 4. Effluent-control-tank installation.

Data Collection

The specific conductance, temperature, rhodamine WT, and pH were measured in situ or in water samples from wells, control tanks filled with effluent, and the recharge pit. These constituents and physical properties were measured in accordance with standard USGS procedures (Fishman and Friedman, 1989). Specific conductance and temperature were measured in situ after the wells had been bailed and samples collected for FC-bacteria, rhodamine WT, and pH determinations. During the fall experiment, pH was measured and additional samples were collected for nitrate, phosphorus, and sodium determinations.

All samples analyzed for FC bacteria, rhodamine WT, and pH were collected with 3-ft plastic bailers. A bailer and pitcher was used for each well to prevent cross-contamination. Only one to two well-casing volumes were removed prior to sample collection to minimize the effects of pumping on the flow system. The presence of silt and clay hindered FC-bacteria measurements in all wells. This problem was mitigated by collecting the bailed water in 2-L pitchers and allowing the water to stand for 20 minutes. Each sample was decanted from the pitcher into an autoclaved 250-mL glass bottle. Water samples for FC-bacteria determination were stored in sterilized glass containers and packed in ice. Bacteriological determinations were initiated within 4 hours of sample collection; the membrane-filter method was used as described by Britton and Greeson (1988).

DESCRIPTION OF SHALLOW AQUIFER SYSTEM

The shallow aquifer system in southeastern Louisiana is composed of gravel, sand, silt, and clay deposits that range in thickness from 200 to 400 ft. Locally horizontal hydraulic conductivities are highly variable as a result of variations in silt and clay content (Nyman and Fayard, 1978, p. 13). Sieve analysis of core samples from wells 106 and 121 substantiated the high degree of grain-size variability (fig. 5). Bedding structures on the scale of an inch were observed in some core samples.

Ground water throughout the study area is unconfined. The depth to the water table ranged from 0 ft at Bonner Creek to about 50 ft below the ridge crest (fig. 6) in the spring. The depth to the water table in the vicinity of the pit was about 10 ft below land surface in the spring.

Flow Paths and Water Levels

Ground water in the study area flows from the ridge crest near Louisiana Highway 16 (La. 16) to Bonner Creek, the lowest topographic feature (fig. 6). Flow is generally eastward due south of La. 16 and becomes northeastward near Bonner Creek. Near the pit, lateral ground-water flow is from the southwest to the northeast. The area near the pit is an area of ground-water recharge throughout the year.

A comparison of the hydrographs in figure 7 indicates that water levels in the shallow well 112 consistently were higher than those in the deeper well 313. Water levels in wells 112 and 313 varied less than 3 ft throughout 1991 (fig. 7). Case (1979) reported a similar range from 1976 to 1978 in a shallow well completed 0.5 mi from the study site. Variations in water levels during the year are controlled generally by the net recharge (infiltration minus evapotranspiration). Net recharge is less in summer and early fall than in spring as a result of decreased rainfall and increased evapotranspiration.

Flow Rates

Ground-water-flow rates were estimated from water-level measurements in well 313 and stream-discharge measurements at sites S-3 and S-5 (fig. 8). Stream-discharge measurements were made after a week or more of no rainfall and while the water levels in well 313 were declining. The area bordering Bonner Creek is forested, and no additional surface-water sources are between sites S-3 and S-5. If evaporation from Bonner Creek is assumed to be negligible, the difference in stream-discharge measurements between sites S-3 and S-5 is an estimate of the ground-water-discharge rate.

A series of estimates of ground-water-flow rates were made at the beginning of the study, and observation wells (fig. 9) were placed near the pit. The lateral ground-water-flow rate near the pit was estimated from the water-table surface map (fig. 6) and stream-discharge measurements for April 1, 1991. If half of the ground-water discharge is assumed to come from south of Bonner Creek, the net flow rate through the shallow aquifer system (fig. 6) is 0.07 ft^3/s, or 6,000 ft^3/d. From the driller's log of a nearby private well 3,000 ft west of the pit, aquifer thickness near the pit was estimated to be 200 ft. The cross-sectional area of the ground-water-flow path is about 750 ft wide by 200 ft deep, or 150,000 ft^2. Using a gradient of 0.004 ft/ft, the average hydraulic conductivity of the area near the pit is about 10 ft/d. The lateral ground-water velocity near the pit is about 0.2 ft/d, assuming a gradient of 0.005 ft/ft and a porosity of 30 percent.

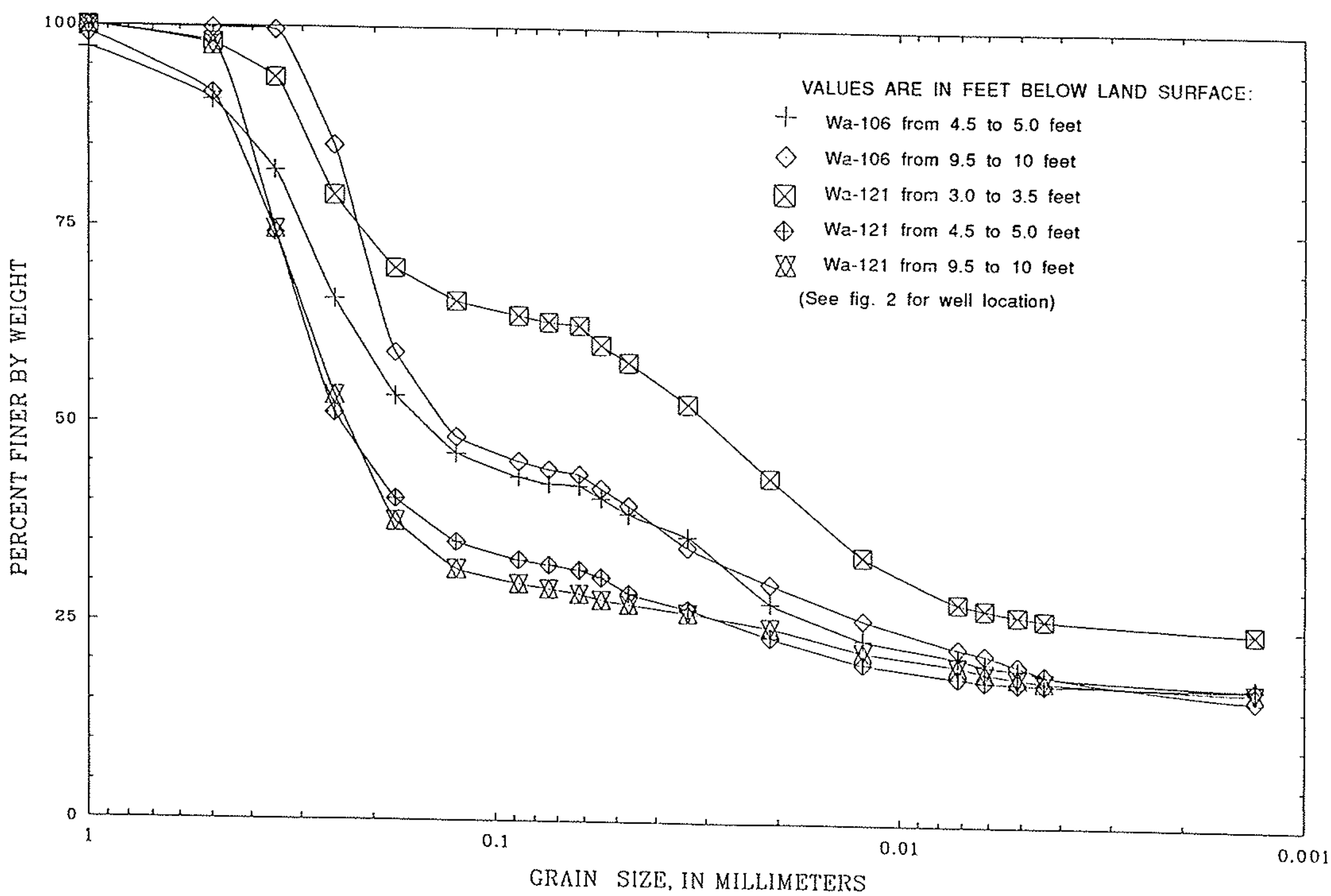


Figure 5. Results of sieve analysis of 1-inch-diameter cores from selected observation wells.

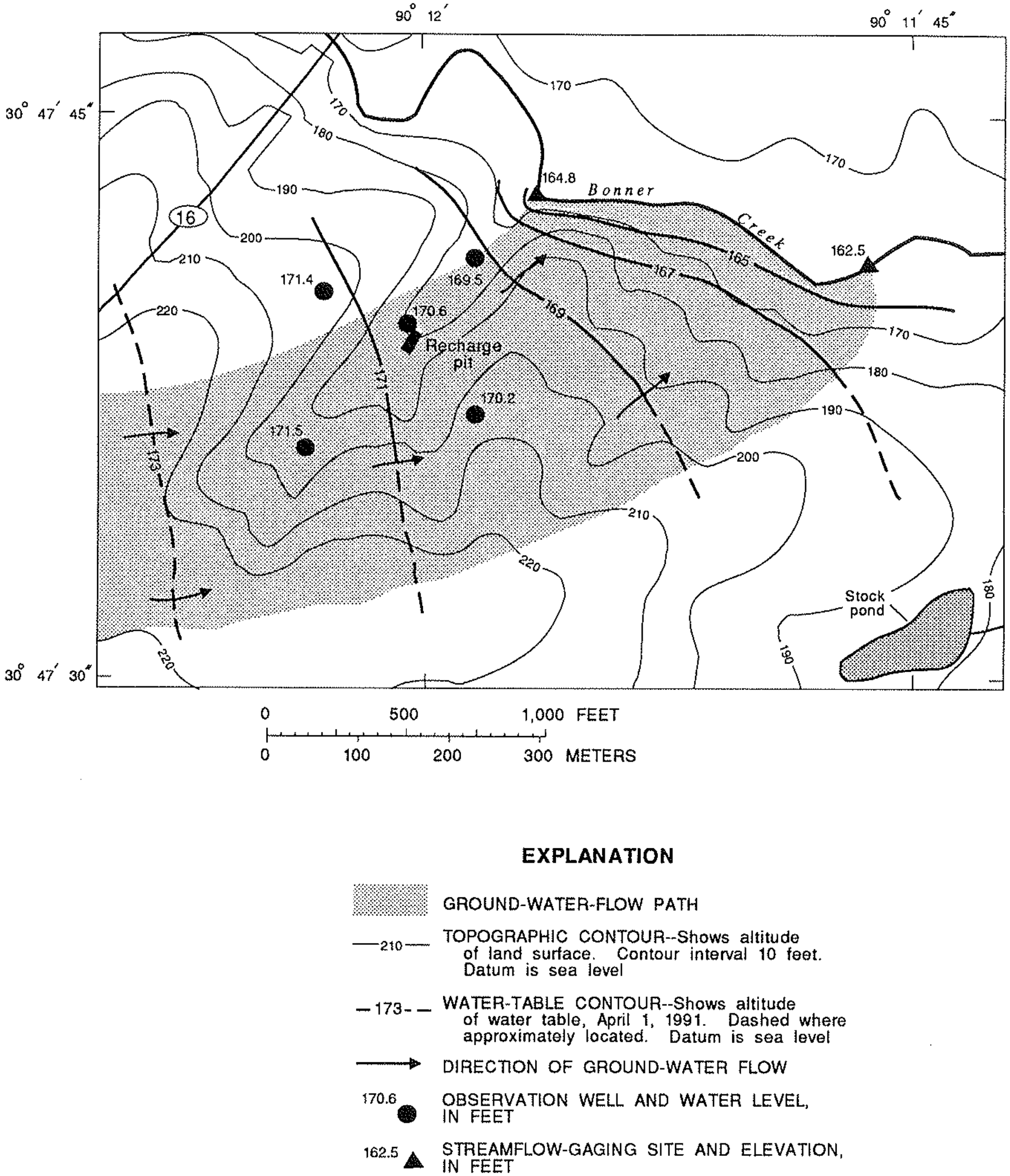


Figure 6. Generalized water-table surface in the shallow aquifer system and flow paths through the shallow aquifer system to Bonner Creek, April 1, 1991.

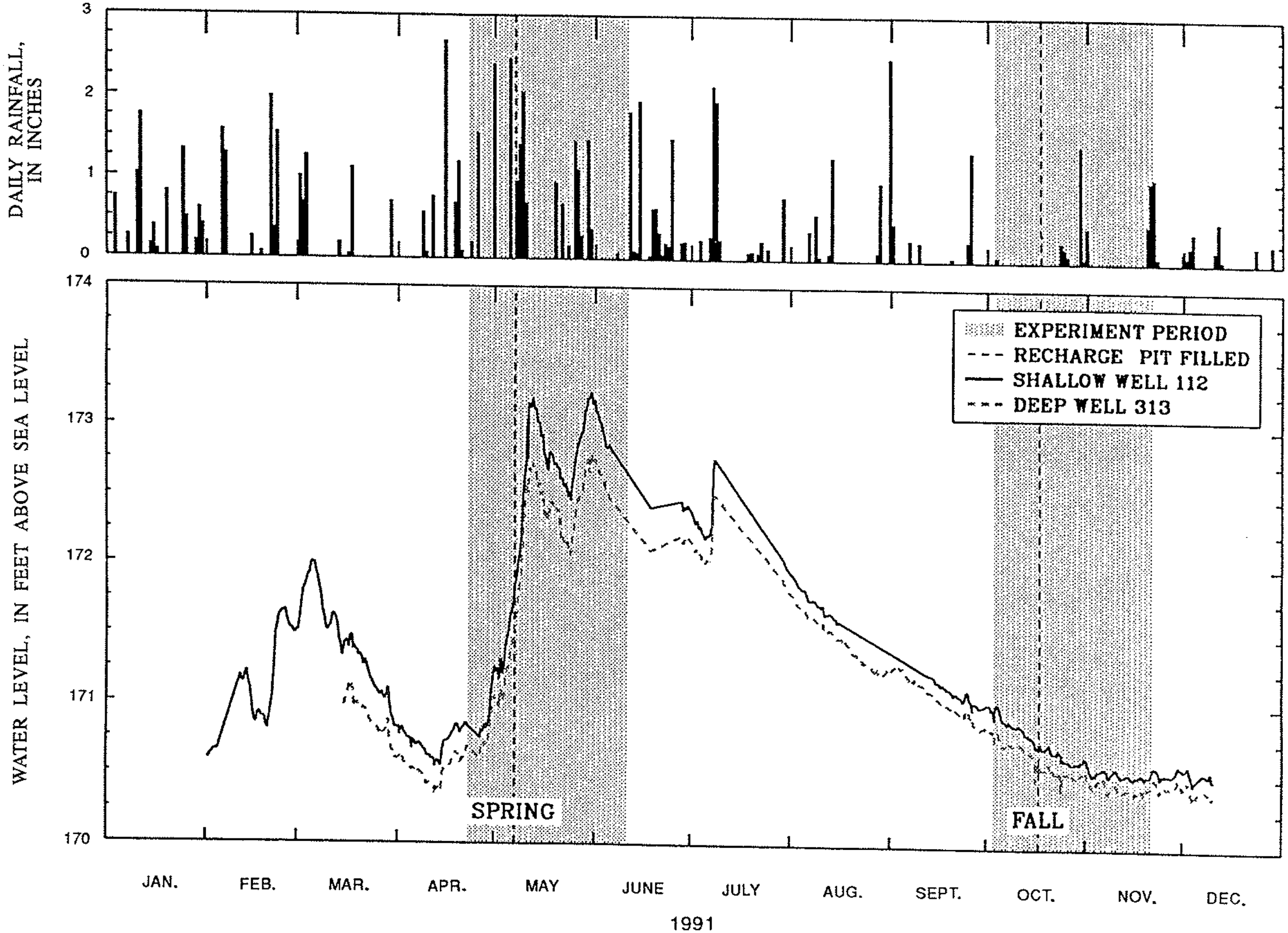


Figure 7. Daily rainfall at site and water levels in a shallow and a deep observation well near the recharge pit during 1991.

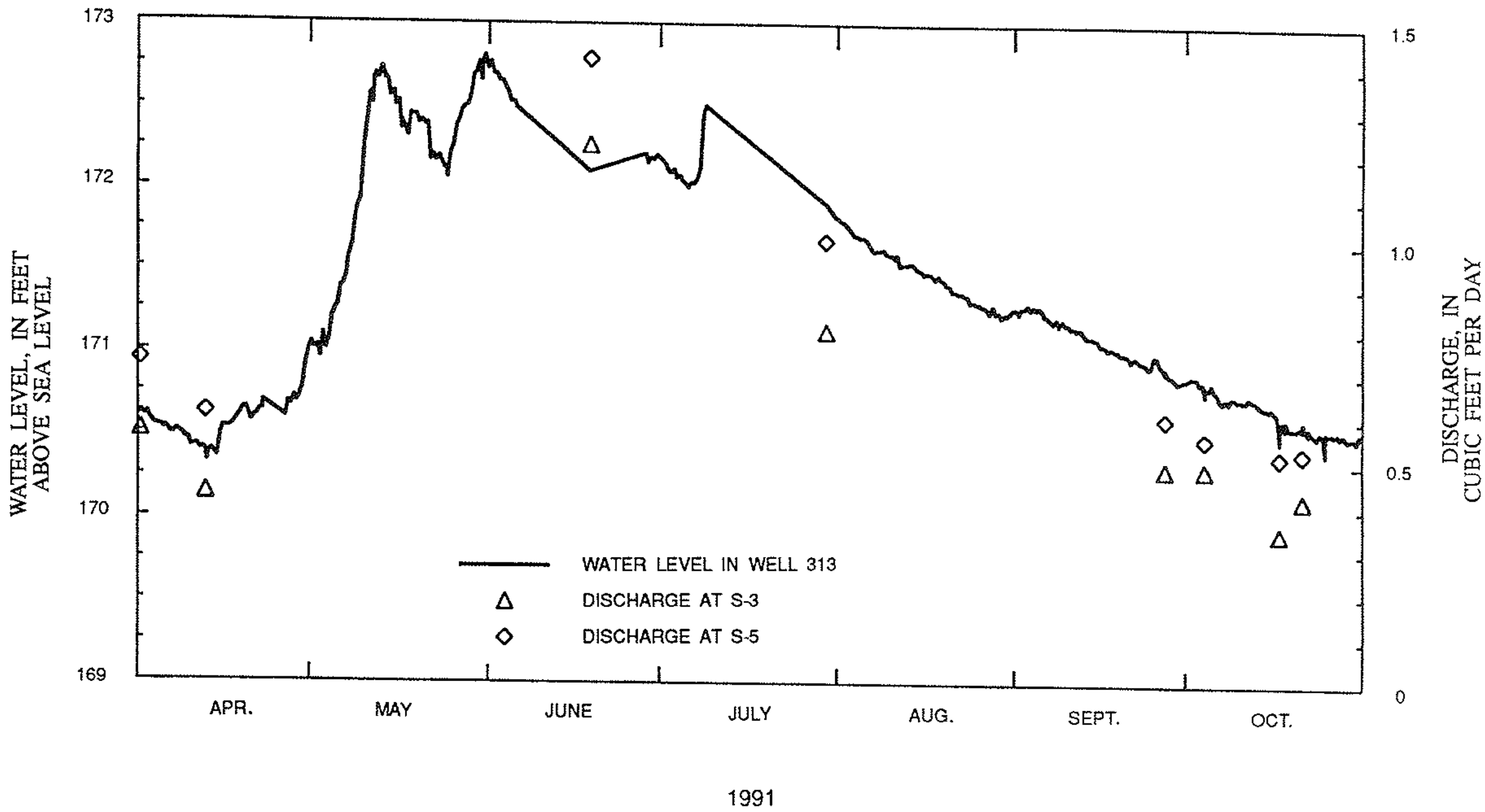


Figure 8. Stream discharge and water level in well 313 in the shallow aquifer system.

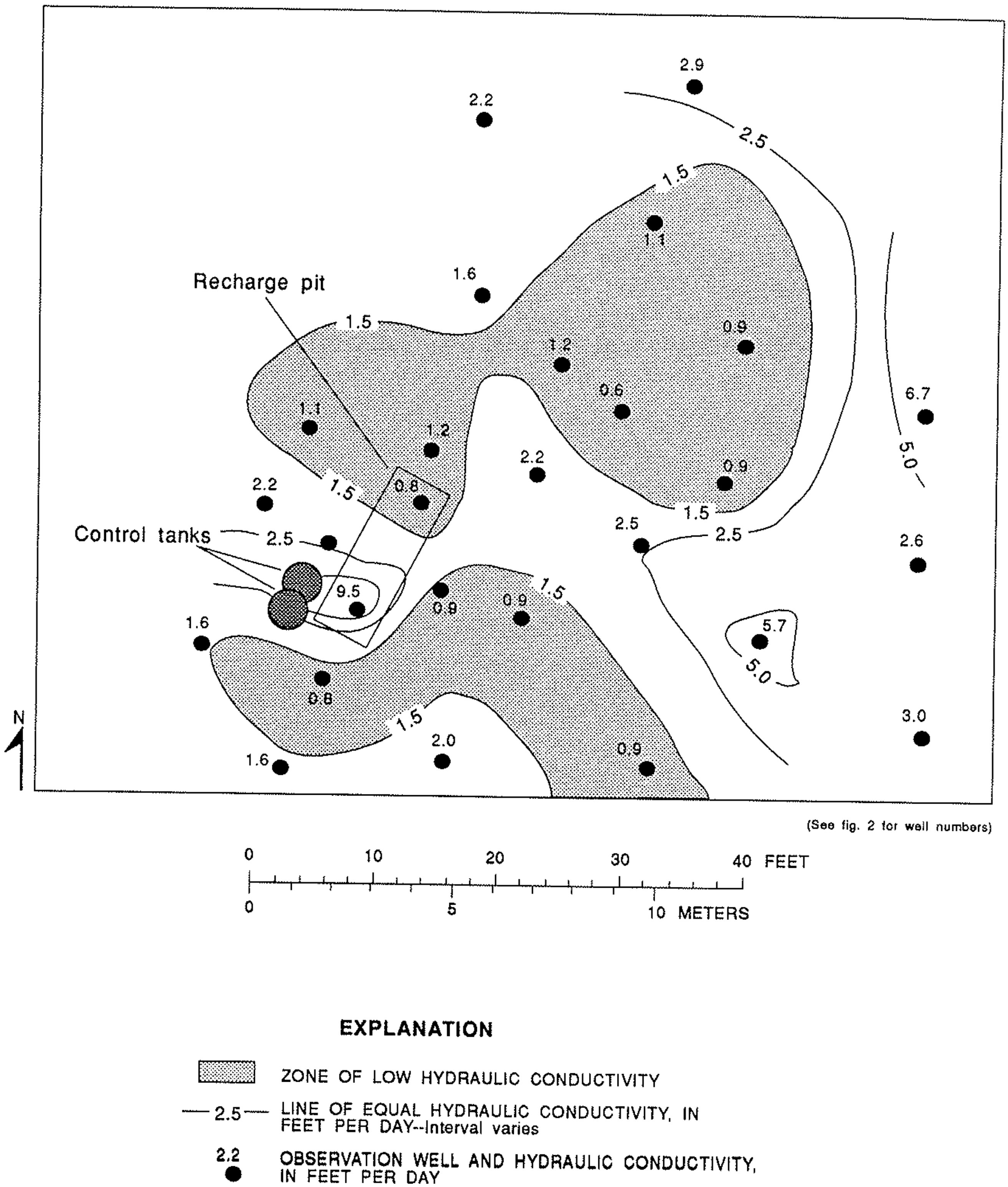


Figure 9. Lines of equal hydraulic conductivity in the shallow aquifer system, April 25, 1991.

Hydraulic Properties

Hydraulic conductivity and specific yield near the pit were determined by means of slug tests of all the wells in the study area on April 25, 1991. Slug-test data for each well were collected by dropping a pressure transducer 6 to 8 ft below the water level in the well and recording the initial water level. A slug displacing 0.057 ft^3, which produced a 2.6-ft water-level change, was then submerged in the well. After the water level returned to its initial level, the slug was removed over a 1-second interval. Water levels were recorded every second for 3 minutes after the slug was removed.

Horizontal hydraulic-conductivity values ranged from 0.1 to 9.5 ft/d and averaged 1.9 ft/d (table 1). A zone in the upper 8 ft of saturated material near the pit and extending to the northeast demonstrated a lower hydraulic conductivity compared to surrounding wells (fig. 9). Hydraulic conductivity varies vertically as shown by wells 117, 217, and 317 in figure 10. The large range of hydraulic-conductivity values agreed with those determined from cores from wells 106 and 122, indicating bedding features on the scale of inches. Specific yield ranged from 0.06 to 0.13 and averaged 0.08 (table 1).

ANALYSIS OF CONTROL DATA

Background specific-conductance values, FC-bacteria concentrations, and information on the viability of FC bacteria were used to evaluate the effectiveness of the method of study and for quality control of the experiments. Water samples were collected from the wells near the pit in spring and fall before each experiment. Before the spring experiment, background specific-conductance values and FC-bacteria concentrations also were determined at sites located farther from the pit; water samples were collected from Bonner Creek and remote wells. Samples of field runoff also were collected.

Background Conditions

In the spring experiment, all the observation wells were sampled for FC bacteria 1 day prior to filling the recharge pit with effluent (table 2). The ungrouted wells located in the coarser-grained material at the bottom of the same topographic trough as the recharge pit (wells 103, 109, 114, 115, 117, and 317) (fig. 2) had substantially higher FC-bacteria concentrations than the ungrouted observation wells installed into finer-grained material. This is likely due to percolation of field runoff containing FC bacteria (table 3) along the outer casing of the recently installed wells down to the screened interval.

Background specific-conductance values varied among the samples from Bonner Creek, those from the remote wells, and those of field runoff, but were highest in the field runoff. Specific-conductance values for Bonner Creek were consistently less than 40 μS/cm, whereas those for samples from remote wells ranged from 40 to 84 μS/cm (table 3). Specific-conductance values measured in samples of field runoff ranged from 79 to 159 μS/cm.

Background concentrations of FC bacteria varied but were highest in samples of field runoff and lowest in samples from the remote wells. Concentrations of FC bacteria measured in samples from Bonner Creek ranged from 50 to 300 cols/100 mL, whereas those in samples from the remote wells ranged from less than 1 to 2 cols/100 mL (table 3). Concentrations of FC bacteria measured in field runoff ranged from 20 to 28,000 cols/100 mL with a standard deviation of 10,000 cols/100 mL. These unweighted measurements of bacteria concentrations in field runoff were higher than the flow-averaged values reported by Boyer and Perry (1987). The FC-bacteria concentrations in samples from Bonner Creek, those from the remote wells, and those of field runoff indicate that the source of the bacteria in Bonner Creek is field runoff.

Table 1. Locations and results of slug tests for observation wells in the study area in Washington Parish, southeastern Louisiana

Well no.	Latitude		Longitude		Altitude of screen center, in feet above sea level	Hydraulic conductivity, in feet per day	Specific yield (dimensionless)
R-1	30°47'36.528"	N	90°12' 3.340"	W	169.61	1.0	0.07
R-2	30°47'40.689"	N	90°12' 2.736"	W	162.99	.1	.08
R-3	30°47'41.581"	N	90°11'58.176"	W	165.53	.8	.08
R-4	30°47'37.475"	N	90°11'58.231"	W	162.02	.5	.08
101	30°47'39.315"	N	90°12' 0.703"	W	168.06	1.6	.06
102	30°47'39.412"	N	90°12' 0.758"	W	168.62	1.6	.06
103	30°47'39.384"	N	90°12' 0.648"	W	167.39	.8	.07
105	30°47'39.315"	N	90°12' 0.538"	W	167.92	2.0	.06
106	30°47'39.439"	N	90°12' 0.648"	W	167.90	9.5	.11
107	30°47'39.521"	N	90°12' 0.703"	W	168.73	2.2	.06
109	30°47'39.453"	N	90°12' 0.538"	W	168.05	.9	.07
110	30°47'39.425"	N	90°12' 0.483"	W	167.62	.9	.08
111	30°47'39.576"	N	90°12' 0.648'	W	168.21	1.1	.07
112	30°47'39.521"	N	90°12' 0.593"	W	166.82	.8	.07
113	30°47'39.563"	N	90°12' 0.539"	W	167.23	1.2	.07
213	30°47'39.564"	N	90°12' 0.538"	W	158.50	1.0	.06
313	30°47'39.563"	N	90°12' 0.537"	W	147.06	.8	.08
114	30°47'39.549"	N	90°12' 0.483"	W	166.60	2.2	.08
115	30°47'39.480"	N	90°12' 0.374"	W	167.60	2.5	.07
116	30°47'39.686"	N	90°12' 0.538"	W	167.37	1.6	.08
117	30°47'39.631"	N	90°12' 0.428"	W	166.09	1.2	.08
217	30°47'39.632"	N	90°12' 0.429"	W	156.11	.1	.09
317	30°47'39.632"	N	90°12' 0.427"	W	145.69	2.1	.07
118	30°47'39.590"	N	90°12' 0.374"	W	166.84	.6	.07
119	30°47'39.535"	N	90°12' 0.264"	W	167.55	.9	.08
120	30°47'39.823"	N	90°12' 0.488"	W	168.13	2.2	.07
121	30°47'39.741"	N	90°12' 0.374"	W	166.46	1.1	.07
122	30°47'39.645"	N	90°12' 0.264"	W	166.00	.9	.08
123	30°47'39.851"	N	90°12' 0.319"	W	166.89	2.9	.06
124	30°47'39.311"	N	90°12' 0.333"	W	164.45	1.0	.13
125	30°47'39.410"	N	90°12' 0.233"	W	164.64	5.7	.11
126	30°47'39.334"	N	90°12' 0.086"	W	166.36	3.0	.12
127	30°47'39.469"	N	90°12' 0.091"	W	164.42	2.6	.10
128	30°47'39.587"	N	90°12' 0.085"	W	164.13	6.7	.09
			Maximum:		169.61	9.5	.13
			Mean:		164.93	1.9	.08
			Minimum:		145.69	.1	.06
			Standard deviation:		5.40	1.9	.02

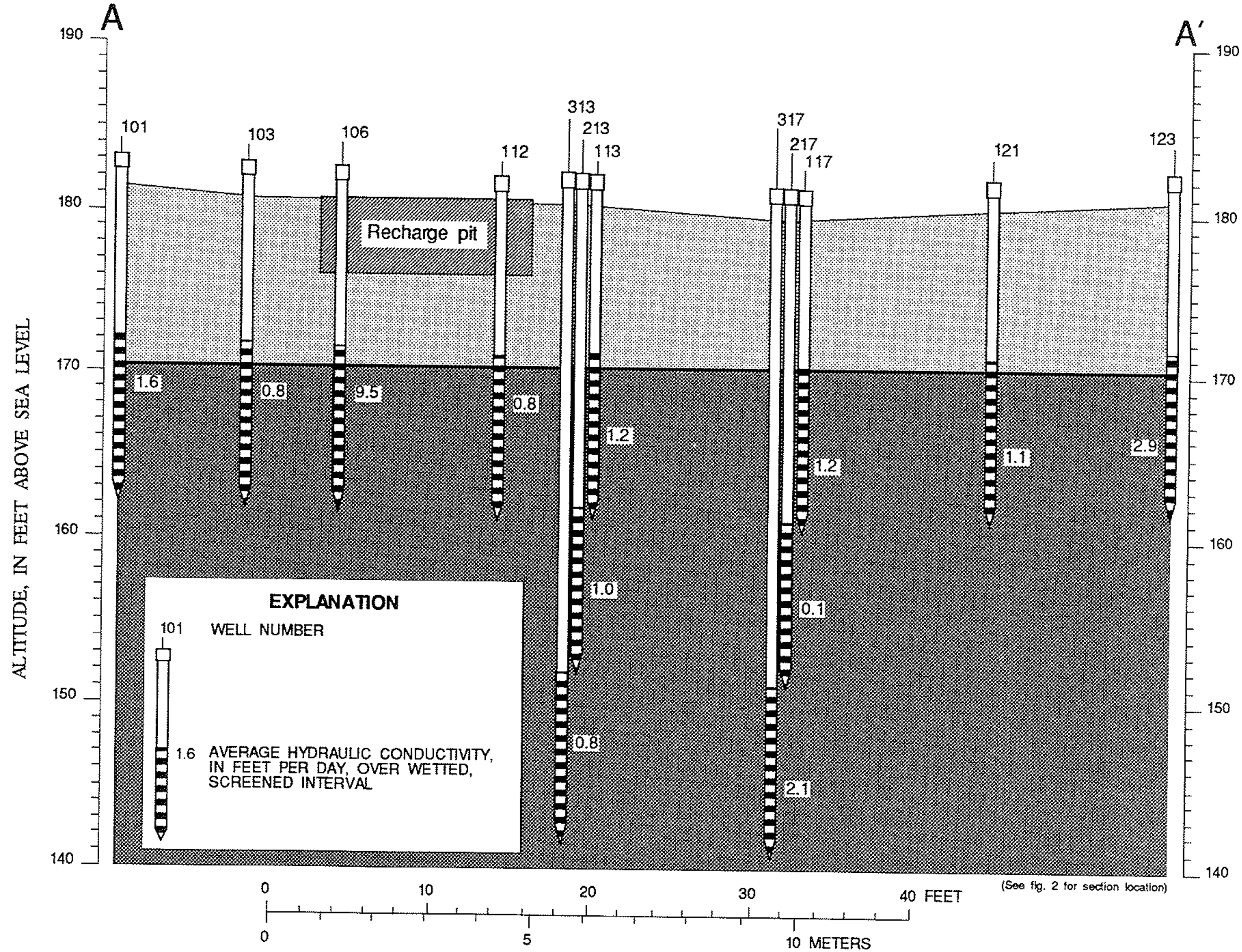


Figure 10. Horizontal hydraulic conductivities at wells along section A-A′.

Table 2. Concentrations of fecal-coliform bacteria in observation wells measured during the spring experiment, 1991, Washington Parish, Louisiana

[cols/100 mL, colonies per 100 milliliters; <, less than]

Well no.	Fecal-coliform bacteria, in cols/100 mL	Well no.	Fecal-coliform bacteria, in cols/100 mL	Well no.	Fecal-coliform bacteria, in cols/100 mL	Well no.	Fecal-coliform bacteria, in cols/100 mL
101	<1	110	3	116	<1	122	<1
102	<1	111	<1	117	30	123	<1
103	50	112	<1	217	<1	124	1
105	<1	113	<1	317	15	125	<1
106	<1	213	<1	118	<1	126	<1
107	<1	313	3	119	<1	127	<1
108	<1	114	3	120	<1	128	8
109	60	115	9	121	<1		

Table 3. Background specific-conductance values and fecal-coliform-bacteria concentrations in Bonner Creek, remote wells, and field runoff measured during the spring experiment, 1991, Washington Parish, Louisiana

[<, less than]

Sample	Number of observations	Minimum	Median	Maximum	Standard deviation
Specific conductance, in microsiemens per centimeter at 25 degrees Celsius					
Bonner Creek	5	31	36	38	2
Remote wells	23	40	63	84	17
Field runoff	7	79	108	159	31
Fecal-coliform-bacteria concentration, in colonies per 100 milliliters					
Bonner Creek	10	50	140	300	110
Remote wells	8	<1	1	2	1
Field runoff	7	20	5,900	28,000	10,000

Half-Life of Fecal-Coliform Bacteria

The concentration of FC bacteria changes as a function of time as a result of predation and mortality rate. The decrease in the population of FC bacteria limits the distance from the source over which the bacteria could be detected. An estimate of this rate of decline is needed to differentiate concentration changes due to population mortality from changes due to diffusion, dispersion, sorption, and filtration.

Dissolved tracers (chloride and a fluorescent dye) were used to differentiate among diffusion, dispersion, sorption, and filtration. These physical processes control the transport distance of the viable bacterial population. Chloride, a conservative dissolved constituent, was used to estimate the rate of attenuation of FC bacteria from diffusive and dispersive effects. Sodium chloride was used because it is readily available. Chloride movement was tracked indirectly by measuring the specific conductance of the water in situ after each well had been bailed. When the specific conductance of the water in a well varied, a depth-integrated average was reported.

A fluorescent dye, an adsorptive dissolved tracer that can be detected in very small concentrations, was used to obtain a rough estimate of the rate of attenuation of FC bacteria due to sorption. Rhodamine WT was chosen rather than fluorescein because fluorescein adsorbs more readily to alluvial aquifer material (Sabatini and Austin, 1991, p. 341-349).

Fecal-coliform bacteria naturally inhabit the intestines of warm-blooded animals. Thus, when the bacteria are placed into another environment, population mortality begins at a rate which depends on environmental conditions. For effluent and other aquatic environments, the FC-bacteria population at a given time, FCP_t, can be approximated by the following equation (Rinaldi and others, 1979, p. 96):

$$FCP_t = FCP_0 e^{-0.693\ t/t_{1/2}} \qquad (1)$$

where,

FCP_0 is the population of FC bacteria at time zero, in colonies per 100 milliliters;
t is time, in days; and
$t_{1/2}$ is the half-life of FC-bacteria population, in days.

The spring and fall experiments were performed to determine the half-life of FC bacteria in the two control tanks. One tank contained effluent with added sodium chloride and rhodamine WT, and the other tank contained unaltered effluent (fig. 11). The presence of sodium chloride and rhodamine WT in the effluent had no discernible effect on the half-life in either experiment. The half-life of FC bacteria during the fall experiment was 3.6 days, 64 percent longer than the half-life of 2.2 days determined during the spring experiment. The specific-conductance and temperature values, rhodamine-WT concentrations, and half-life values for FC bacteria in the control tanks are listed in table 4.

The FC-bacteria concentrations in the control tanks decreased to the State's standard of 200 cols/100 mL more rapidly during the spring experiment than during the fall experiment. The initial FC-bacteria concentration in the spring experiment, 12,000,000 cols/100 mL, decreased to 200 cols/100 mL in 34 days. The initial FC-bacteria concentration for the fall experiment, 700,000 cols/100 mL, decreased to the standard in 42 days.

Table 4. Average specific-conductance and temperature values, rhodamine-WT concentrations, and half-life of fecal-coliform bacteria in the control tanks during the spring and fall experiments, 1991, Washington Parish, Louisiana

Type of effluent	Specific conductance, in microsiemens per centimeter at 25 degrees Celsius	Temperature, in degrees Celsius	Rhodamine-WT concentration, in milligrams per liter	Half-life of fecal-coliform bacteria, in days
	Spring experiment			
Effluent containing sodium chloride and rhodamine WT	3,300	22.6	410	2.2
Unaltered effluent	2,200	22.6	0	2.2
	Fall experiment			
Effluent containing sodium chloride and rhodamine WT	2,200	18.5	22,000	3.6
Unaltered effluent	1,100	18.7	0	3.5

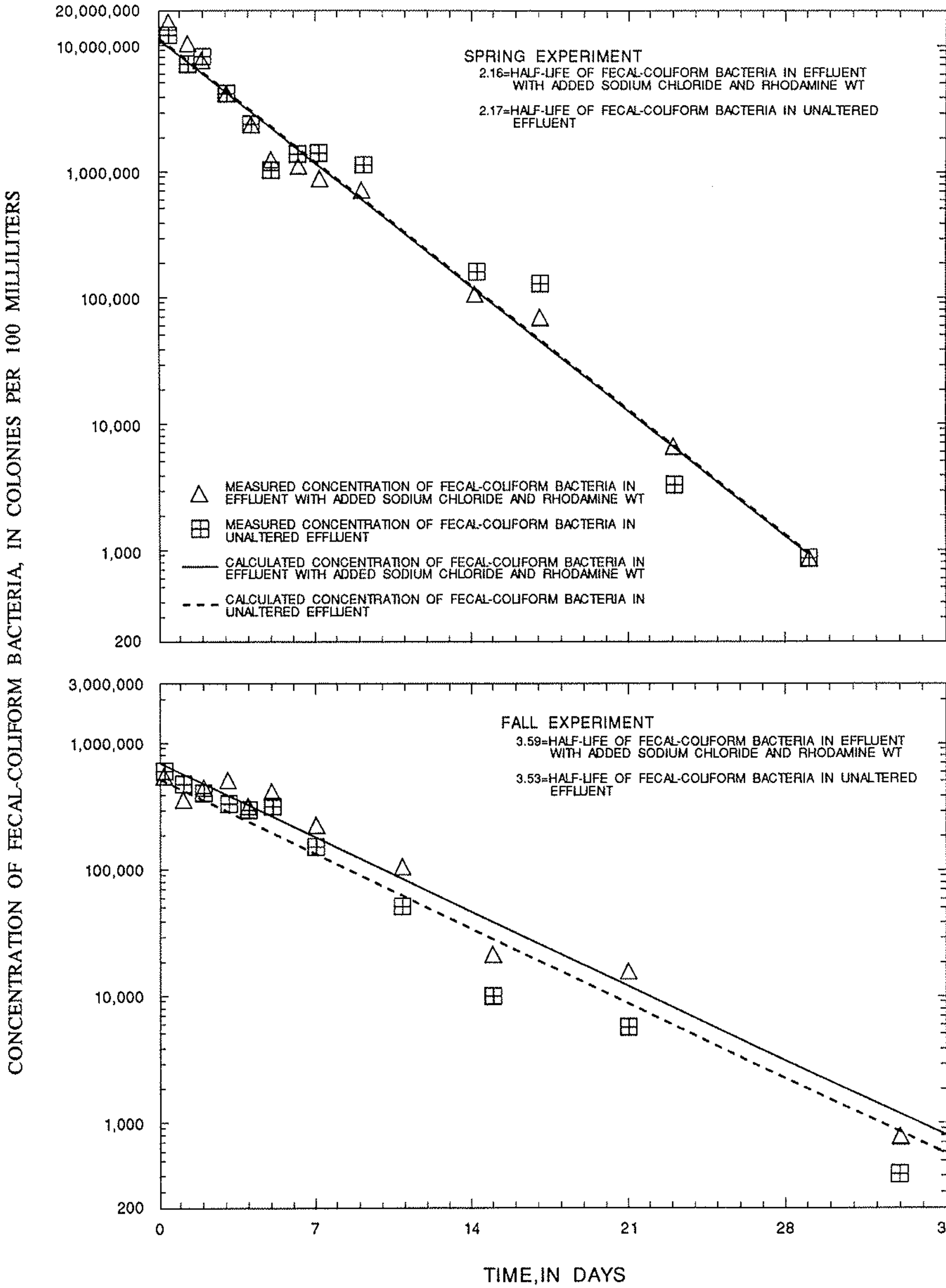


Figure 11. Change in concentration of fecal-coliform bacteria with time in the control tanks during the spring and fall experiments, 1991.

MOVEMENT AND FATE OF FECAL-COLIFORM BACTERIA

The spring and fall experiments were conducted to characterize FC-bacteria movement during periods of maximum and minimum flow in a shallow aquifer system. The spring experiment was conducted during maximum flow rate through the system, whereas the fall experiment was conducted during a minimum flow rate. Time was measured in consecutive days for each experiment. Filling the pit with effluent marked time zero.

Effects of Rainfall on Effluent Movement

During the spring and fall experiments, fluctuations in ground-water levels in the shallow aquifer system corresponded closely with seasonal rainfall. The spring experiment was dominated by heavy and frequent rainfall (fig. 7). A typical configuration of the water table in the shallow aquifer system near the pit during the spring experiment is shown in figure 12. Field runoff periodically ponded south of the pit during the first week of the spring experiment. Recharge from ponding produced a rise in the water table near the pit (fig. 12). Lateral gradients as large as 0.1 ft/ft were associated with this rise but decreased to 0.006 ft/ft a short distance northwest of the rise.

The fall experiment was conducted when the water table was fairly uniform with little or no mounding (fig. 12). Ground-water flow generally was uniform from the west-southwest to the east-northeast. The average lateral gradient near the pit was 0.005 ft/ft.

Recharge Pit

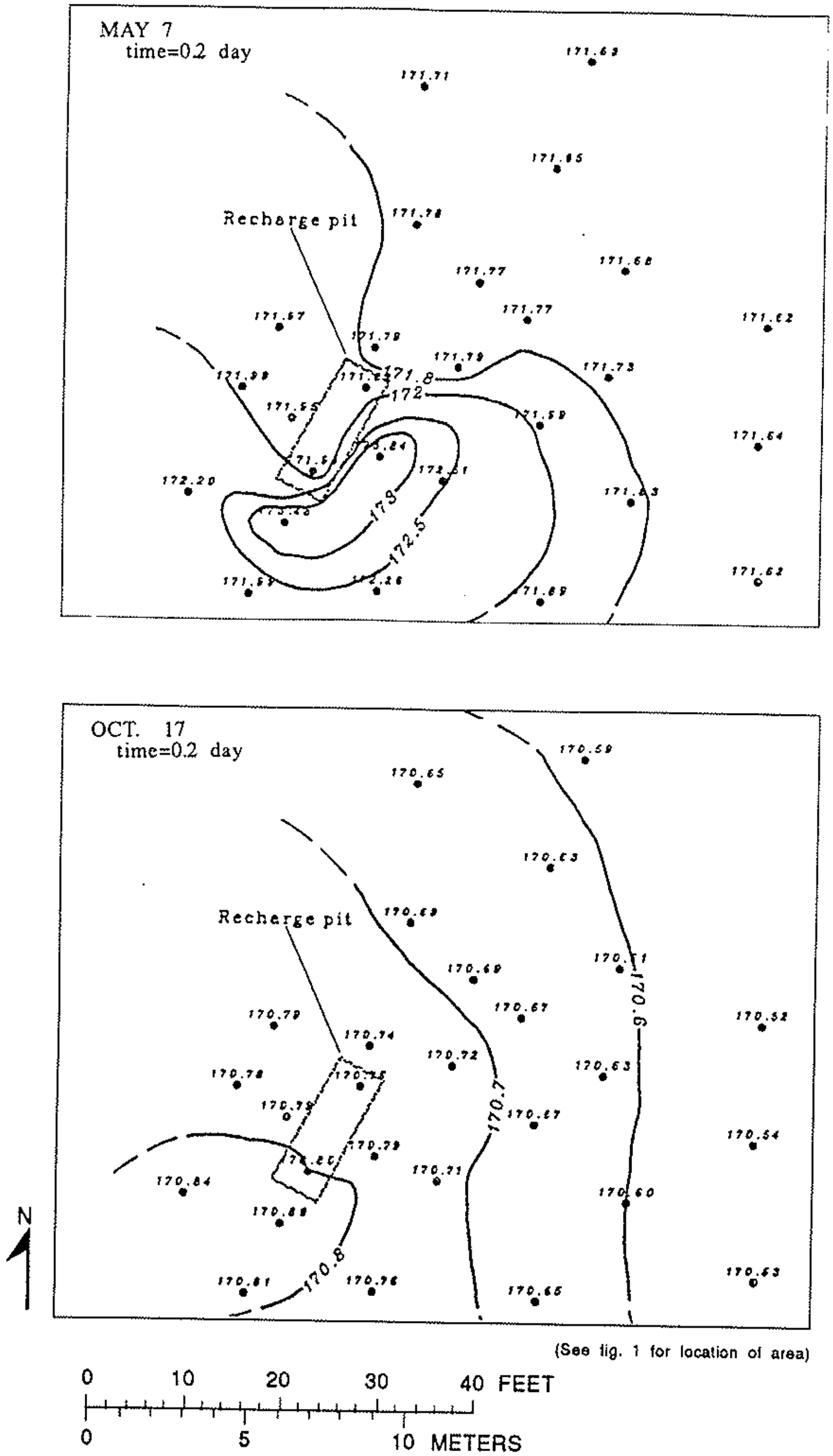
The rate of effluent movement through the floor of the recharge pit into the unsaturated zone depended on the recharge-pit discharge rate, Q_d. For purposes of discharge computation, the pit was conceptualized as a bucket with a leaky bottom (Ross, 1974, p. 87) and the discharge rate was approximated by:

$$Q_d = -\beta (h - \eta) A_{pit}, \tag{2}$$

where,

- β is the average leakance from the recharge pit, in 1/day;
- h is the effluent level in the recharge pit, in feet;
- η is the average apparent pressure head just below the leaky bottom (outlet head), in feet; and
- A_{pit} is the floor area of the recharge pit, in square feet.

Average leakance from the recharge pit, β, quantifies the resistance of the pit bottom to effluent movement. Most of the resistance resulted from suspended particles that settled on the bottom of the pit and formed a thin, fine-grained layer. The outlet head, η, is a function of the soil type and saturation beneath the pit. Both variables, β and η, controlled the rate of effluent movement from the pit.



(See fig. 1 for location of area)

EXPLANATION

—171.8— — WATER-TABLE CONTOUR--Shows altitude of water table. Dashed where approximately located. Contour interval varies in feet. Datum is sea level

170.65 ● CONTROL POINT AND WATER LEVEL--In feet above sea level (See fig. 2 for well numbers)

Figure 12. Typical configuration of the water table in the shallow aquifer system near the recharge pit during the spring and fall experiments, 1991.

The coefficients β and η were not measured, but the effluent level was measured (fig. 13). The measured effluent level, h, in the pit was approximated by:

$$\hat{h} = \alpha e^{-\beta (t - t_0)} + \eta, \tag{3}$$

where,

- $\hat{h}$ is the calculated effluent level, in feet;
- α is the head difference at t_0 (initial time) between effluent level and the pit bottom;
- t is the time, in days;
- t_0 is initial time;
- η is the average apparent pressure head just below the leaky bottom (outlet head), in feet; and
- h_{t_0} is the initial condition.

$$\alpha = h_{t_0} - \eta \text{ , in feet,} \tag{4}$$

which was derived by separating the variables in equation 4, integrating each side, and using h_{t_0} as the initial condition. The coefficients β and η were evaluated by fitting the calculated effluent levels, $\hat{h}$, to the measured effluent levels, h. The coefficients were determined for both the spring and the fall experiments (fig. 13). Two curve fits were done for the spring experiment, because the pit was refilled by runoff 10 days after the initial pit filling. The relatively constant value of β during the spring experiment indicated most of the suspended particles in the effluent had settled quickly after the pit was filled. The lower pit-leakance value in the fall experiment than in the spring experiment is consistent with the increase in effluent and, therefore, particulate matter.

During the spring experiment, the outlet head, η, was above the pit floor for the first 3 weeks of the experiment (fig. 13) because the ground was almost saturated as a result of the high recharge rates around the pit produced by ponding of runoff from heavy and frequent rainfall (fig. 7). The highest water level measured during the spring was 175.5 ft above sea level, which is only 2 ft below the bottom of the pit. In the fall experiment, the water table was 2 to 4 ft lower than it was in the spring (fig. 12) and the unsaturated zone had been draining for 2 months. The outlet head was 0.4 ft below the pit floor and 151 ft^3 of effluent was discharged to the unsaturated zone in about 6 days (fig. 13).

Unsaturated Zone

The rate of effluent movement from the pit is not directly proportional to the rate at which effluent enters the unsaturated zone. The two rates differ in both magnitude and areal distribution. A cross-sectional flow model of the unsaturated zone was constructed by using computer program VS2D (Lappala and others, 1987) to aid in further understanding the mechanics of effluent movement through the unsaturated zone. The model is not a calibrated flow model.

The model area extends laterally from the pit center to a distance of 20 ft perpendicularly from the long centerline and downward 7.25 ft from the pit bottom. Laterally, the model was uniformly discretized to a distance of 5 ft from the centerline in 20 columns and exponentially discretized to a distance of 20 ft in 20 additional columns. Vertically, the model was uniformly discretized into 29 rows, each 0.25 ft wide. The lateral boundaries and upper boundary were defined as no-flow boundaries. The lower boundary was defined as a specified-pressure-head boundary such that water-table conditions occurred 7 ft below the bottom of the pit. The initial conditions were specified as a -2.0-ft pressure head everywhere except from the water table to a height at which the system was in equilibrium with a pressure head of -2.0 ft.

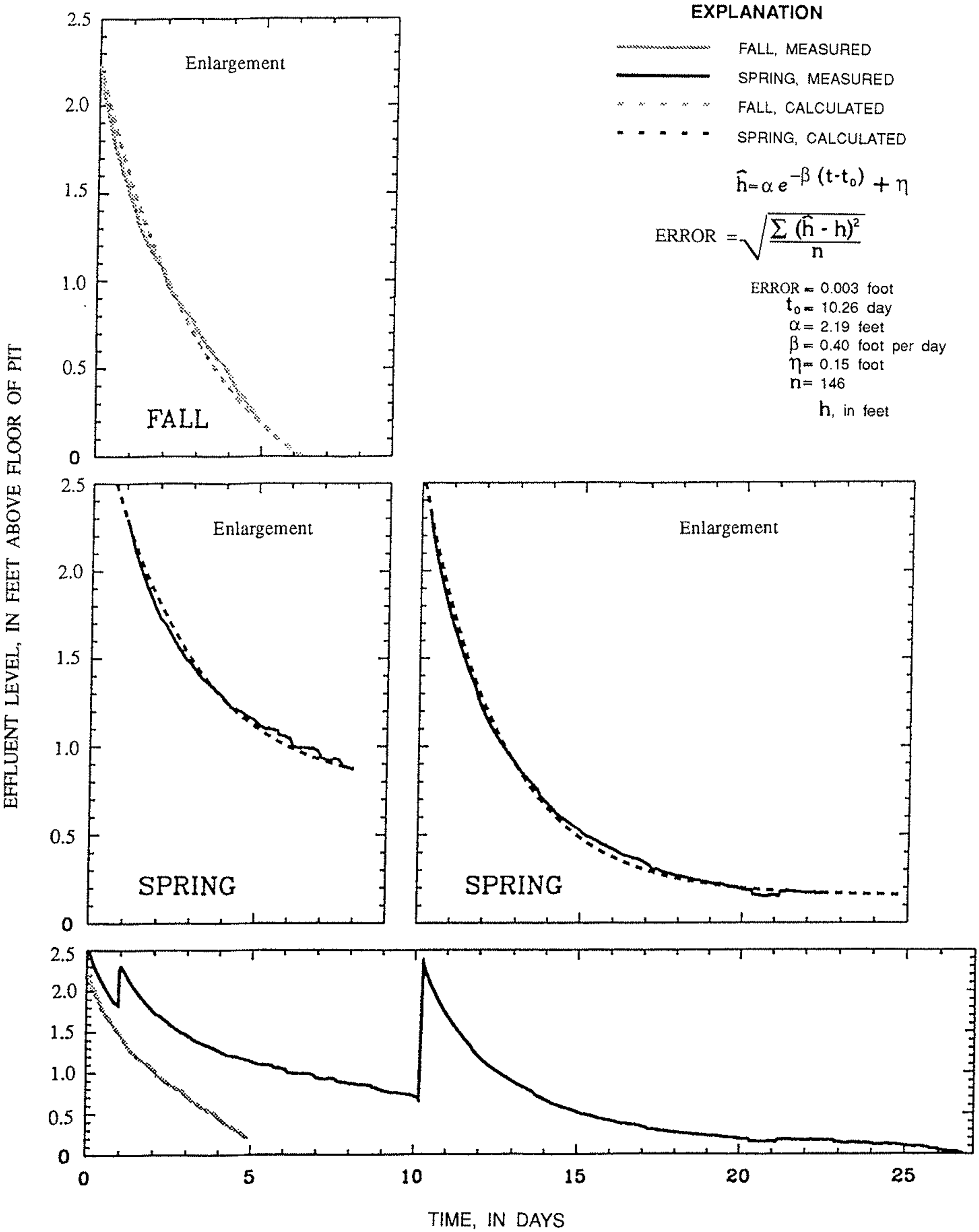


Figure 13. Measured and calculated discharge from the recharge pit during the spring and fall experiments, 1991.

The medium was assumed to be a homogeneous fine sand with an average horizontal hydraulic conductivity of 3.0 ft/d, a vertical hydraulic conductivity of 1.5 ft/d, and a porosity of 0.34. Volumetric moisture content, specific moisture capacity, and relative hydraulic conductivity were approximated by using Van Genuchten relations with the fitting parameters for residual moisture content, Θ_r, scaling length, α', and pore-size distribution, β', set to 0.07, -3.0 ft, and 5.0, respectively (Lappala and others, 1987, p. 20).

Two 81-day simulations were performed from day -60 to day 21. The first simulation was performed to establish the distribution and amount of drainage from the unsaturated zone to the saturated zone without additional stresses. The second simulation differed from the first at day 0 when recharge was applied to the unsaturated zone. The recharge was uniform from the centerline to the pit edge and was calculated by using equation 4 with the fitting parameters from the fall experiment (fig. 14). The equation was applied step-wise in 40 stress periods over a 6.3-day interval. The effect of this slug-like recharge on discharge from the unsaturated zone was calculated by subtracting the base discharge (first simulation) value from the discharge value obtained from the second simulation (fig. 14).

Slug movement of effluent in the unsaturated zone attenuated the peak-recharge rate of effluent into the saturated zone. The lag between the time that effluent first entered the unsaturated zone and the time it first left was primarily the result of storage (filling of the pore space). As effluent drained from the unsaturated zone into the saturated zone, the saturation of effluent in the unsaturated zone decreased. As effluent saturation in the unsaturated zone decreased, the rate at which effluent drained from the unsaturated zone decreased. After 21 days from day 0, 96 percent of the effluent introduced into the unsaturated zone had drained. This percentage was obtained by dividing the area under the dashed curve by the area under the solid curve (fig. 14).

The effluent recharge velocity into the unsaturated zone was evenly distributed across the pit bottom. As time passed, the effluent drainage became evenly distributed by dispersion and diffusion within the unsaturated zone.

This dispersion resulted in the dilution of the effluent and decreased the concentrations of fecal-coliform bacteria, chloride, and rhodamine WT in the unsaturated and saturated zones. For slug movement of effluent, dilution first occurred as the effluent mixed with in situ water in the unsaturated zone. The effluent was diluted further by the prolonged drainage from the unsaturated zone, which allowed more water in the saturated zone to pass beneath the drainage area. Effluent was effectively diluted by diffusion and dispersion of effluent as it moved from the pit into the unsaturated zone (fig. 14). The effluent was dispersed over a larger area as it moved from the unsaturated zone to the saturated zone. This indicates that the effect of drainage from a recharge pit on ground-water quality at a given site decreases with increasing distance of the pit above the water table.

During the fall experiment, filling the pit with effluent had a discernible effect on water levels near the pit because no rain had fallen for 2 months. The spatial and temporal distribution of effluent movement to the saturated zone during the fall experiment was determined by comparing measured and estimated water levels.

Before the pit was filled for the fall experiment, the rate of water-level change in the shallow wells near the pit averaged -0.015 ft/d from September 12 to October 16, 1991, with a standard deviation of 0.0014 ft/d (table 5). This small variation indicated that the rate of water-level change in all of the shallow wells would be similar in an undisturbed system. The average water-level change in wells not influenced by recharge from the pit, wells 120 through 128, was used as an estimate of water-level changes in an undisturbed system in wells that were influenced by recharge from the pit.

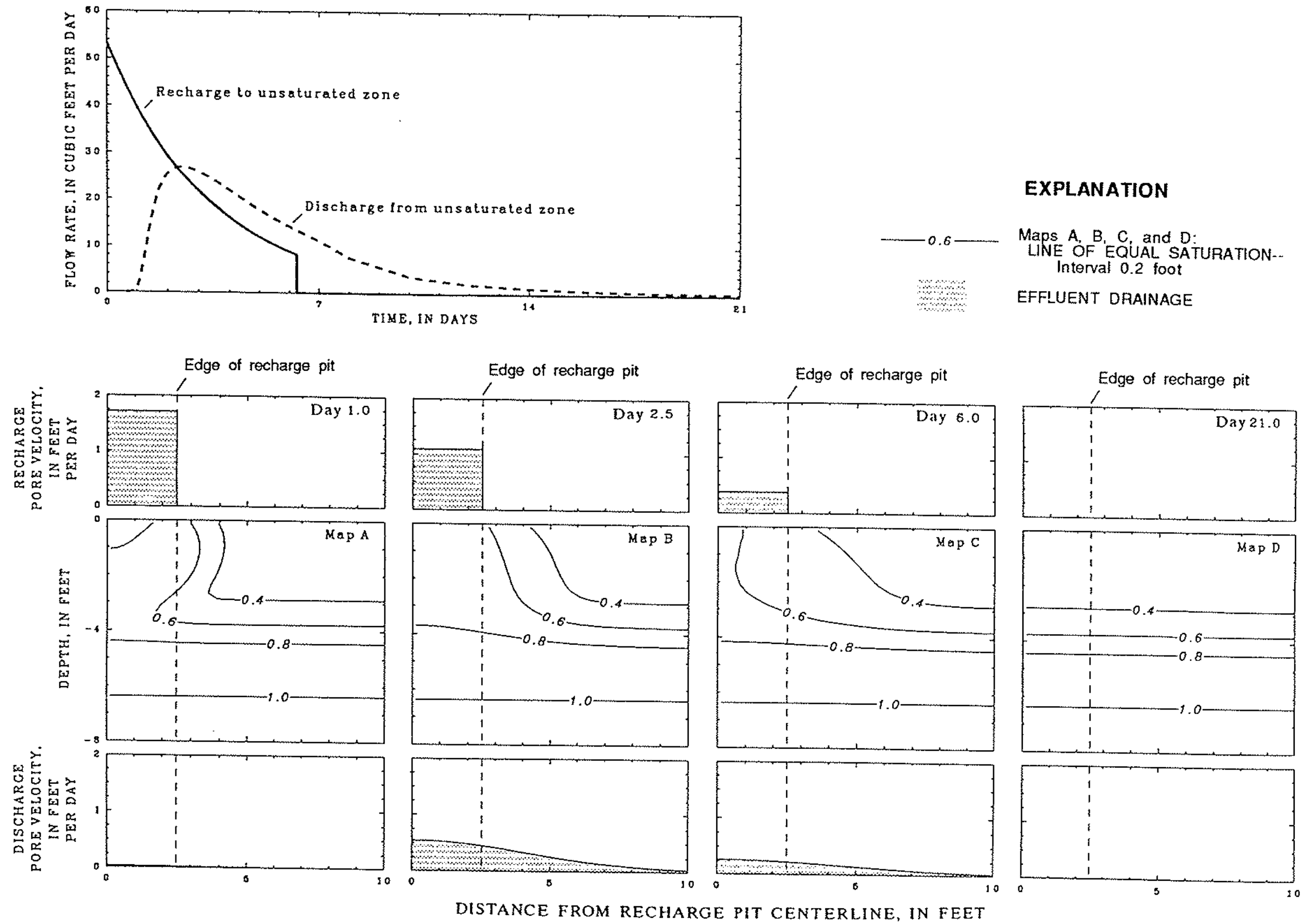


Figure 14. Simulated movement of effluent into, through, and out of the unsaturated zone into the saturated zone, fall experiment, 1991.

Table 5. Average variation of rate of water-level change among shallow wells near the recharge pit during the fall experiment, 1991, Washington Parish, Louisiana

Date		Elapsed time before and after filling the pit with effluent, in days		Average standard deviation of rate of water-level change, in feet per day
From	To	From	To	
9-12	10-16	-34.82	-0.90	0.0014
10-16	10-24	-.90	7.09	.0129
10-24	11-01	7.09	15.09	.0058
11-01	11-19	15.09	33.09	.0015

The difference between measured water-level change in a well and its estimated water-level change in an undisturbed system at a given time, d_n, is calculated by:

$$d_n = h_n - \bar{h}_n - (h_{ref} - \bar{h}_{ref}), \qquad (5)$$

where,

h_n is the water level in the <u>*n*th</u> well at a given time;
$\bar{h}_n$ is the average water level in the *n*th well from 35 days prior to filling the pit;
h_{ref} is the average water level in wells 120 through 128 at a given time; and
$\bar{h}_{ref}$ is the average water level in wells 120 through 128, from 35 days prior to filling the pit.

The effects of recharge were most pronounced in wells 103 and 109 (fig. 15), near the southern end of the pit, indicating that the recharge between these wells was routed through a zone of high permeability. A time series of water-level differences between wells 103, 106, and 109 calculated by using equation 7 and discharge rates from the unsaturated zone during the fall experiment is shown in figure 15.

Discharge from the unsaturated zone was approximated by assuming that discharge in any location was proportional to the water-level difference, $\partial(x,y)$, and the medium was homogeneous. This implied that $\partial h/\partial x$ and $\partial h/\partial y$ were zero at the water table and all effluent movement in the saturated zone near the water table was vertical. This was not the case, but because the vertical components of flow probably were much greater than the lateral components, ignoring their effects was acceptable. The discharge rate, Q, from the unsaturated zone, uz, at any time can be calculated by:

$$Q_{uz} = \lambda V, \qquad (6)$$

where,

λ is the proportionality constant that is a function of the average vertical leakance near the water table, in 1/day, and

$$V = \int_{y_{min}}^{y_{max}} \int_{x_{min}}^{x_{max}} \partial(x, y)\, \partial x \partial y, \text{ in cubic feet.} \qquad (7)$$

The volume (V) associated with water-level differences was evaluated at the times shown in figure 16. Only water-level differences greater than 0.02 ft were used because these were considered direct results of effluent movement. The 0.02-ft threshold was twice the 0.01-ft standard deviation of water-level differences calculated for wells 120 through 128 from October 17 to November 7, 1991.

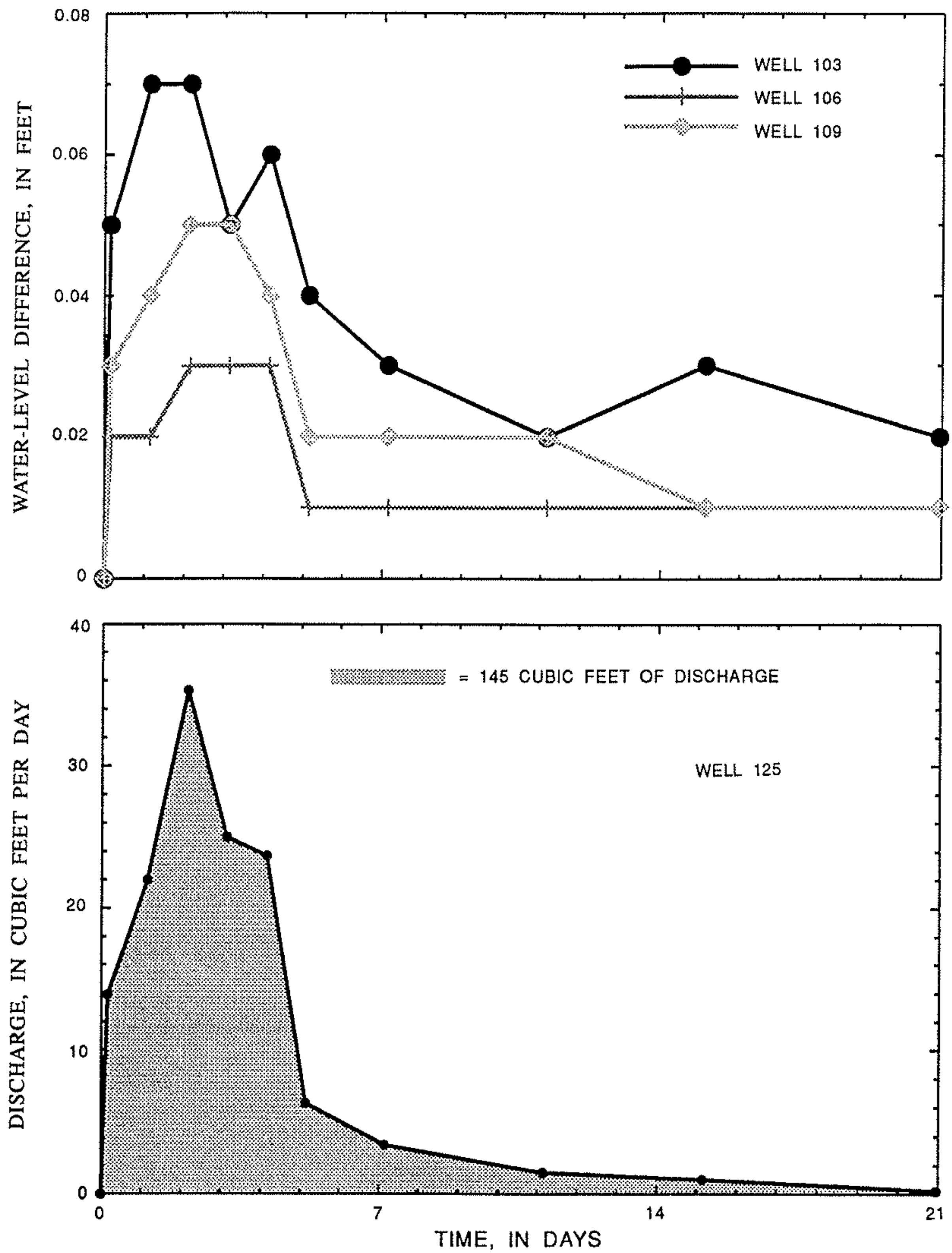


Figure 15. Water-level differences between selected wells and well 125 during the fall experiment, 1991, and discharge rates for the unsaturated zone.

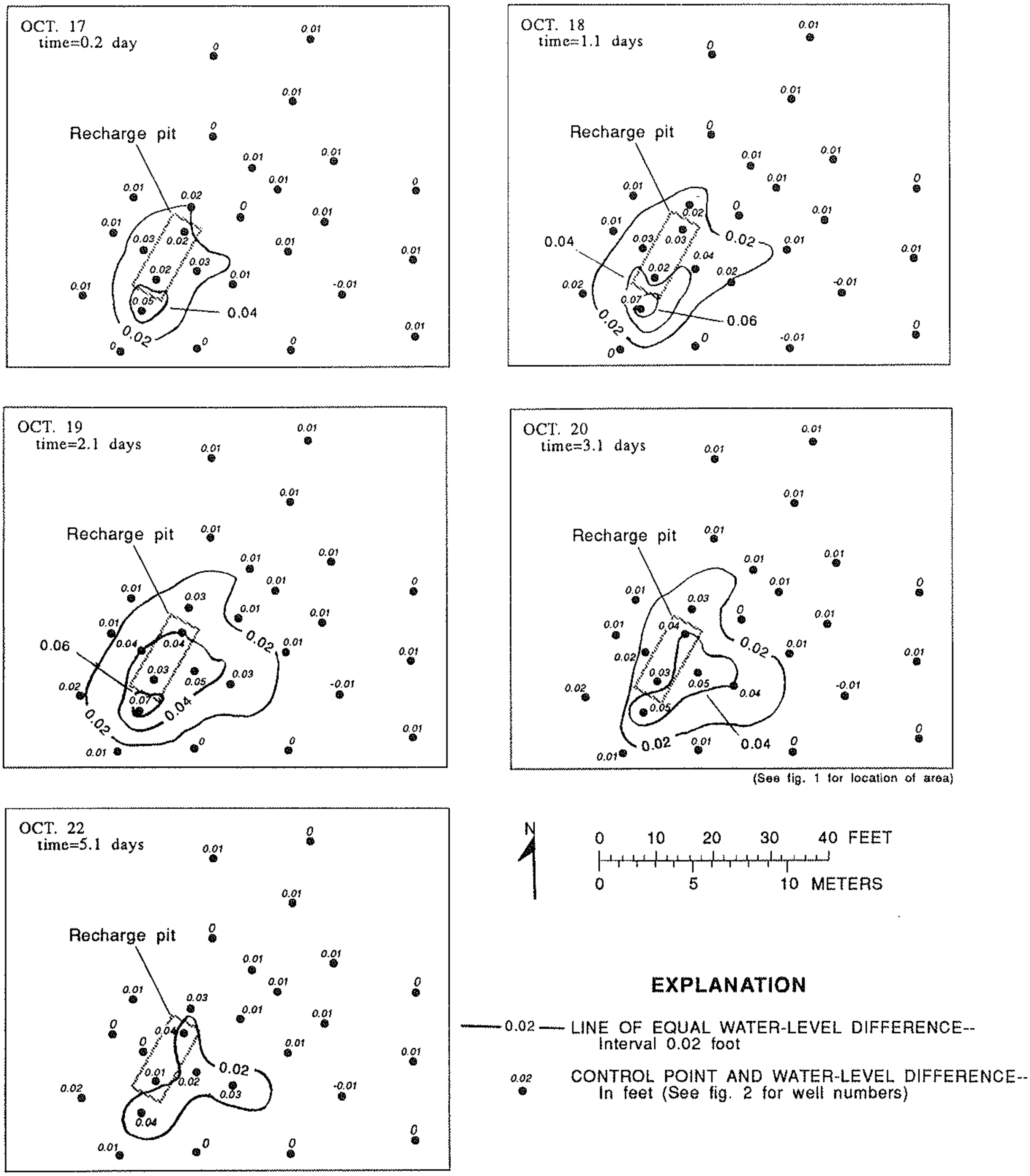


Figure 16. Water-level differences in the shallow aquifer system during the fall experiment, 1991.

By assuming that 96 percent of the effluent, 145 ft^3, had drained from the unsaturated zone after 21 days, the proportionality constant was calculated by:

$$\lambda = \frac{145\ ft^3}{\int_0^{21} V\ \partial t}, \qquad (8)$$

and was equal to 2.0/day. Selected water-level-difference maps and their associated rates of discharge from the unsaturated zone are shown in figure 16.

A quantitative analysis of effluent movement from the unsaturated zone to the saturated zone was not feasible for the spring experiment. Extreme rainfall and recharge rates masked the effects of the pit during the spring experiment.

Saturated Zone

During the spring and fall experiments, movement of effluent through the saturated zone was tracked laterally and vertically by measuring FC-bacteria concentrations, specific conductance, rhodamine-WT concentrations, and water levels. Because the data collected were for experimental purposes and represent artificial conditions, the data were not stored in the USGS's computerized data base.

The relation between chloride concentrations and specific conductance was investigated to determine mass-balance estimates. The chloride concentrations and specific-conductance values were determined for 186 samples collected from wells completed in the study area. Chloride concentrations ranged from 3 to 210 mg/L, with a mean of 18 mg/L. Specific-conductance values ranged from 44 to 698 µS/cm, with a mean of 94 µS/cm. The slope of the regression line is 0.305 $\frac{mg/L}{\mu S/cm}$ and its intercept is -10.5 mg/L. Chloride concentration was positively correlated to specific conductance, with a regression coefficient, r^2, of 0.97.

Mass-balance estimates were determined for rhodamine-WT and chloride concentrations to account for the effluent and compare the overall attenuation of tracers relative to one another. Cumulative tracer masses discharged from the pit and total tracer masses measured in the shallow part of the saturated zone were estimated at selected times during both experiments. The total tracer mass, M_{sz}, in the shallow part of the saturated zone was calculated by:

$$M_{sz} = Cn \frac{A_s b \phi}{\sum_{j=1}^{m} r_j^2} \sum_{j=1}^{m} (c_{t_j} - c_{0_j}) r_j^2, \qquad (9)$$

where,

Cn is the constant used to convert units (varies for each tracer);

A_s is the area accounted by the observation wells, 3,245 ft^2 (table 6);

b is the average thickness of shallow saturated zone, in feet;

ϕ is the average effective porosity, 0.30;

c_{0_j} is the concentration of tracer in the *nth* well at time zero, in mass per liter;

c_{t_j} is the concentration of tracer in the *nth* well after a period of time, t, in days, in mass per liter;

r_j is the average distance between nearest wells, in feet; and

m is the number of shallow wells, 27.

This method is an areally weighted scheme, which was used rather than polygonal approximation to retain the full area monitored.

Table 6. Area accounted by each observation well, Washington Parish, Louisiana

Well no.	Average radius, in feet	Radius-square-weighted Area, in square feet	Radius-square-weighted Percent of total area
101	5.0	78	2.4
102	5.6	98	3.0
103	4.2	55	1.7
105	6.4	129	4.0
106	3.3	34	1.0
107	4.0	50	1.5
108	3.8	45	1.4
109	5.7	102	3.1
110	6.6	137	4.2
111	6.3	125	3.8
112	3.8	45	1.4
113	4.7	69	2.1
114	4.5	64	2.0
115	6.0	1,123	3.5
116	6.6	137	4.2
117	4.8	72	2.2
118	5.2	85	2.6
119	6.1	117	3.6
120	9.0	254	7.8
121	6.5	133	4.1
122	6.6	137	4.2
123	7.6	181	5.6
124	8.3	216	6.6
125	6.7	141	4.3
126	8.6	232	7.1
127	7.1	158	4.9
128	8.7	238	7.3
Minimum	3.3	34	
Average	6.0	120	
Maximum	9.0	254	
Standard deviation	1.5	62	
		Total: 3,245	

Spring Experiment, 1991

Differences in ground-water levels among the observation wells varied during the spring experiment (fig. 17). The areal extent of FC-bacteria contamination is shown in figure 18. Changes in FC-bacteria concentrations and specific-conductance values in more than 70 percent of the wells near the pit were greater than background levels (figs. 18 and 19).

Effluent movement during the first few days of the experiment was rapid. All three tracers were clearly present in samples from wells 109 and 119 (figs. 20 and 21) 2 days after the pit was filled. The tracers were present a day later in well 128 (fig. 22) and at depth in well 313 (fig. 23). The FC-bacteria (fig. 18) and specific-conductance distributions (fig. 19) coupled with responses of deeper wells to FC bacteria, specific conductance, and rhodamine WT (fig. 23) indicated that most of the effluent moved laterally. Chloride mass-balance estimates indicated that the effluent introduced to the shallow part of the saturated zone moved through the saturated zone quickly during the first 7 days (table 7), as indicated by the percentage decrease from 0.2 to 2.2 days and percentage increase after 7 days.

Migration of FC bacteria was attenuated more than rhodamine-WT and chloride migration. The discharged FC bacteria in the shallow part of the saturated zone averaged 0.47 percent. This is $^1/_{60}$ of the average chloride response (29 percent).

Unlike chloride migration, FC-bacteria migration was retarded by sorption and filtration. A disparity existed between FC-bacteria (fig. 18) and specific-conductance (fig. 19) distributions around the northern end of the pit, which was also a region of low hydraulic conductivity, as compared to the surrounding area (fig. 9), indicating that FC-bacteria migration was attenuated more by filtration or sorption than chloride.

Throughout the spring experiment, the tracer concentrations in samples from well 119 (fig. 21) were anomalously greater than those in samples from well 109 (fig. 20), partly because water levels in well 109 were more than 2 ft above the top of the screened interval on May 10 (fig. 24), and because most of the effluent probably entered the saturated zone somewhere between wells 103 and 109. The lateral effluent velocity near the pit in the saturated zone probably was greater than the vertical effluent velocity throughout most of the spring experiment, causing the effluent to move as a thin sheet above most of the screened interval of well 109. A possible hydraulic-conductivity distribution agreed with this hypothesis. Slug-test results and the tracer concentrations measured indicated that the most likely explanation for the lower tracer concentrations at well 109 compared to concentrations at well 119 is an area of lower hydraulic conductivities across the lower parts of wells 103 and 109 than the hydraulic conductivities in the upper parts of these wells (fig. 24). The lateral velocity of the effluent decreased with increasing distance from the pit, as the effluent approached well 119, and the effluent stream expanded vertically to cover the entire screen. Consequently, greater tracer concentrations were measured in samples from well 119 than in those from well 109.

The combined effects of dilution, sorption, and filtration greatly attenuated FC-bacteria concentrations in the shallow aquifer system. The maximum FC-bacteria concentration measured, 2,100 cols/100 mL in well 119, was only 0.04 percent of the control-tank concentration of 5,900,000 cols/100 mL at the same time. Concentrations of FC bacteria greater than the State's standard, 200 cols/100 mL, for primary contact were not detected beyond 40 ft from the pit during the spring experiment (fig. 18), although FC bacteria in concentrations greater than 50 cols/100 mL did migrate more than 50 ft from the pit.

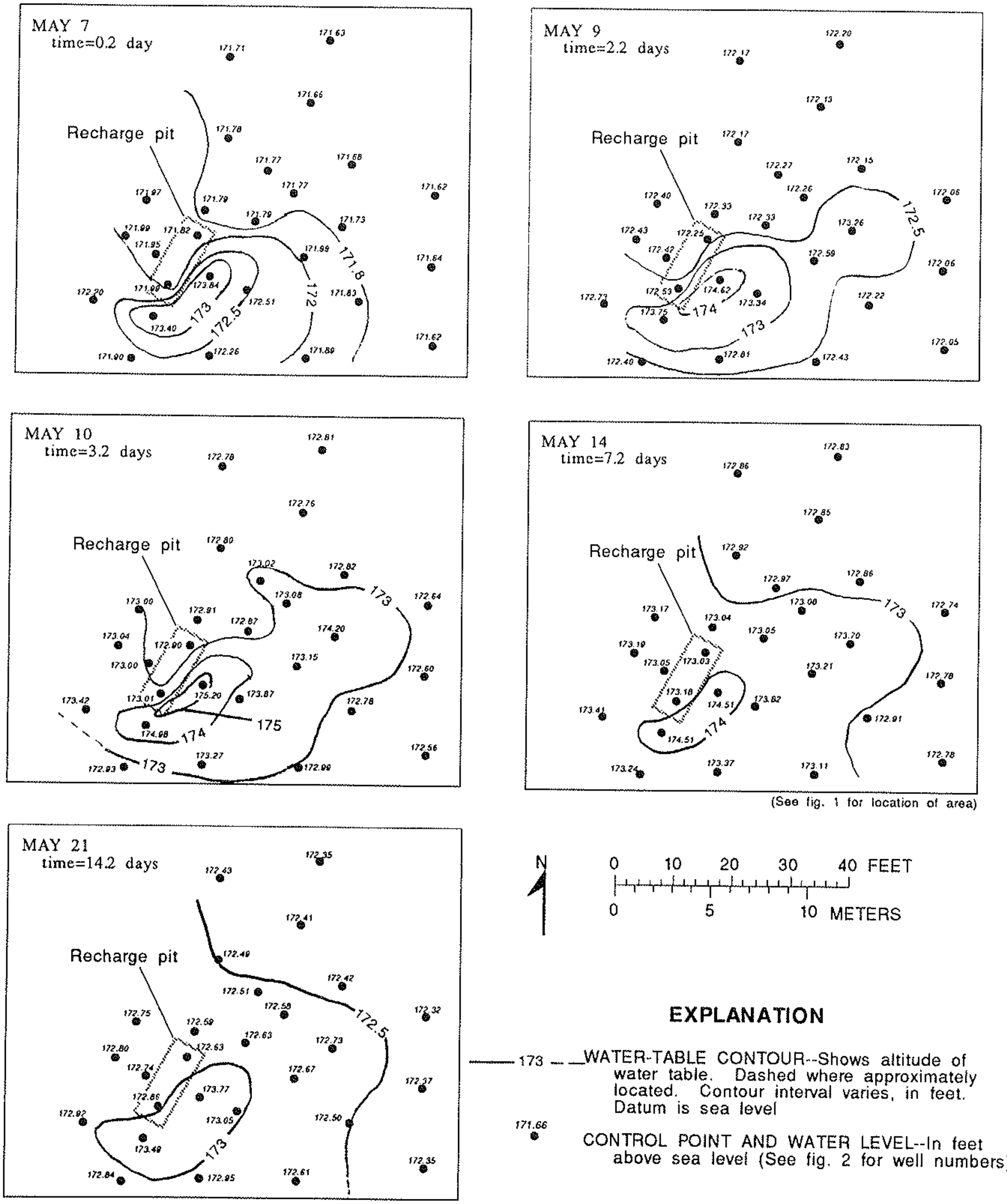


Figure 17. Water-table configuration in the shallow aquifer system near the recharge pit during the spring experiment, 1991.

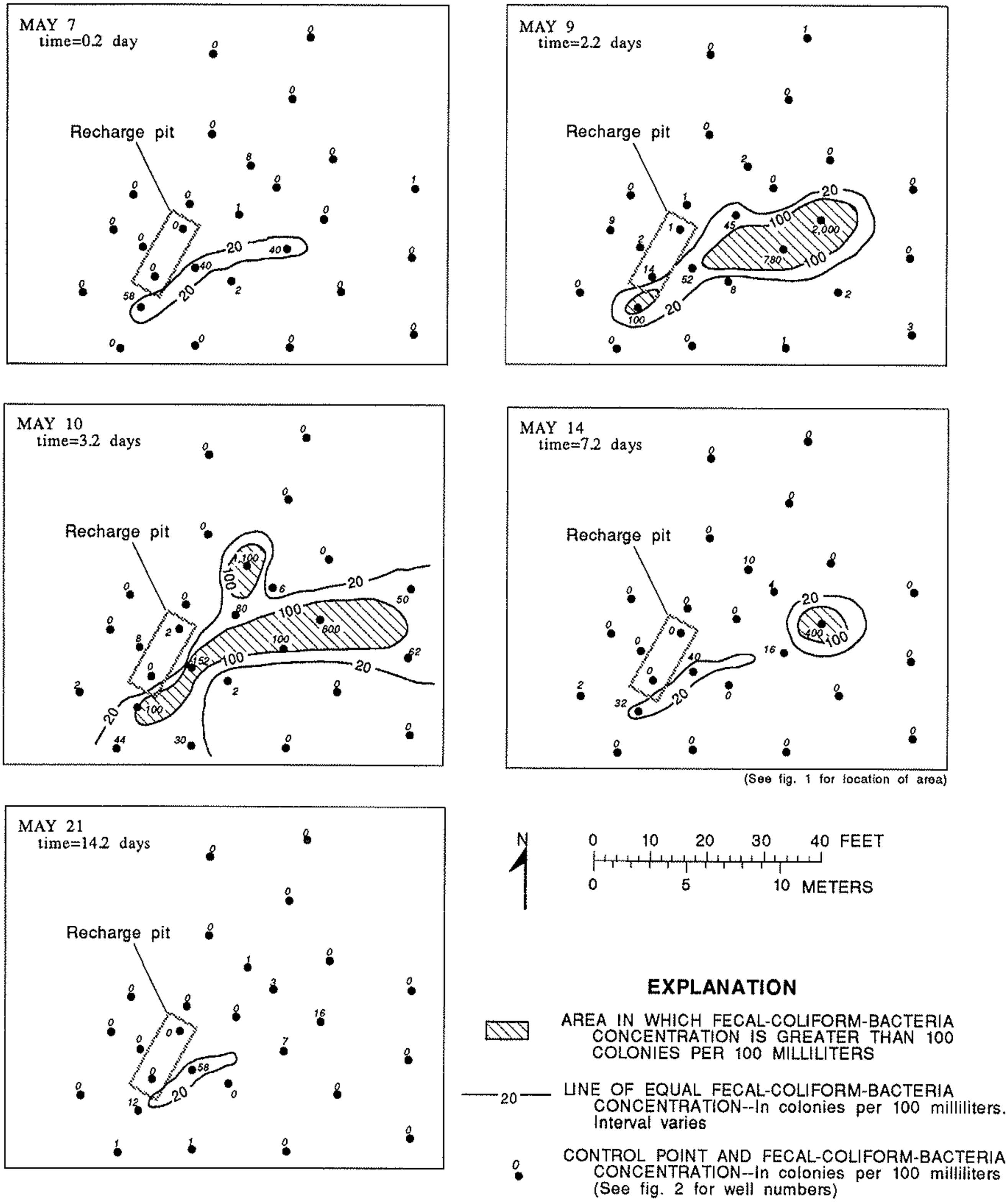


Figure 18. Concentration of fecal-coliform bacteria near the recharge pit during the spring experiment, 1991.

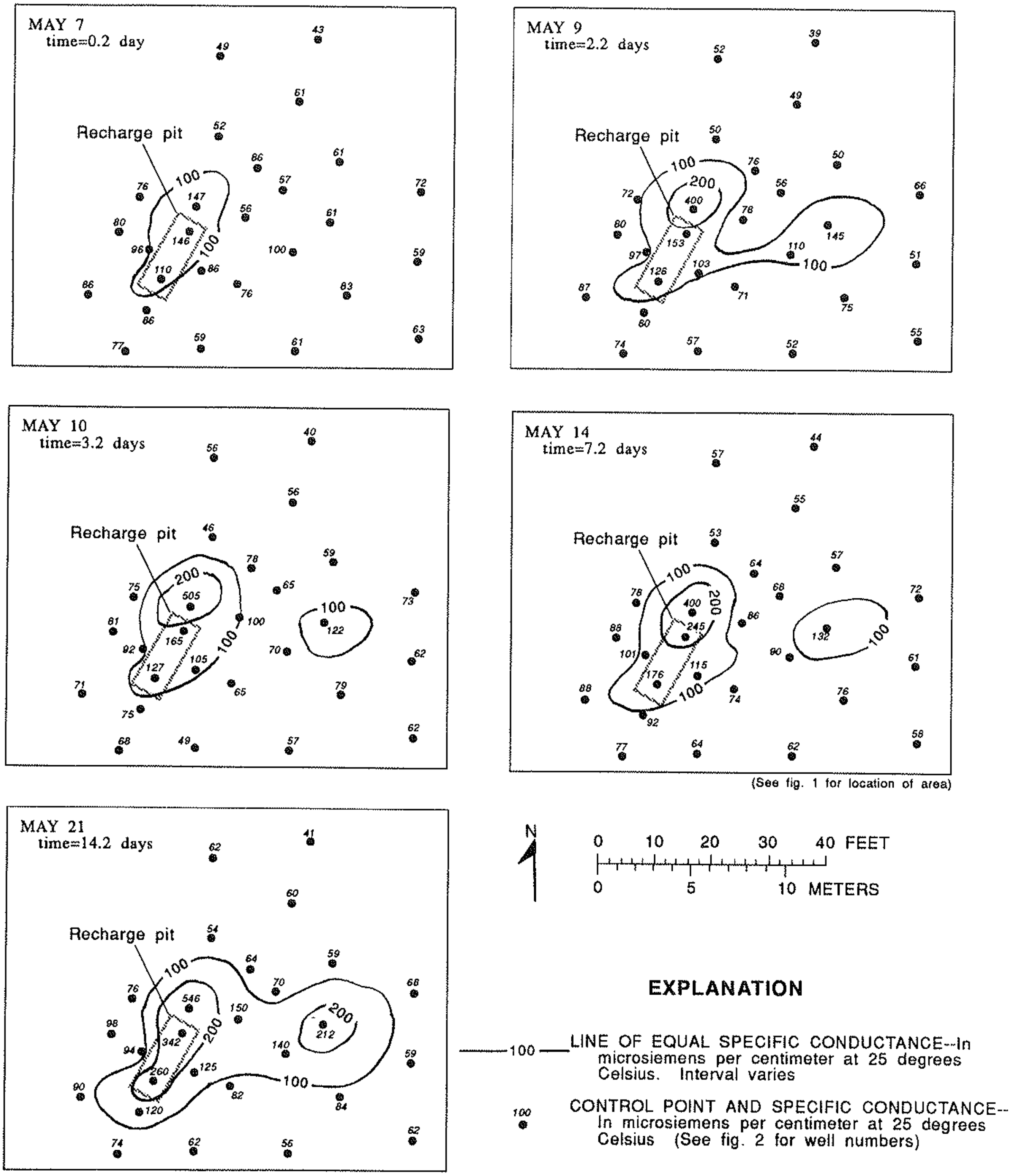


Figure 19. Specific conductance of ground water near the recharge pit during the spring experiment, 1991.

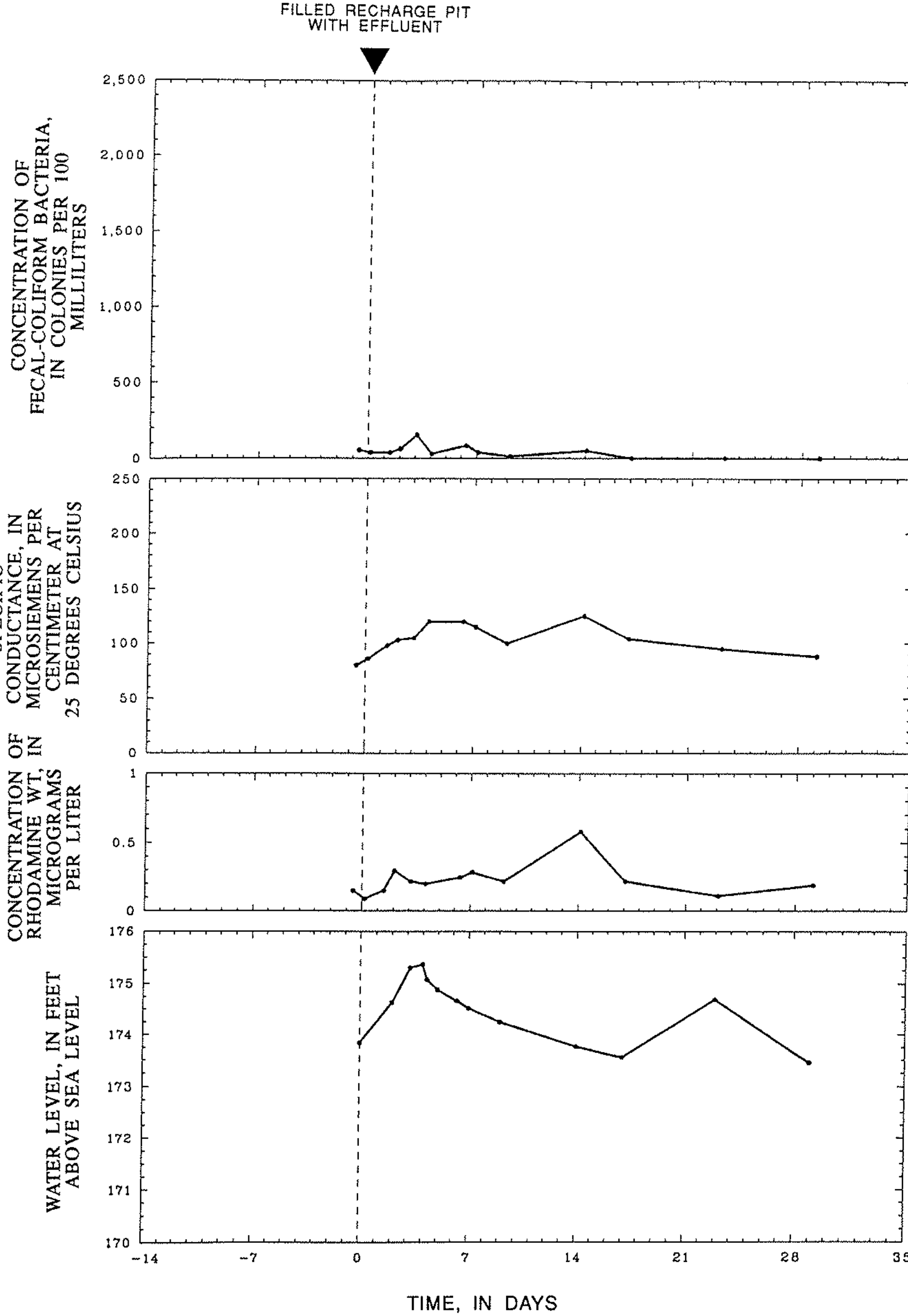


Figure 20. Fecal-coliform-bacteria concentrations, specific-conductance values, rhodamine-WT concentrations, and water levels in observation well 109 during the spring experiment, 1991.

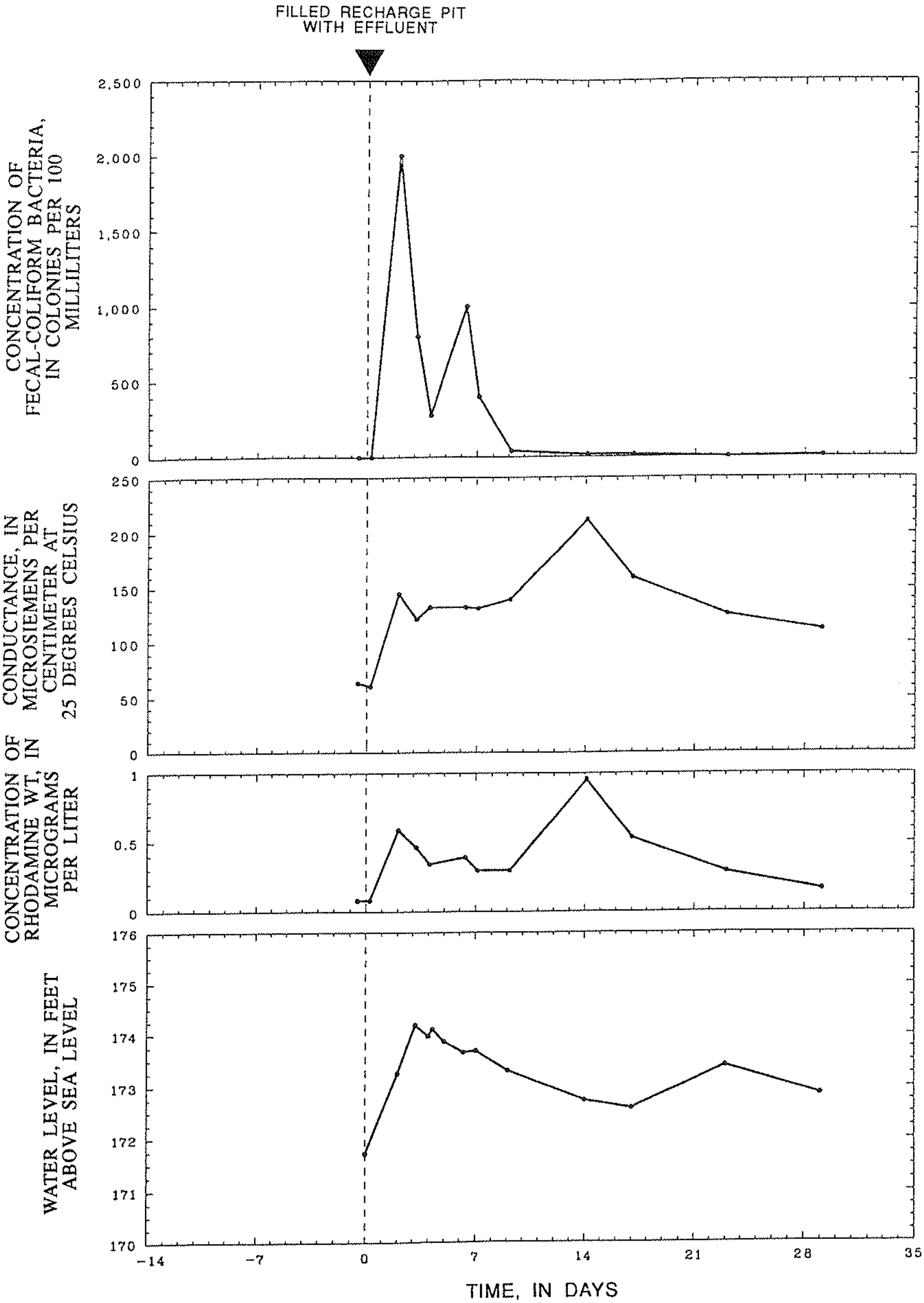


Figure 21. Fecal-coliform-bacteria concentrations, specific-conductance values, rhodamine-WT concentrations, and water levels in observation well 119 during the spring experiment, 1991.

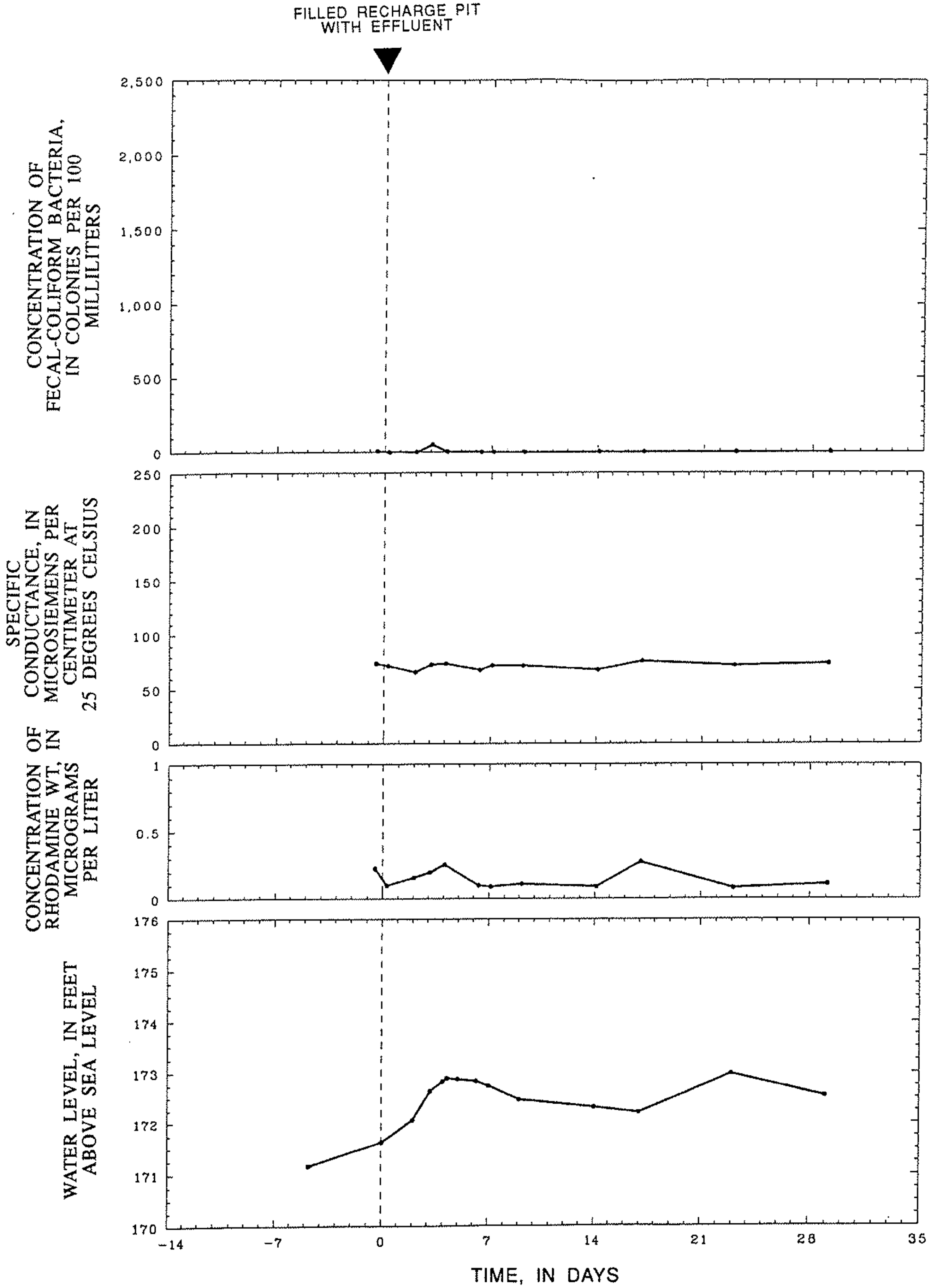


Figure 22. Fecal-coliform-bacteria concentrations, specific-conductance values, rhodamine-WT concentrations, and water levels in observation well 128 during the spring experiment, 1991.

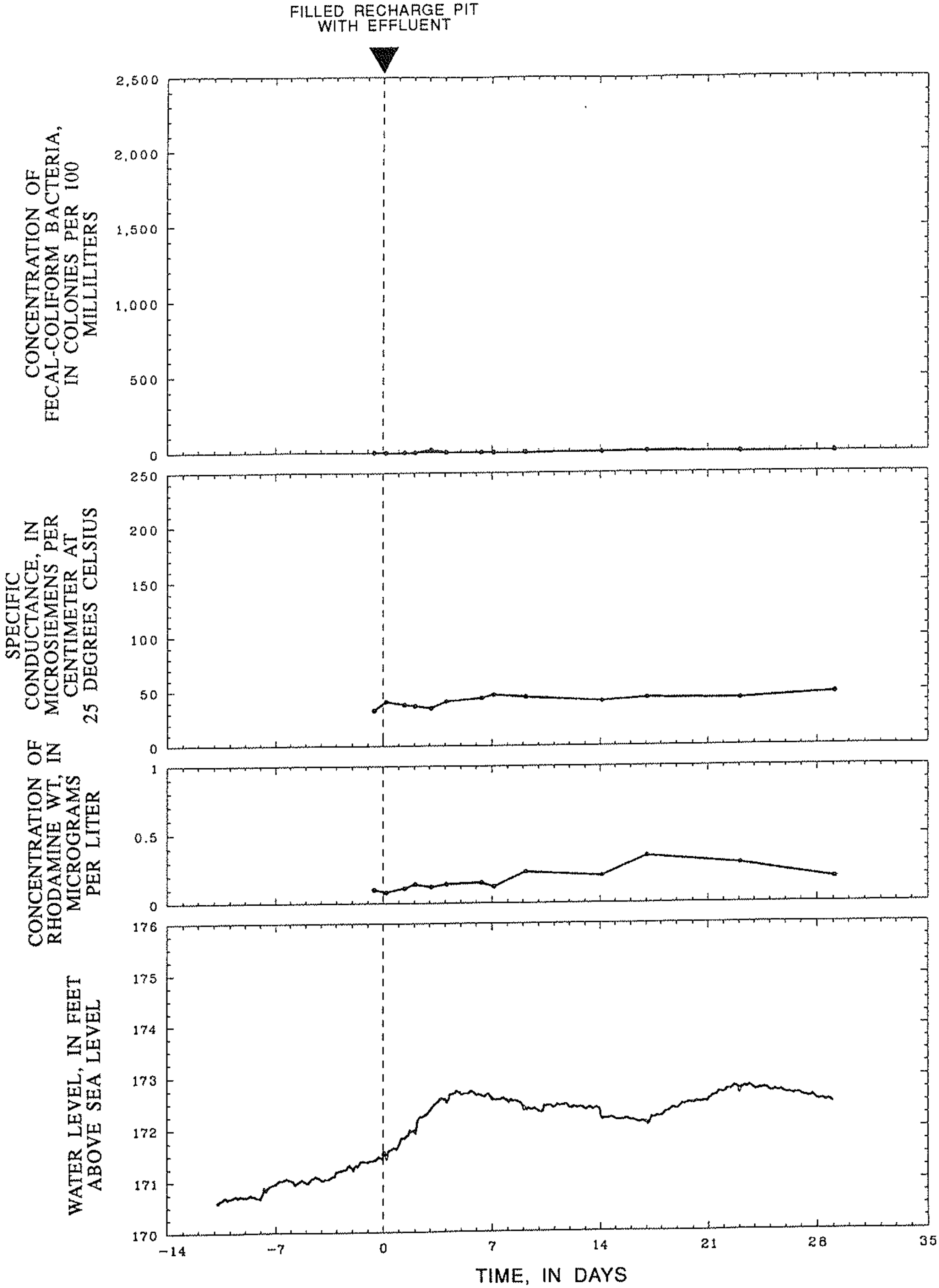


Figure 23. Fecal-coliform-bacteria concentrations, specific-conductance values, rhodamine-WT concentrations, and water levels in observation well 313 during the spring experiment, 1991.

Table 7. Net movement of chloride and fecal-coliform bacteria from the recharge pit into the shallow part of the saturated zone during the spring experiment, 1991, Washington Parish, Louisiana

[Initial volume of effluent, 170 cubic feet[1]; initial specific conductance, 3,300 microsiemens per centimeter at 25 degrees Celsius; initial chloride concentration, 1,000 milligrams per liter; initial fecal-coliform bacteria concentration, 12,000,000 colonies per 100 milliliters]

Date	Elapsed time, in days	Initial effluent in recharge pit, percent[2]	Cumulative discharge, in cubic feet	Initial effluent discharged, percent	Cumulative chloride discharge from recharge pit, in grams	Net chloride in shallow saturated zone, in grams	Discharged chloride detected in shallow saturated zone, percent[3]
5- 7	0.2	100	12	7	350	100	29
5- 9	2.2	79	86	46	2,200	500	23
5-10	3.2	79	106	55	2,600	670	26
5-14	7.2	79	140	70	3,400	900	27
5-21	14.2	15	270	88	4,200	1,700	41
5-24	17.2	15	290	90	4,300	1,600	37
5-30	23.2	15	310	91	4,400	1,300	29
6- 5	29.2	15	320	92	4,400	960	22
						Average percent:	29

Date	Elapsed time, in days	Net fecal-coliform-bacteria colonies: Bacteria in control tank, in colonies per 100 milliliters	Bacteria discharge from recharge pit, in millions of colonies per 100 milliliters	Bacteria detected in shallow saturated zone, in millions of colonies per 100 milliliters	Discharged bacteria detected in shallow saturated zone, percent[3]	Bacteria percent divided by chloride percent
5- 7	0.2	11,000,000	39,000	8.7	0.02	0.08
5- 9	2.2	6,000,000	130,000	240	.18	.81
5-10	3.2	4,300,000	110,000	170	.15	.59
5-14	7.2	1,200,000	40,000	39	.10	.36
5-21	14.2	130,000	5,300	6.2	.12	.29
5-24	17.2	48,000	2,100	3.3	.16	.44
5-30	23.2	7,000	300	2.3	.74	2.6
6- 5	29.2	1,000	45	1.0	2.3	10.7
				Average percent:	0.47	

[1]Recharge pit was overtopped twice during the spring experiment. See figure 13, t = 1.0 day and t = 10.26 days.

[2]Percentage calculated as final specific conductance divided by initial specific conductance. Assumed concentrations of chloride, fecal-coliform bacteria, rhodamine WT, and salt (sodium chloride) in added water were negligible relative to initial concentrations in the recharge pit.

[3]The fecal-coliform-bacteria response was $^1/_{60}$ of the chloride response, as derived by dividing the average percentage of fecal-coliform bacteria discharged in the shallow part of the saturated zone by the average percentage of chloride discharged in the shallow part of the saturated zone.

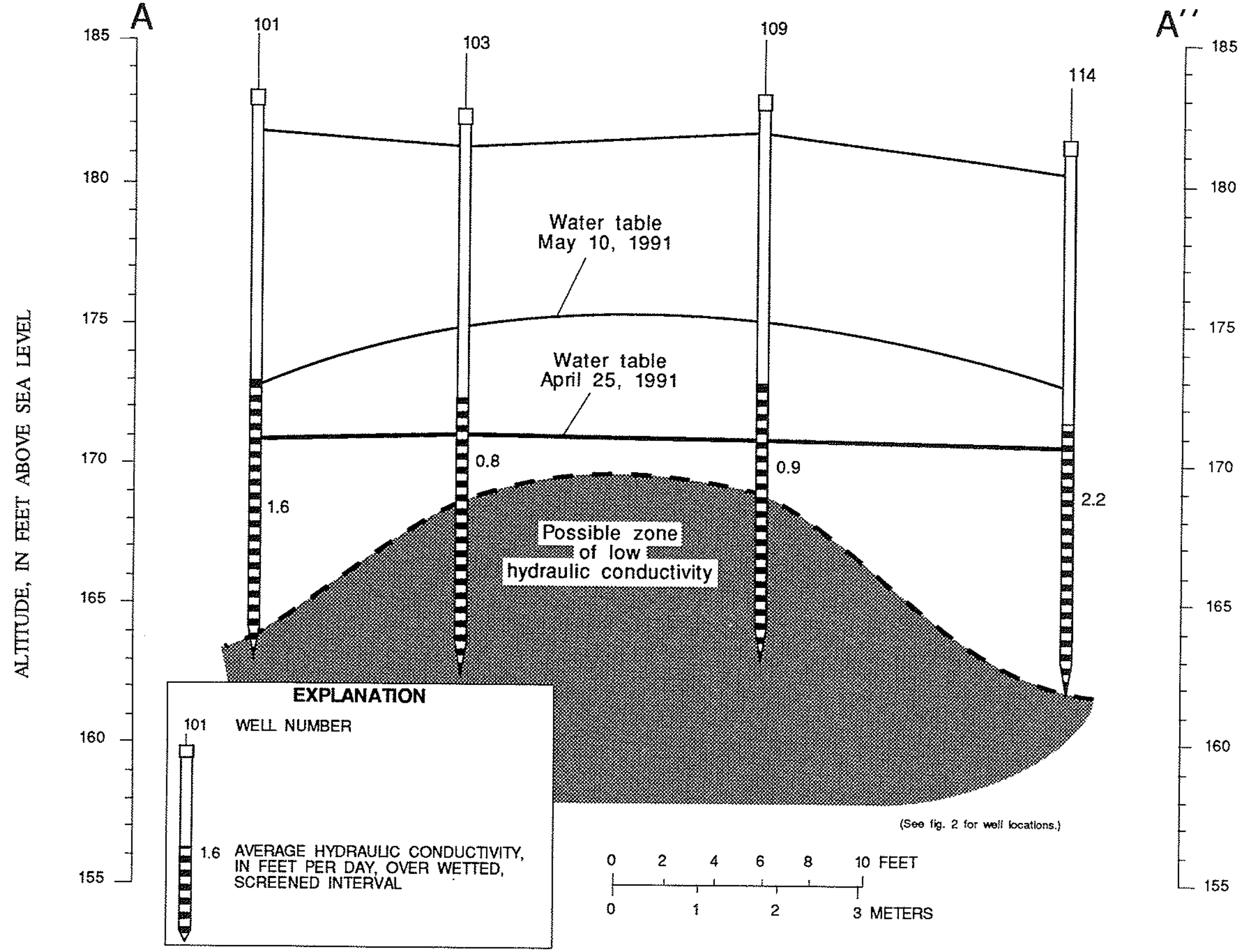


Figure 24. Section A-A'' showing a possible hydraulic-conductivity distribution among selected observation wells.

Fall Experiment, 1991

Ground-water levels were somewhat stable during the fall experiment because water movement was slow (fig. 25). A lateral ground-water gradient of 0.005 ft/ft that dipped to the east-northeast was maintained throughout the fall experiment. Residual effluent from the spring experiment was still present when the fall experiment began. A map of specific-conductance values measured 14 days prior to filling the pit with effluent during the fall experiment clearly shows a faint plume emanating from the pit (fig. 26).

Only a small volume of water in the shallow part of the saturated zone near well 103 (fig. 27) was contaminated by effluent during the fall experiment; therefore, a map showing the areal extent of contamination was not prepared. FC-bacteria concentrations, rhodamine-WT concentrations, and specific conductance increased rapidly in well 103 (fig. 27) within a few hours after the pit was filled. A weak response in these variables was apparent at depth in well 313 (fig. 28) in comparison to the response in well 103. Water in most of the other shallow wells, such as well 128 (fig. 29), was not substantially affected by the effluent movement. Specific-conductance maps (fig. 26) show slow lateral dispersion of the effluent compared to that observed during the spring experiment (fig. 19). The volume of water in the aquifer that was contaminated by effluent was greater during the spring experiment than during the fall experiment.

Chloride mass-balance estimates indicated that effluent movement through the shallow part of the saturated zone was slower during the fall experiment than during the spring experiment (table 8). The discharged chloride detected in the shallow part of the saturated zone averaged 24 percent of the cumulative chloride discharged from the pit. The rhodamine-WT migration was about 5 percent of the chloride migration throughout the fall experiment (fig. 30). The discharged FC bacteria detected in the shallow part of the saturated zone averaged 0.004 percent. This was 300 times less than the average rhodamine-WT response and 6,000 times less than the average chloride response. The large difference between responses of chloride, rhodamine WT, and FC bacteria indicates that filtration attenuated FC-bacteria concentrations more than sorption. The greater attenuation of FC bacteria also resulted in part from the presence of a layer of fine-grained suspended particles that settled on the bottom of the pit.

Concentrations of FC bacteria greater than the State's standard, 200 cols/100 mL, for primary contact were not detected in the shallow aquifer system during the fall experiment. The maximum FC-bacteria concentration detected was 95 cols/100 mL in well 103 (fig. 27), 7 days after filling the pit with effluent; this concentration was 0.05 percent of the control-tank FC-bacteria concentration of 180,000 cols/100 mL at that time

The effect of drainage from a recharge pit on ground-water quality at a given site decreases with increasing distance of the pit above the water table. The unsaturated zone allowed for greater filtration and adsorption of FC bacteria than the saturated zone by dispersing effluent over a larger volume of aquifer and exposing the effluent to more surface area. The rapid decrease in concentrations of FC bacteria, compared to relatively slow ground-water movement, substantially limited the extent of contamination of the shallow aquifer during the fall experiment.

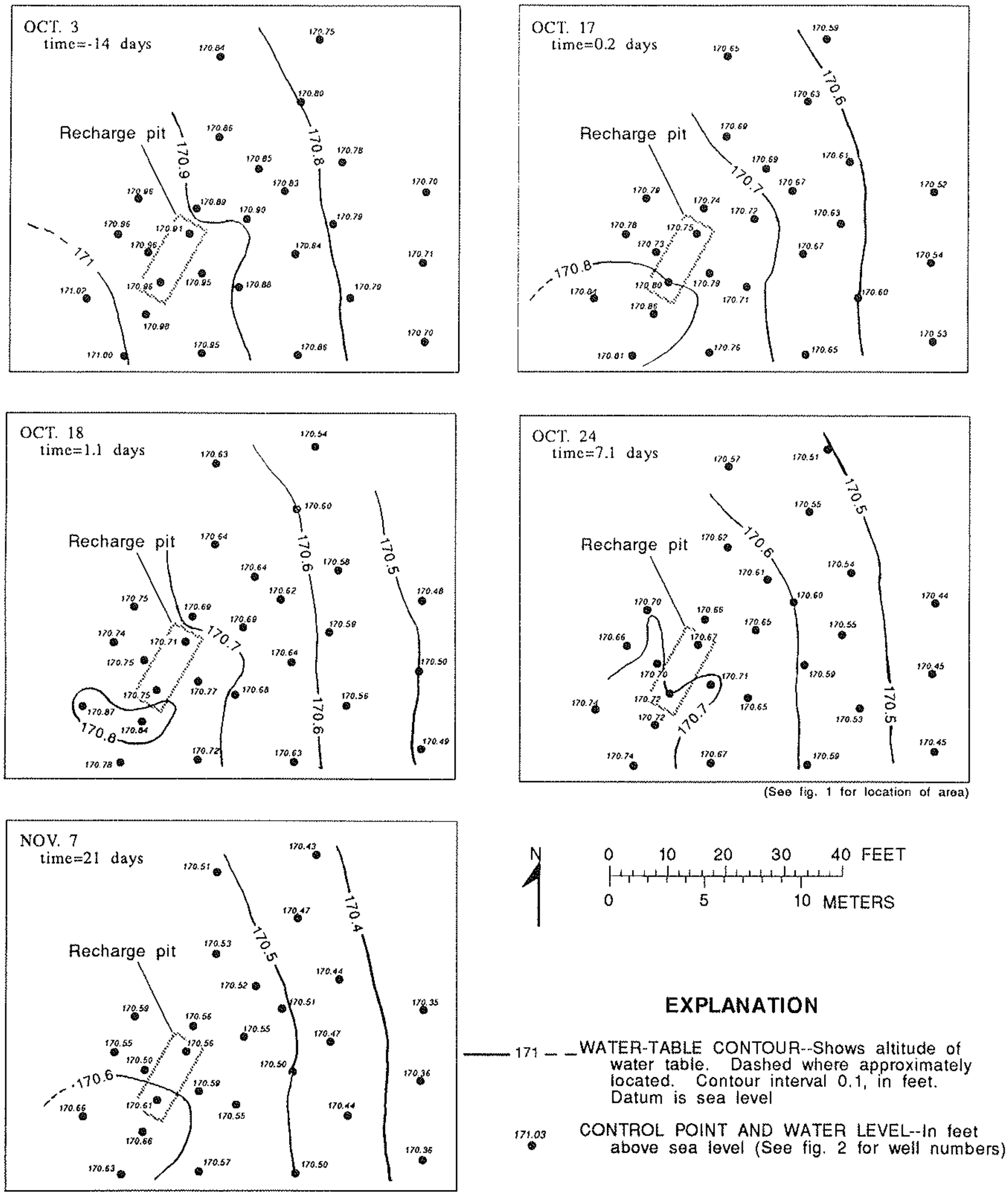


Figure 25. Water-table configuration in the shallow aquifer system near the recharge pit during the fall experiment, 1991.

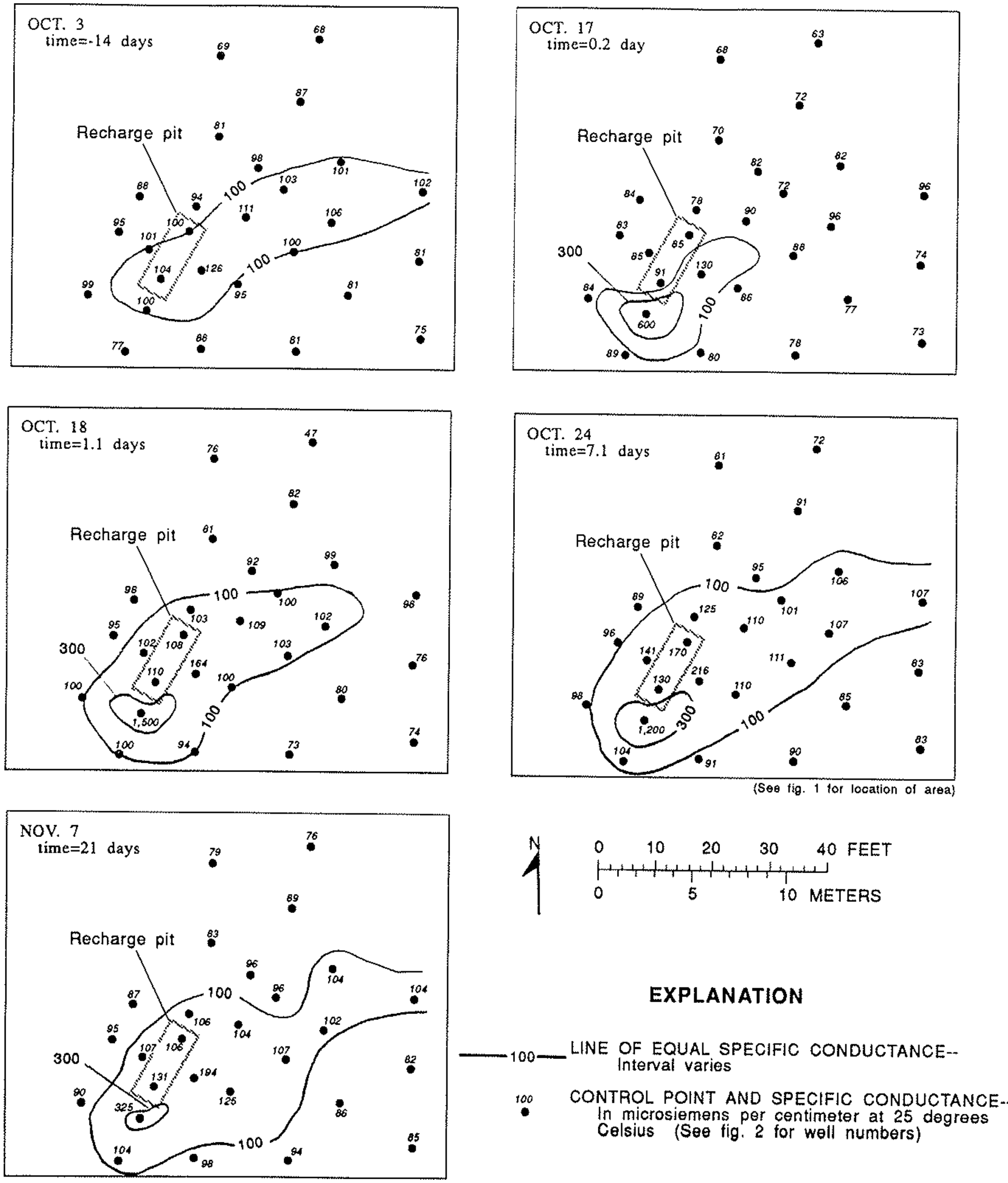


Figure 26. Lines of equal specific conductance of ground water near the recharge pit during the fall experiment, 1991.

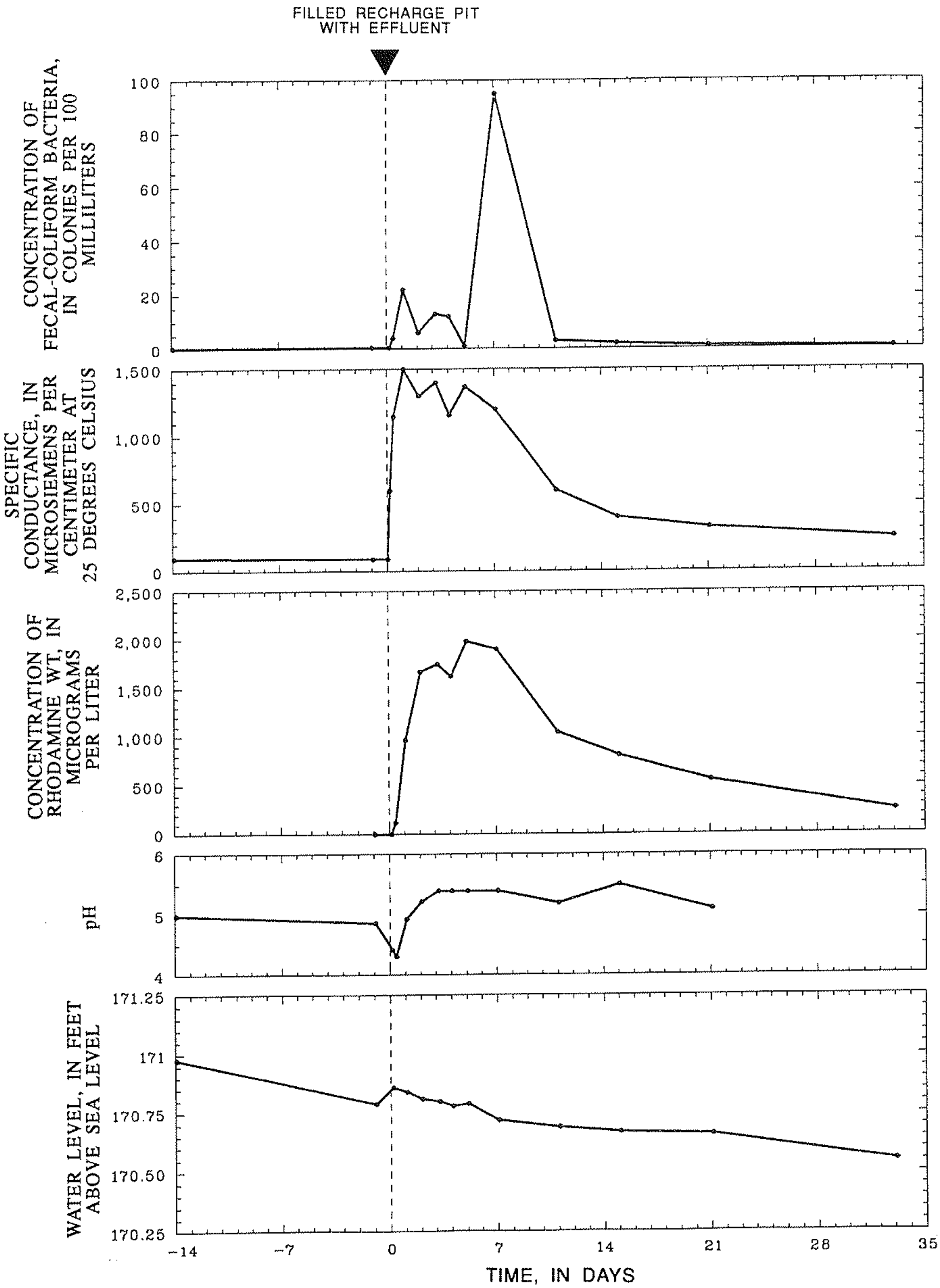


Figure 27. Fecal-coliform-bacteria concentrations, specific-conductance values, rhodamine-WT concentrations, pH, and water levels in observation well 103 during the fall experiment, 1991.

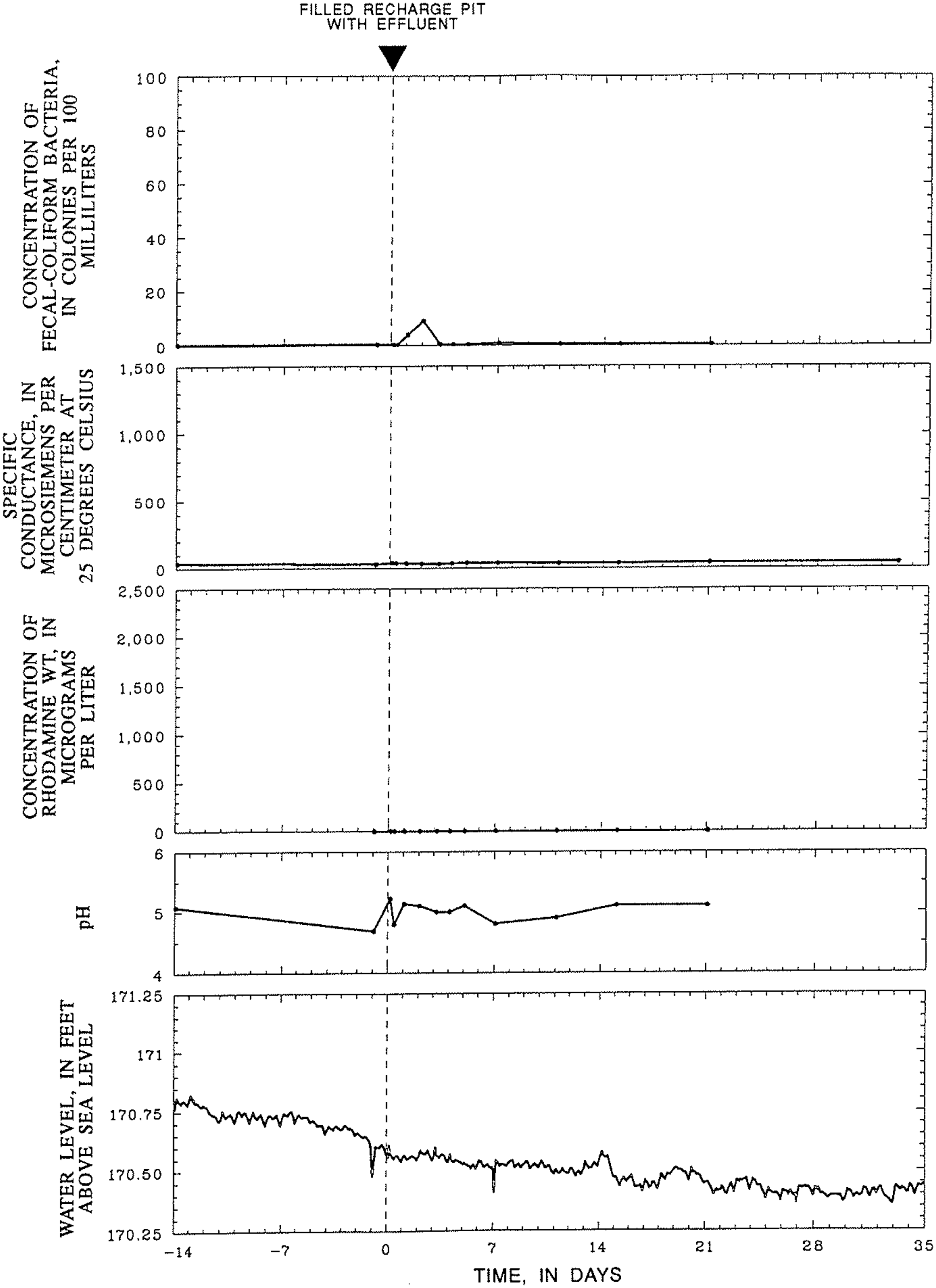


Figure 28. Fecal-coliform-bacteria concentrations, specific-conductance values, rhodamine-WT concentrations, pH, and water levels in observation well 313 during the fall experiment, 1991.

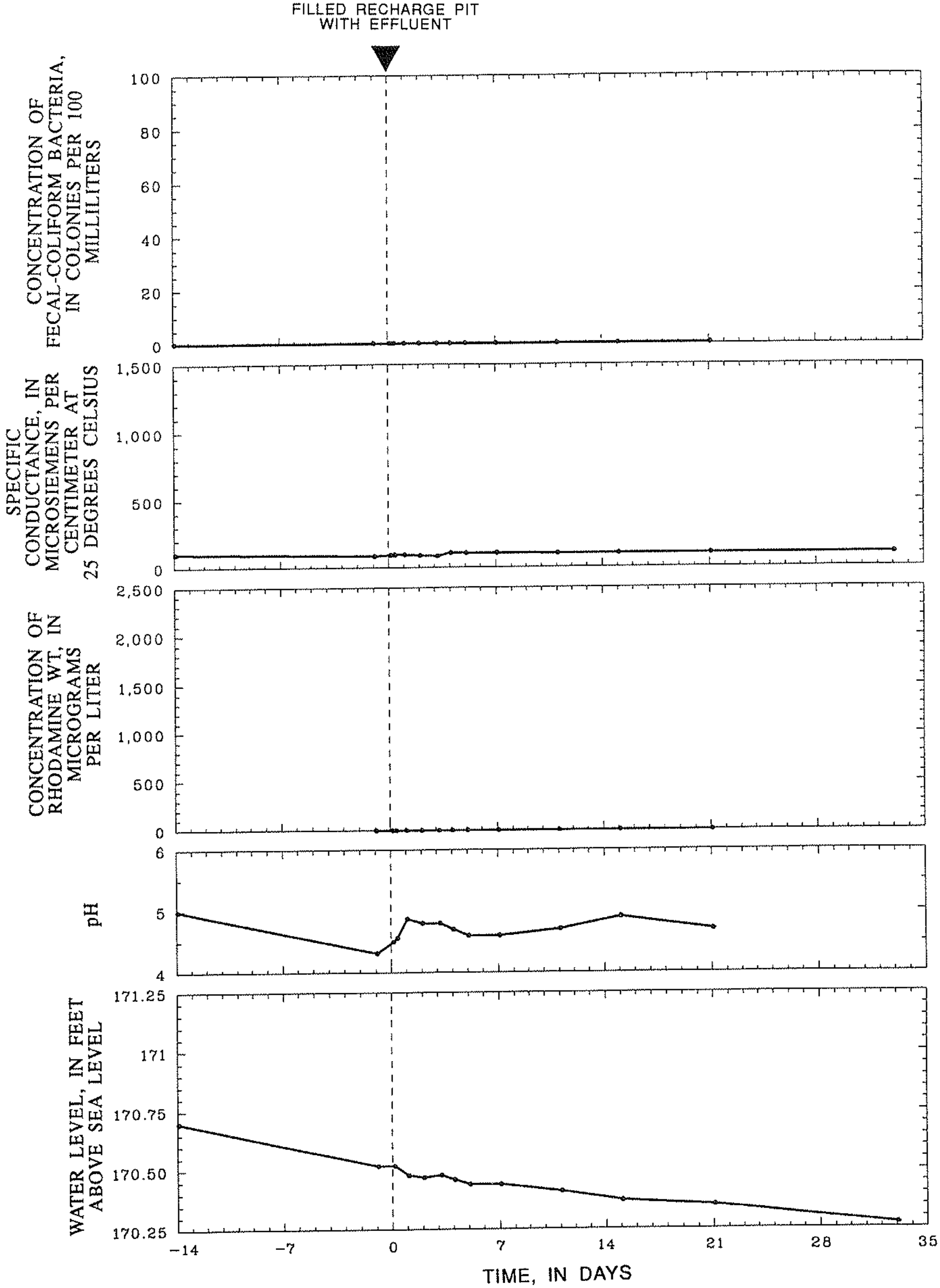


Figure 29. Fecal-coliform-bacteria concentrations, specific-conductance values, rhodamine-WT concentrations, pH, and water levels in observation well 128 during the fall experiment, 1991.

Table 8. Net movement of chloride and fecal-coliform bacteria from the recharge pit into the shallow part of the saturated zone during the fall experiment, 1991, Washington Parish, Louisiana

[Initial volume of effluent, 151 cubic feet; initial specific conductance, 2,300 microsiemens per centimeter at 25 degrees Celsius; initial chloride concentration, 690 milligrams per liter; initial fecal-coliform-bacteria concentration, 700,000 colonies per 100 milliliters]

Date	Elapsed time, in days	Cumulative discharge, in cubic feet	Initial effluent discharged, in percent	Cumulative chloride discharge from pit, in grams	Net chloride in shallow saturated zone, in grams	Discharged chloride detected in shallow saturated zone, in percent[1]
10-17	0.2	8	5	160	27	17
10-17	.4	20	14	400	131	33
10-18	1.1	49	33	950	570	59
10-19	2.1	83	55	1,600	550	34
10-20	3.2	110	73	2,100	670	31
10-21	4.1	126	83	2,400	450	19
10-22	5.1	139	92	2,700	480	18
10-24	7.1	151	100	2,900	490	17
10-28	11.1	151	100	2,900	340	12
11- 1	15.1	151	100	2,900	300	10
11- 7	21.1	151	100	2,900	300	10
					Average percent:	24

		Net fecal-coliform-bacteria colonies				
Date	Elapsed time, in days	Bacteria in control tank, in colonies per 100 milliliters	Bacteria discharge from recharge pit, in millions of colonies per 100 milliliters	Bacteria detected in shallow saturated zone, in millions of colonies per 100 milliliters	Discharged bacteria detected in shallow saturated zone, in percent	Bacteria percent divided by chloride percent
10-17	0.2	680,000	1,600	0.12	0.008	0.04
10-17	.4	650,000	3,700	.02	.001	.00
10-18	1.1	570,000	7,900	.30	.004	.01
10-19	2.1	470,000	11,000	.33	.003	.01
10-20	3.2	380,000	12,000	.21	.002	.01
10-21	4.1	320,000	11,000	.11	.001	.01
10-22	5.1	260,000	10,000	.02	.000	.00
10-24	7.1	180,000	7,600	.75	.010	.06
10-28	11.1	83,000	3,500	.05	.001	.01
11- 1	15.1	38,000	1,600	.12	.007	.07
11- 7	21.1	12,000	508	.04	.008	.08
				Average percent:	0.004	

[1]The fecal-coliform-bacteria response is 6,000 times less than the chloride response, as derived by dividing the average percent of fecal-coliform bacteria discharged in the shallow saturated zone by the average percentage of chloride discharged in the shallow part of the saturated zone.

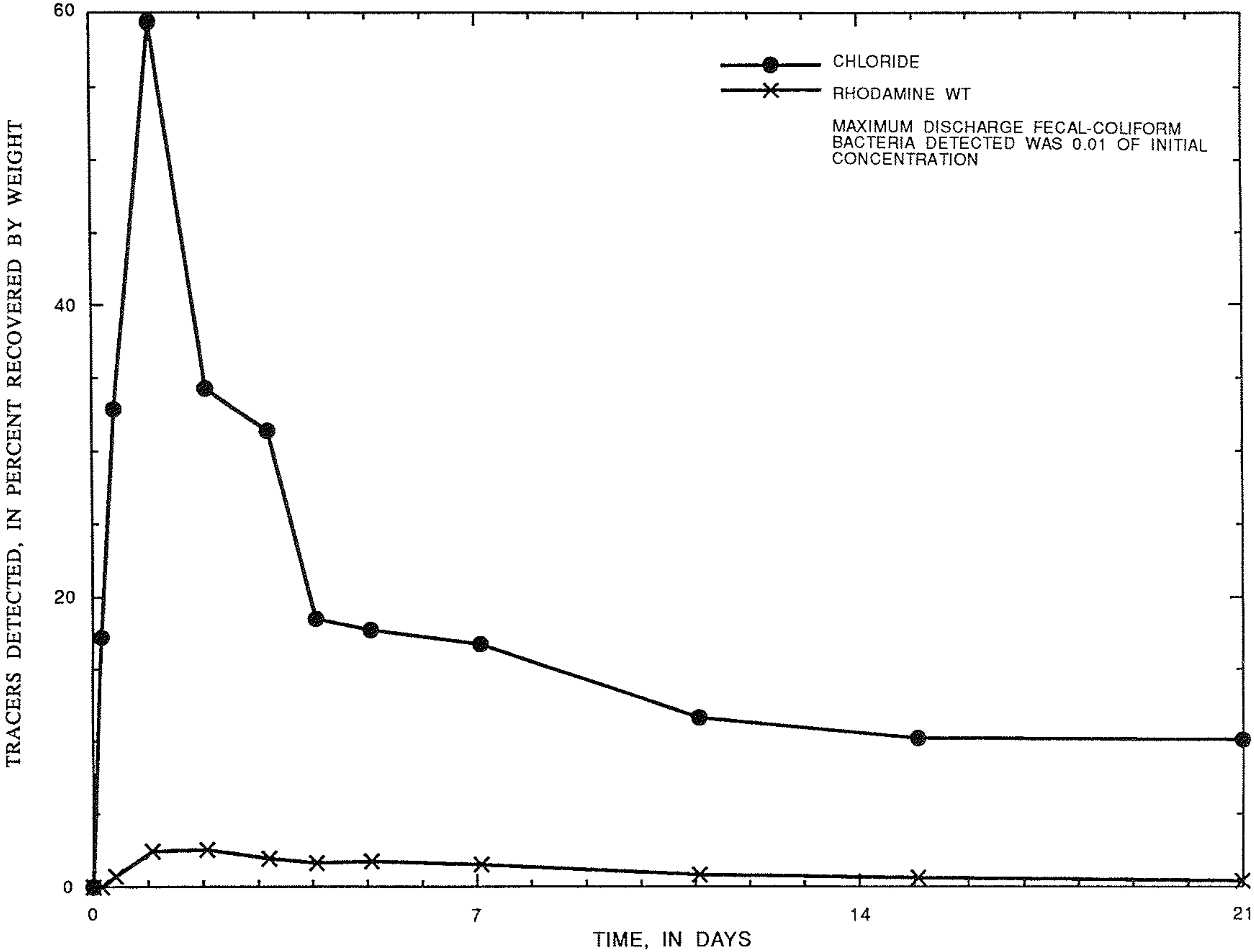


Figure 30. Percentage of discharged tracers detected in the shallow part of the saturated zone during the fall experiment, 1991.

SUMMARY AND CONCLUSIONS

In 1991, two experiments were conducted to determine the rate and direction of movement, and fate of viable FC (fecal coliform) bacteria in a shallow aquifer system typical of southeastern Louisiana. Dairy-farm pastureland was selected for the experiments as dairy cattle are the primary source of FC bacteria in this area. A ground-water recharge pit was constructed and shallow observation wells were installed around the pit. The pit was filled with an effluent containing high concentrations of FC bacteria and chloride and rhodamine-WT tracers during the spring and fall experiments. Two 30-gallon control tanks were placed next to the recharge pit, to determine fecal-coliform half-lives and assess the potential effects of chloride and rhodamine-WT tracers on bacterial viability. The movement of effluent through the shallow aquifer system was monitored by collecting water samples from the observation wells, Bonner Creek, and remote wells, and samples of field runoff. The spring experiment was conducted during a maximum flow rate through the system, whereas the fall experiment was conducted during a minimum flow rate.

During the spring experiment, the initial FC-bacteria concentration in the effluent in the pit was 12,000,000 cols/100 mL , and decreased in a control tank to less than 200 cols/100 mL in 34 days. The combined effects of dilution, sorption, and filtration greatly attenuated FC-bacteria concentrations in the shallow aquifer system. The maximum FC-bacteria concentration measured in a well, 2,100 cols/100 mL, was only 0.04 percent of the control-tank concentration of 5,900,000 cols/100 mL at the same time. Concentrations of FC bacteria greater than the State's standard, 200 cols/100 mL, for primary contact were not detected beyond 40 feet from the pit during the spring experiment, although FC bacteria in concentrations greater than 50 cols/100 mL did migrate more than 50 feet from the pit.

During the fall experiment, the initial FC-bacteria concentration in the effluent in the pit was 700,000 cols/100 mL, and the FC-bacteria concentration in a control tank decreased to less than 200 cols/100 mL in 42 days. A large difference between responses of rhodamine WT and FC bacteria indicated that filtration attenuated FC-bacteria concentrations more than sorption. Concentrations of FC bacteria greater than the State's standard for primary contact were not detected in the shallow aquifer system during the fall experiment. The maximum FC-bacteria concentration detected in a well was 95 cols/100 mL , 7 days after filling the pit with effluent; this concentration was 0.05 percent of the control-tank FC-bacteria concentration of 180,000 cols/100 mL at that time.

A greater volume of water in the shallow aquifer system was contaminated by effluent during the spring experiment than during the fall experiment. Specific conductance during the fall experiment indicated slower lateral dispersion of the effluent than during the spring experiment. Also, chloride mass-balance estimates indicated that effluent movement through the shallow part of the saturated zone was slower than during the spring experiment. The discharged chloride detected in the shallow part of the saturated zone in the fall experiment averaged 24 percent of the cumulative chloride discharged from the pit. This response was similar to the chloride movement in the spring experiment. The detected FC bacteria in the shallow part of the saturated zone averaged 0.004 percent of those discharged, about a hundredth of the FC bacteria movement during the spring experiment.

The effect of drainage from a recharge pit on ground-water quality at a given site decreases with increasing distance of the pit above the water table. The unsaturated zone allows greater filtration and adsorption from FC bacteria than the saturated zone because effluent in the unsaturated zone is dispersed over a larger volume of aquifer and is exposed to more surface area. The rapid decrease in concentrations of FC bacteria, compared to relatively slow ground-water movement, substantially limits the extent of contamination of shallow aquifers.

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