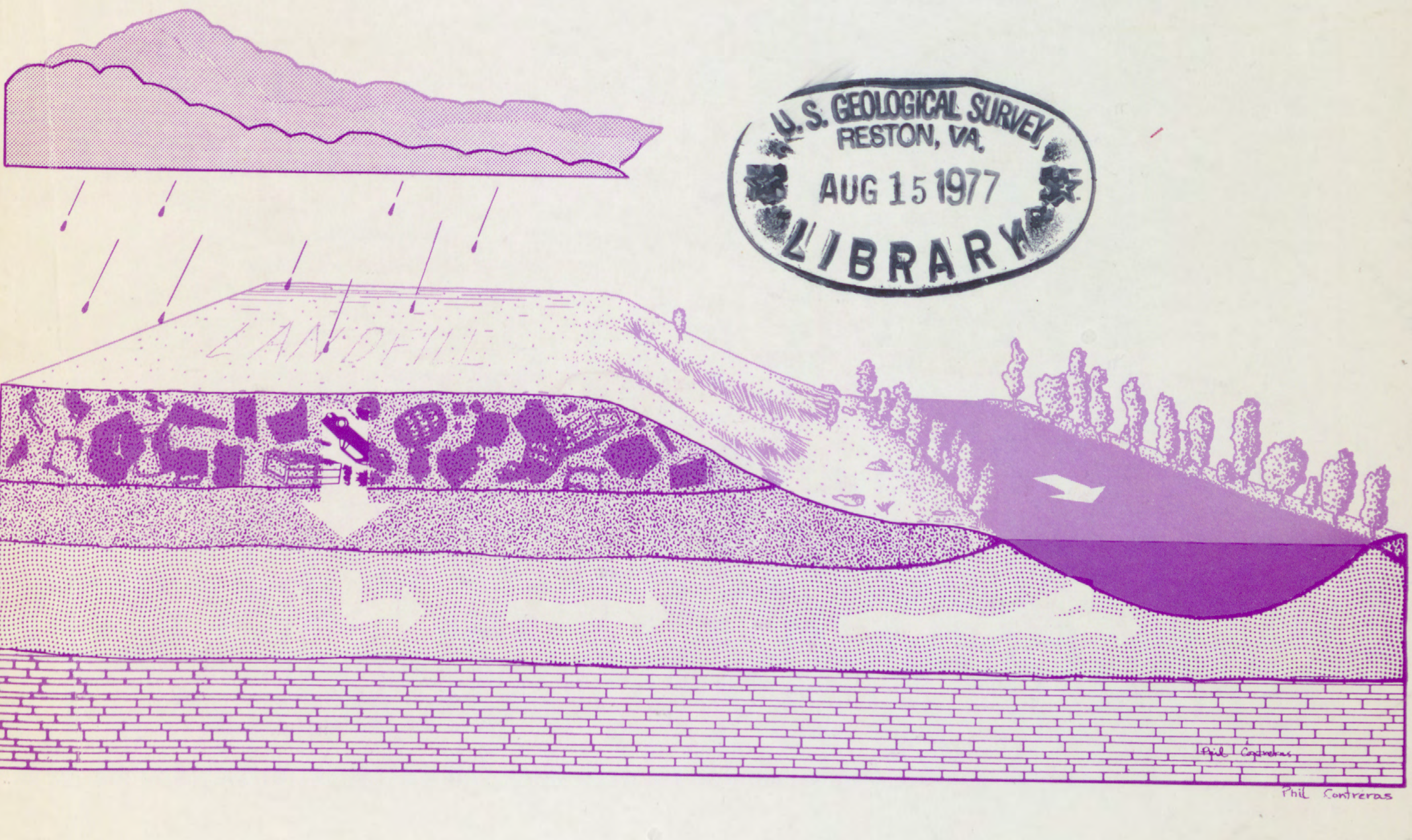
NATURE AND EXTENT OF GROUND-WATER QUALITY CHANGES RESULTING FROM SOLID-WASTE DISPOSAL, MARION COUNTY, INDIANA

U.S. GEOLOGICAL SURVEY WATER-RESOURCES INVESTIGATIONS 77-40

Prepared in cooperation with the Department of Public Works, Indianapolis, Indiana



Phil Contreras

BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No.
4. Title and Subtitle NATURE AND EXTENT OF GROUND-WATER-QUALITY CHANGES RESULTING FROM SOLID-WASTE DISPOSAL, MARION COUNTY, INDIANA			5. Report Date June 1977 6.
7. Author(s) Robert A. Pettijohn			8. Performing Organization Rept. No. USGS/WRI 77-40
9. Performing Organization Name and Address U.S. Geological Survey, Water Resources Division 1819 North Meridian Street Indianapolis, Indiana 46202			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address U.S. Geological Survey, Water Resources Division 1819 North Meridian Street Indianapolis, Indiana 46202			13. Type of Report & Period Covered Final (1972-75) 14.

15. Supplementary Notes

Prepared in cooperation with the Department of Public Works, Indianapolis, Indiana

16. Abstracts Studies of seven landfills in the Indianapolis area indicate that in five of the landfills movement of ground water is from the deep aquifers into the uppermost aquifer. In the other two landfills, movement of ground water is from the shallow aquifers to the deeper aquifers, so that leachate is transported into the deeper aquifers. In all the landfills, the predominant direction of ground-water movement is lateral. Placing solid waste into the landfills has occasionally altered the local, but not the regional, flow patterns.

Ground-water mounding at shallow depths beneath two of the landfills has caused flow toward the edges of the two fills. Leachate at these fills is moving downward and outward and has affected water quality at shallow depths.

Pumping near two other landfills has reversed the direction of regional ground-water flow, allowing leachate to move toward the pumping wells.

Leachate at the three remaining landfills is moving downgradient and is discharging into single streams adjacent to each landfill.

17. Key Words and Document Analysis. 17a. Descriptors

*Chemical analysis, *Groundwater movement, *Landfills, *Leachate, *Observation wells, *Water quality, Aquifers, Discharge, Dispersion, Dissolved solids, Hydraulic conductivity, Hydraulic gradient, Impaired water quality, Indiana, Infiltration, Metals, Organic wastes, Pumping, Self purification, Solid waste, Water levels.

17b. Identifiers/Open-Ended Terms

Marion County, Indianapolis, Leachate plume

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
No restriction on distribution	UNCLASSIFIED	129
	20. Security Class (This Page) UNCLASSIFIED	22. Price

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June 1977

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

The following factors may be used to convert the English units used in this report to the International System of Units (SI):

Multiply English Unit	By	To obtain SI unit
	Length	
feet (ft)	0.3048	meters (m)
inches (in)	2.540	centimeters (cm)
inches (in)	25.40	millimeters (mm)
miles (mi)	1.609	kilometers (km)
	Area	
acres	0.4047	hectares (ha)
	Volume	
cubic yards (yd^3)	0.7646	cubic meters (m^3)
gallons (gal)	3.785×10^{-3}	cubic meters (m^3)
	Volume and length per unit of time	
gallons per day per square foot [(gal/d)ft^2]	0.041	meters per day (m/d)
gallons per day per square mile [(gal/d)/mi^2]	1.461	liters per day per square kilometer [(L/d)/km^2]
million gallons per day (Mgal/d)	3.785×10^3	cubic meters per day (m^3/d)
feet per day (ft/d)	.3048	meters per day (m/d)
feet per year (ft/yr)	.3048	meters per year (m/yr)
	Weight	
pounds (lb)	4.536×10^2	grams (g)
tons, short (2,000 lb)	9.072×10^2	kilograms (kg)
tons, short (2,000 lb)	.9072	tons (t)

NATURE AND EXTENT OF GROUND-WATER QUALITY CHANGES RESULTING FROM SOLID-WASTE DISPOSAL, MARION COUNTY, INDIANA

By Robert A. Pettijohn

ABSTRACT

The hydrogeologic environment and the water quality of aquifers underlying seven solid-waste landfills in the Indianapolis area were studied to determine the nature and the extent of ground-water contamination by leachate from the landfills. In five of the landfill areas (U.S. Highway 52 and Senour Road, 2561 Kentucky Avenue, 800 West Raymond Street, Banta Road and Tibbs Avenue, and 4300 West Southport Road), the movement of ground water is from the deep aquifers into the uppermost aquifer, which precludes leachate contamination in the lower aquifers. In two of the landfill areas (West 96th Street and Zionsville Road and 2700 South Emerson Avenue), the movement of ground water is from the shallow aquifers to the deeper aquifers, so that leachate is transported to the deeper aquifers. In all the landfills, the predominant direction of ground-water movement is lateral.

Placing refuse in the landfills has occasionally altered the local, but not the regional, flow patterns. However, local ground-water pumping has altered regional flow patterns beneath two landfills, one at 2561 Kentucky Avenue and the other at 800 West Raymond Street.

Ground-water flow beneath the landfill at U.S. Highway 52 and Senour Road is upward and southeast. Leachate has been found only in water of the shallow aquifer beneath and at the southeast corner of the refuse pile.

Ground-water mounding at shallow depths beneath the landfills at West 96th Street and Zionsville Road and at 2700 South Emerson Avenue has caused flow toward the perimeter of these two fills. Leachate at these two landfills is moving downward and outward to the edge of the fill area and has affected the water quality at shallow depths along the landfill perimeter.

Pumping near two landfills, one at 2561 Kentucky Avenue and the other at 800 West Raymond Street, has reversed the direction of regional ground-water flow. Consequently, ground water containing leachate is moving toward the pumping wells.

Ground-water flow beneath two other landfills, one near the intersection of Banta Road and Tibbs Avenue and the other near 4300 West Southport Road, is toward the White River. Ground water that is receiving leachate from the refuse is being discharged into the White River.

INTRODUCTION

Contamination[1] of ground water by leachate from solid waste (refuse) in landfills is a potential problem of multicounty scope in the Indianapolis area. Contamination involves not only health and safety of the inhabitants but also development and management of the water resources. Contamination of ground water can cause increased costs of water treatment as well as loss of water resources. Furthermore, no landfill program can be effective unless the relationships between ground-water contamination and land-use requirements have been resolved.

Establishing effective policies to control ground-water contamination in areas of concentrated ground-water use requires knowledge of the contaminants and their behavior in the environment. Establishing hydrogeologic criteria to determine whether natural safeguards are adequate to protect ground-water reservoirs against contamination, and engineering specifications to provide protection where natural safeguards are lacking, can help define these policies.

Evaluating the potential for ground-water contamination from refuse-disposal operations involves consideration of the potential for (1) production of leachates by rainfall infiltration, saturation of the refuse by ground water or surface-water flooding, and (2) access of the leachates to the aquifers. Maximum protection from contamination can be expected in areas where aquifers are separated from the refuse by earth material of low permeability and the water table is well below the refuse. In the Indianapolis area, however, abandoned gravel pits and quarries have commonly been used as sites for open dumps or landfills, either because of convenience or economic benefits.

Purpose and Scope of Investigation

This report is the result of a cooperative study by the Department of Public Works of Indianapolis and the U.S. Geological Survey from July 1, 1972, to July 1, 1975. The general objective of the study was to determine the nature and the extent of ground-water contamination by solid-waste disposal in the vicinity of the seven landfill sites in Marion County. More specifically, the objective was to determine direction and rate of movement, and dispersion of leachate in the ground-water system.

Because ground-water and leachate movement beneath the sites is slow and the period of data collection was brief, this report provides only a general description of contamination and ground-water flow at each of the landfill sites.

[1]In this report, a change in the quality of a receiving water is referred to as contamination.

Water-quality limits used in this report are those recommended in section II, Public Water Supplies, of the report, "Water Quality Criteria, 1972," by the U.S. Environmental Protection Agency (1973, p. 48-104). This reference includes a discussion of the relation of various constituents or properties to water quality. Color, some constituents and their symbols, and the recommended limit of their concentrations are listed in table 1. Constituents or properties whose concentrations at landfills exceed the limits are indicated in the respective tables for each landfill.

Previous Investigations

No previous studies relating the effects of refuse dumps or landfills to ground-water quality in Marion County have been made, but several studies pertaining to the water resources of the county have been made (Cable and others, 1971; Maclay and Heisel, 1972; Meyer, Reussow, and Gillies, 1975; Nyman and Pettijohn, 1970; Roberts and others, 1955). Maps and reports from geological studies are also available (Harrison, 1973; Malott, 1922; Wier and Gray, 1961).

The principal studies of contamination or potential contamination of ground water by leachates from refuse dumps or landfills have been made in California, Illinois, Pennsylvania, South Dakota, and Florida. These studies show that the leachates are highly mineralized and that the concentration of many of the chemical constituents in the leachates is several times that of the concentration in receiving water. Several reports, including those by Apgar and Langmuir (1971) and Hughes and others (1971), discuss the effect of the soil regime on the leachate and the attenuation mechanisms of dilution, adsorption, and microbial degradation. Most of the reports suggest criteria for selection of landfill sites. A recent report by Bleuer (1970) gives criteria for selecting such sites in Indiana.

Methods of Investigation

Test holes were drilled both upgradient and downgradient from each landfill and through the refuse. On the basis of the lithology, monitoring wells were constructed in a major aquifer at each site and (or) strategically in the refuse or till. The number of wells at each test site was determined primarily by the number and the thickness of unconsolidated aquifers underlying the site. Usually, separate wells were constructed at the top and the bottom of the thickest aquifers at each site. Initially, the number of wells at each landfill ranged from 11 to 36. Additional wells were constructed after sufficient water-quality data had been collected to indicate that more wells were needed to define the ground-water gradient and the movement of leachate. The wells were developed by pumping, and their altitudes were determined in reference to mean sea level datum.

Table 1.--Limits recommended by EPA (U.S. Environmental Protection Agency) for quality of drinking water (U.S. Environmental Protection Agency, 1973, p. 48-104)

Constituent or property	Symbol	Recommended limits (in milligrams per liter, except color)
Color	------	1/ 75
Chloride	Cl	250
Sulfate	SO_4	250
Iron	Fe	.3
Manganese	Mn	.05
Ammonia - nitrogen	NH_3 - N	2/ .5
Nitrite	NO_2	2/ 1.0
Nitrate	NO_3	2/ 10.0
Phenols	------	.001
Methylene blue active substance	MBAS	.5
Fluoride	F	(3/)
Arsenic	As	.1
Mercury	Hg	.002
Barium	Ba	1.0
Cadmium	Cd	.010
Chromium	Cr	.05
Copper	Cu	1
Lead	Pb	.05
Zinc	Zn	5

1/ Color units were determined by comparing color of water to that of colored glass disks that have been calibrated to correspond to the platinum-cobalt scale of Hazen (1892).

2/ Expressed as nitrogen.

3/ Maximum-concentration limit varies with temperature. For annual average of maximum daily air temperatures in the range 50°-54° Fahrenheit, the recommended maximum limit is 2.4 mg/L; for the range 80°-91° Fahrenheit, the recommended maximum limit is 1.4 mg/L. Degrees Fahrenheit can be converted to degrees Celsius as follows: 5/9 (°F-32) = Degrees Celsius.

Water samples from the observation wells upgradient from the landfill were analyzed to determine the natural (or background) quality of the ground water, and water samples from wells downgradient from the landfill were analyzed to determine the water quality as affected by leachate from the solid waste. Wells--some in the refuse and some below the refuse--were used as sampling points for collecting leachate from the refuse and for determining the height and the lateral extent of a ground-water mound at the landfill and the downward movement of the leachate. The quality of surface-water bodies adjacent to the landfill was also determined where relevant.

The hydraulic gradient in the area of the landfill was determined from water-level measurements. Vertical direction of flow was determined from the water level in wells at different depths at the same site.

Measurement of water levels and sampling for field analysis were made approximately monthly at all wells. Water samples for laboratory analysis were collected about every 3 months. These samples were analyzed in the U.S. Geological Survey laboratories using procedures described by Brown, Skougstad, and Fishman (1970) and Goerlitz and Brown (1972).

In this report the term "shallow well" refers to well depths less than 50 ft and the term "deep well," to well depths greater than 50 ft. Also, estimates of leachate movement based on ground-water flow velocities assume that leachate moves at the same rate as ground water.

Acknowledgments

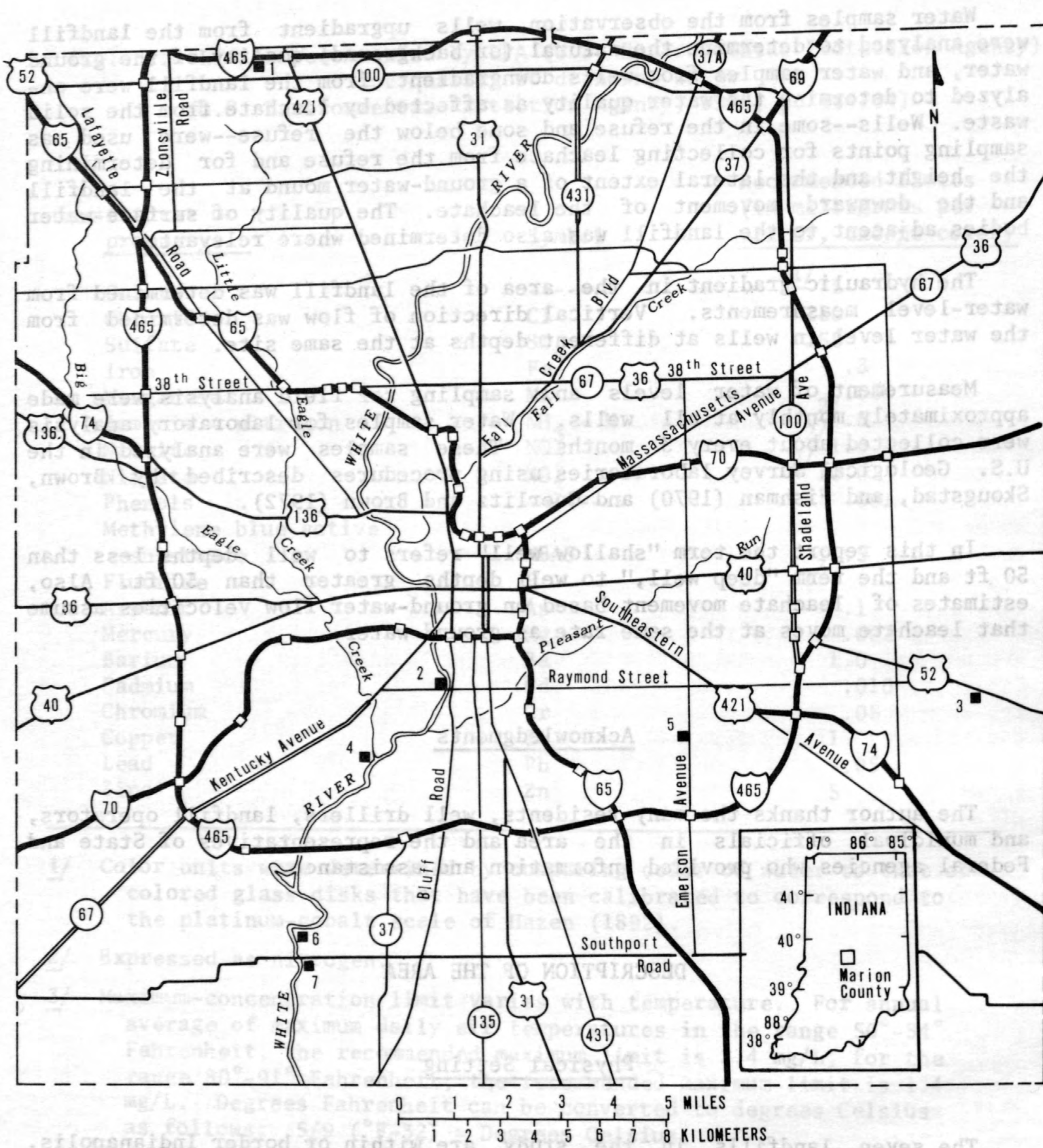
The author thanks the many residents, well drillers, landfill operators, and municipal officials in the area and the representatives of State and Federal agencies who provided information and assistance.

DESCRIPTION OF THE AREA

Physical Setting

The seven landfills in the study are within or border Indianapolis, which occupies about 75 percent of Marion County, the most densely populated county in Indiana. Six are in the southern half, and one is near the northwest corner (fig. 1) of the county. The area at each landfill is less than 1.0 mi^2. Each landfill is adjacent to a stream; thus, leachate can be conveyed to streams by surface runoff and ground-water discharge.

The White River bisects the county. The two largest tributaries, Eagle and Fall Creeks, join the White River within the county. Other large tributaries include Buck, Little Buck, Crooked, Mud, White Lick, and Williams Creeks; and Pleasant Run.



EXPLANATION

■ Landfill site

1. West 96th Street and Zionsville Road
2. 800 West Raymond Street
3. U.S. Highway 52 and Senour Road
4. 2561 Kentucky Avenue
5. 2700 South Emerson Avenue
6. Banta Road and Tibbs Avenue
7. 4300 West Southport Road

Figure 1.-- Study area and location of landfill sites.

One characteristic that is usually specified in selecting a landfill site is that base materials be of low permeability, such as fine silt and (or) clay till. This type of material allows partial renovation of leachate through various physical and chemical processes and minimizes the rate at which leachate is introduced into a water supply. Although most of Marion County is covered with fine-grained till, only two of the seven landfills are in this material. The other five are in stratified beds of sand and gravel.

Geology

As reported by Harrison (1963, p. 9, and pl. 1), bedrock in Marion County consists of limestone and shale of Late Ordovician age; limestone, dolomite, and shale of Silurian age; limestone and shale of Devonian age; and limestone, shale, and sandstone of Early Mississippian age. Regional dip of these rocks is southwest.

Unconsolidated deposits of Quaternary age cover the bedrock in Marion County and makes up the characteristic features of the present land surface. This material consists primarily of thick deposits of glacial and some alluvial sediments that were deposited mostly during Wisconsin Glaciation. It is predominantly glacial till but includes some stratified beds of clay, silt, sand, and gravel. The stratified beds are outwash deposits from glacial melt water. The sorting action of stream transport and deposition tends to segregate the outwash into separate layers according to grain size. The layers of outwash sand and gravel are the best aquifers. They occur primarily along White River, Fall Creek, and some of the smaller streams.

The valleys of White River and Fall Creek (fig. 2) are the most conspicuous of the glacial erosional features in the county. These valleys are deeply incised into the till plain and are very straight to moderately sinuous. Coarse, highly permeable sediments deposited in these incised valleys by melt water from glaciers make excellent aquifer material. The landfills at 2561 Kentucky Avenue, 800 West Raymond Street, Banta Road and Tibbs Avenue, and 4300 West Southport Road, overlie this type of material.

Climate

Climate plays an important role in leachate production and movement. Refuse decays slowly in areas of arid or semiarid climates. For example, in such areas print on paper buried for 20 years remains legible. Refuse decays much faster in humid areas such as Marion County because the soil usually contains water. When the water comes in contact with the refuse, bacterial and enzymatic decay are accelerated.

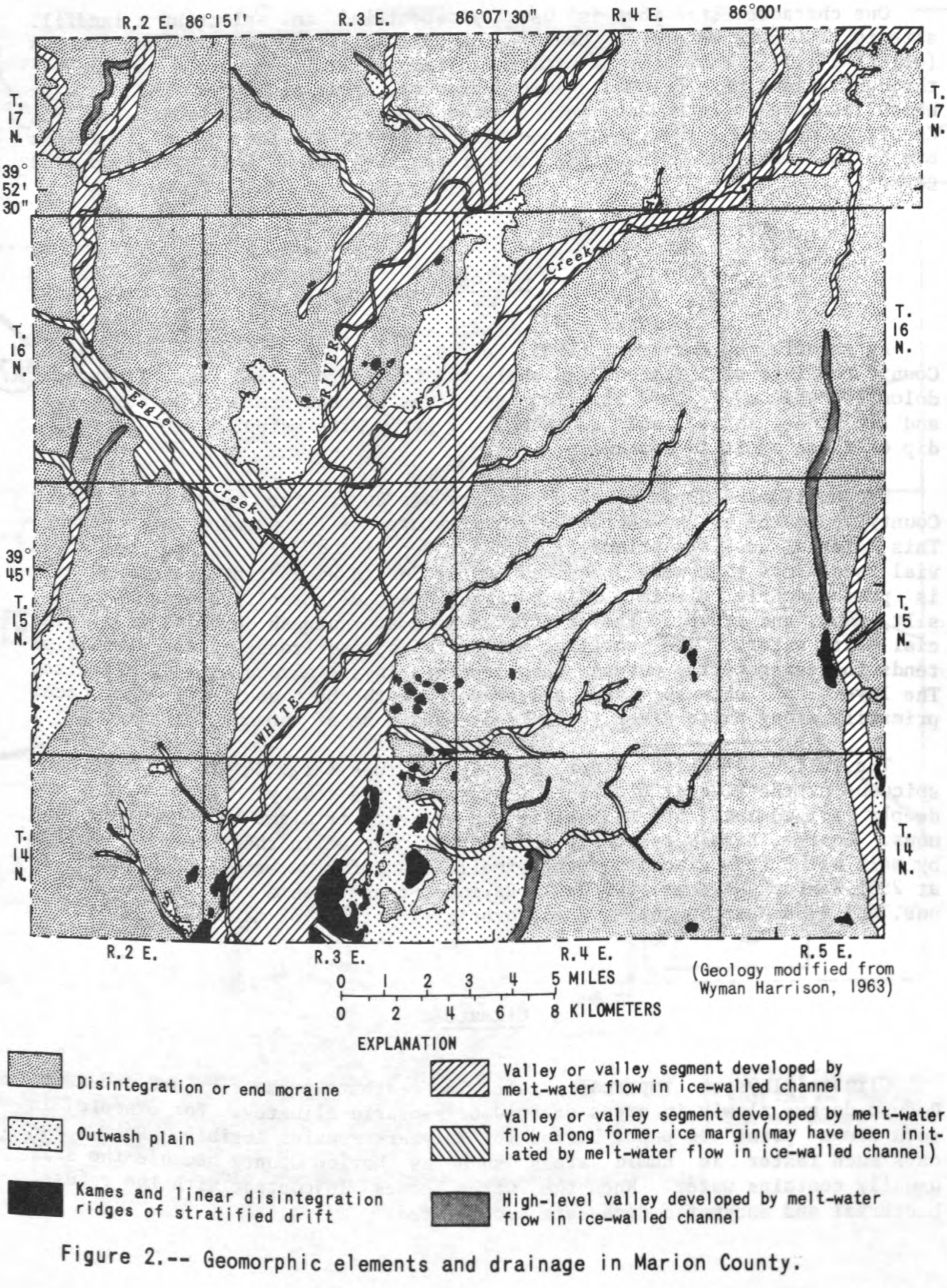


Figure 2.-- Geomorphic elements and drainage in Marion County.

Average annual precipitation in Marion County is 39.3 in; seasonal variations are small. Average temperature for July is 22.8°C (Celsius) (National Oceanic and Atmospheric Administration, 1974). The moderately warm and humid summer climate of the county provides optimum temperature for bacterial action. Eastward moving masses of cold polar air from the north and warm gulf air from the south frequently cause cyclonic storms across the county, which help remove gases generated within the refuse.

Population and Waste Production

Most waste is generated by people. Zanoni (1972) reported that the average amount of solid waste collected in the United States exceeds 5.3 lb per person per day, or 190 million short tons per year, and predicted that the waste collected per person per day will increase to 8 lb by 1980 and 12 lb by 1990.

The population of Marion County has increased from about 600 in 1822 to 792,299 in 1970 (U.S. Bureau of the Census, 1971). On the basis of the daily production of 5.3 lb of waste per resident, citizens of Marion County generated more than 2,000 tons of waste per day in 1970 or 5,300 yd^3 per day. The projected population for the county is 1 million by 1990. Assuming that each person will generate 12 lb of solid waste per day, the population of Marion County will generate 6,000 tons per day or 15,000 yd^3 per day by 1990.

Water Movement and Leachate Production

The various aquifers of Marion County are hydraulically connected. Thus, leachate migrates from the landfill along paths of ground-water flow. This migration continues until a point of discharge, such as a pumping water well, is reached.

Water used in Marion County in 1967 was 116 Mgal/d, of which 37 Mgal/d was estimated to be ground water. Water used in 1971 was estimated to be 126 Mgal/d of which 50 Mgal/d was estimated to be ground water (Meyer and others, 1975). These data indicate that the county depends on ground water for about 40 percent of its water supply.

Leachate is the liquid produced by water percolating through refuse in a landfill. The amount produced is directly related to (1) whether the refuse is within the zone of saturation (below the water table) or (2) the amount of percolation. In Marion County, about 30 percent of the average annual precipitation of 39.3 inches percolates through the soil (or refuse) and reaches the water table in the valleys of the White River and Fall Creek. Recharge rates to the aquifers in the till-plain area are generally much less than the annual precipitation. This recharge to the water table tends to be greatest during the time period between late fall and early spring.

LANDFILL AT U.S. HIGHWAY 52 AND SENOUR ROAD

Description and History of the Area

This landfill, just south of U.S. Highway 52 near the Hancock County line (fig. 1) in eastern Marion County, consists of 70 acres. The landfill is on the west side of the Grassy Creek flood plain, near the confluence of Grassy and Buck Creeks. The topography is moderately sloping, except for flat areas near the streams. The area is underlain by sand, gravel, and finer sediments deposited at the waning of the Wisconsin Glaciation. Layering according to particle size, indicated by well logs in table 9, is probably due to variation in the velocity of the melt water. After the retreat of the glacier, decreasing velocity allowed clay and silt to deposit over the sand and gravel to depths of 15 ft in the valleys.

During the 1950's, mining of sand and gravel on the flood plain created a pit about 50 ft deep. In the early 1960's the pit became a local dump ground. In the late 1960's, the 72-acre site was designated a landfill and began receiving domestic, commercial, and industrial refuse. The pit area was filled first by alternating layers of wastes and dirt. The same procedure was used for the rest of the landfill area. Much of the time, spreading of dirt was delayed for days while a specific area received wastes. Silty clay loam removed from the landfill area was used as the dirt or cover material. The height of fill is about 830 ft above mean sea level along the northeast side of the landfill at the edge of Grassy Creek. The graded landfill surface slopes toward the south. The top of the fill is about 35 ft above the water level in Grassy and Buck Creeks.

The landfill was about three-fourths full in 1975. When it becomes full, approximately 3.5 million cubic yards of compacted refuse will have been buried there. Although part of the landfill has been seeded with grass, vegetation is sparse. Exposed refuse and rilling is evident on the slopes.

Aquifers and Data-Collection Network

Thirty-six observation wells were constructed at 12 sites in and around the landfill to determine geologic framework, direction of water movement, background quality of the ground water, and quality of the leachate (fig. 3). The number of wells at each site ranged from one to six, depending on the number of aquifers penetrated. The well at site G is downgradient from a former settling pond that received liquid waste until February 1973. Wells at sites H and I were completed at three depths: in the refuse, at the bottom of the refuse, and in the first aquifer below the refuse.

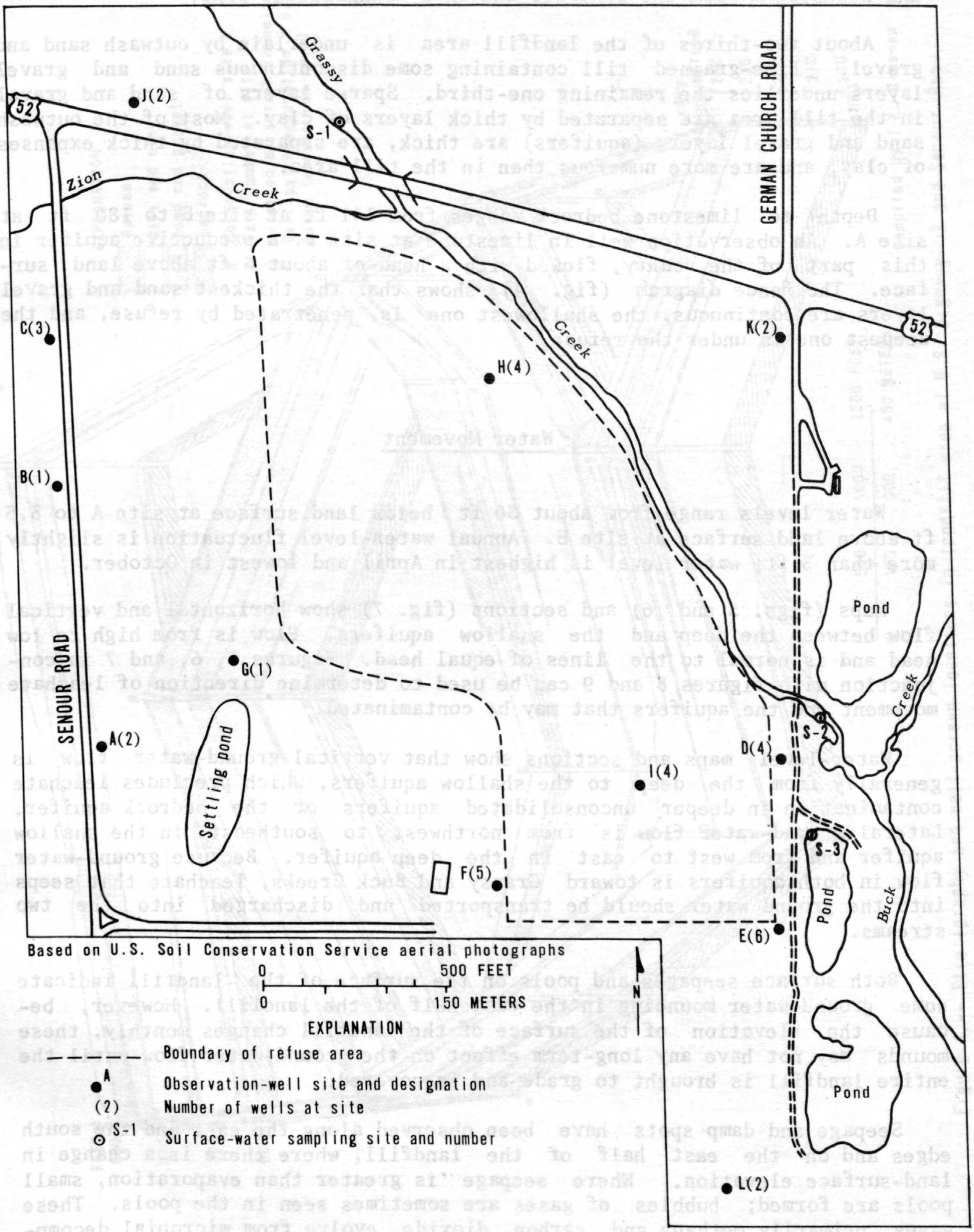


Figure 3.-- Location of well sites in landfill area at U.S. Highway 52 and Senour Road.

Surface-water sampling sites were established on Grassy Creek upstream and downstream from the landfill and on a downgradient pond.

About two-thirds of the landfill area is underlain by outwash sand and gravel. Fine-grained till containing some discontinuous sand and gravel layers underlies the remaining one-third. Sparse layers of sand and gravel in the till area are separated by thick layers of clay. Most of the outwash sand and gravel layers (aquifers) are thick, are separated by thick expanses of clay, and are more numerous than in the till area.

Depth to limestone bedrock ranges from 141 ft at site E to 180 ft at site A. An observation well in limestone at site E, a productive aquifer in this part of the county, flowed with a head of about 6 ft above land surface. The fence diagram (fig. 4) shows that the thickest sand and gravel layers are continuous, the shallowest one is penetrated by refuse, and the deepest one is under the refuse.

Water Movement

Water levels range from about 30 ft below land surface at site A to 3.5 ft above land surface at site E. Annual water-level fluctuation is slightly more than 3 ft; water level is highest in April and lowest in October.

Maps (figs. 5 and 6) and sections (fig. 7) show horizontal and vertical flow between the deep and the shallow aquifers. Flow is from high to low head and is normal to the lines of equal head. Figures 5, 6, and 7 in conjunction with figures 8 and 9 can be used to determine direction of leachate movement and the aquifers that may be contaminated.

Water-level maps and sections show that vertical ground-water flow is generally from the deep to the shallow aquifers, which precludes leachate contamination in deeper unconsolidated aquifers or the bedrock aquifer. Lateral ground-water flow is from northwest to southeast in the shallow aquifer and from west to east in the deep aquifer. Because ground-water flow in both aquifers is toward Grassy and Buck Creeks, leachate that seeps into the ground water should be transported and discharged into the two streams.

Both surface seepages and pools on the surface of the landfill indicate some ground-water mounding in the east half of the landfill. However, because the elevation of the surface of the landfill changes monthly, these mounds may not have any long-term effect on the ground-water flow until the entire landfill is brought to grade and is covered.

Seepage and damp spots have been observed along the east and the south edges and on the east half of the landfill, where there is a change in land-surface elevation. Where seepage is greater than evaporation, small pools are formed; bubbles of gases are sometimes seen in the pools. These gases, primarily methane and carbon dioxide, evolve from microbial decomposition of waste materials below the surface. Leachate on the surface causes unsightly, offensive, and odorous conditions.

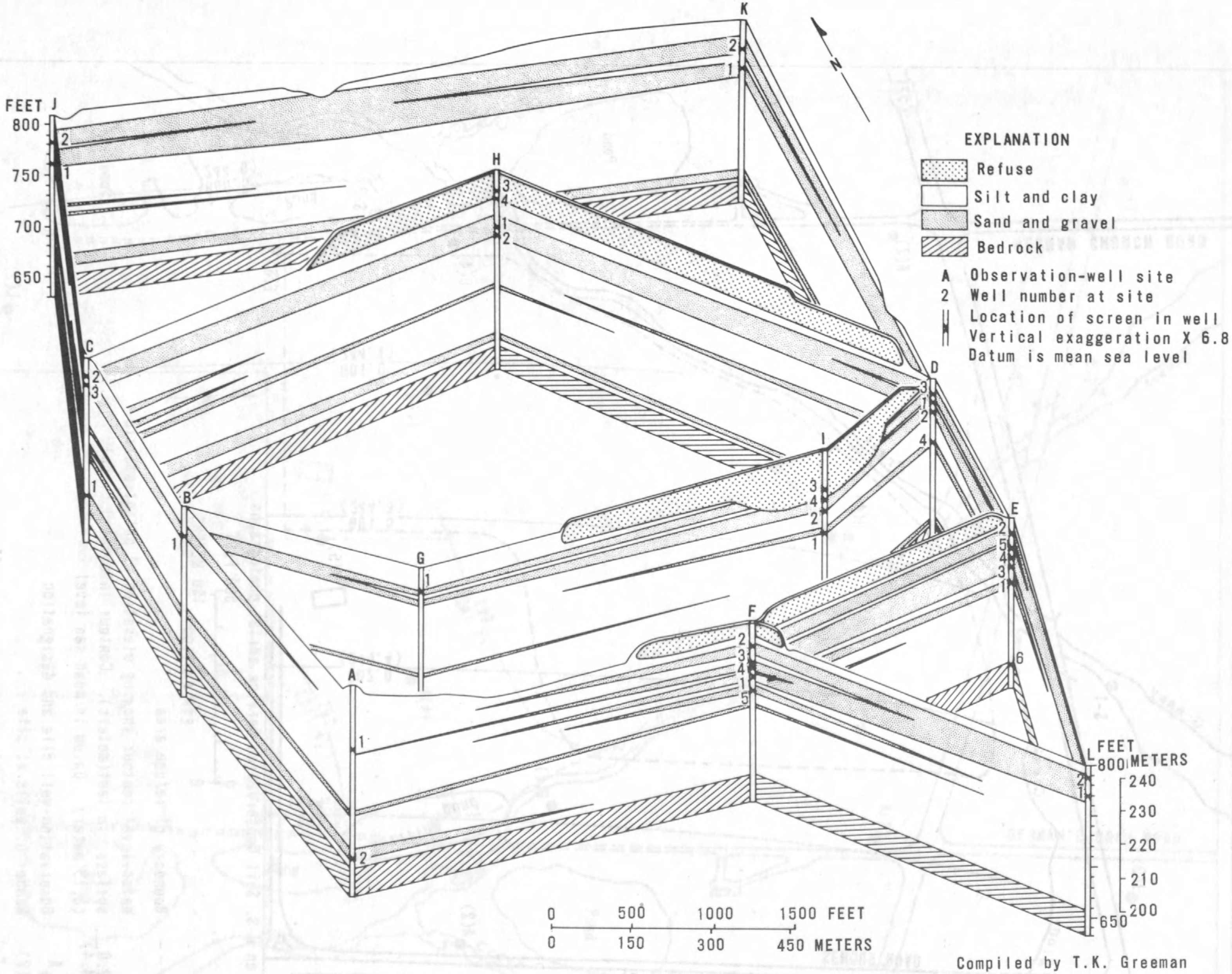


Figure 4.-- Stratigraphy and well-screen locations in landfill area at U.S. Highway 52 and Senour Road.

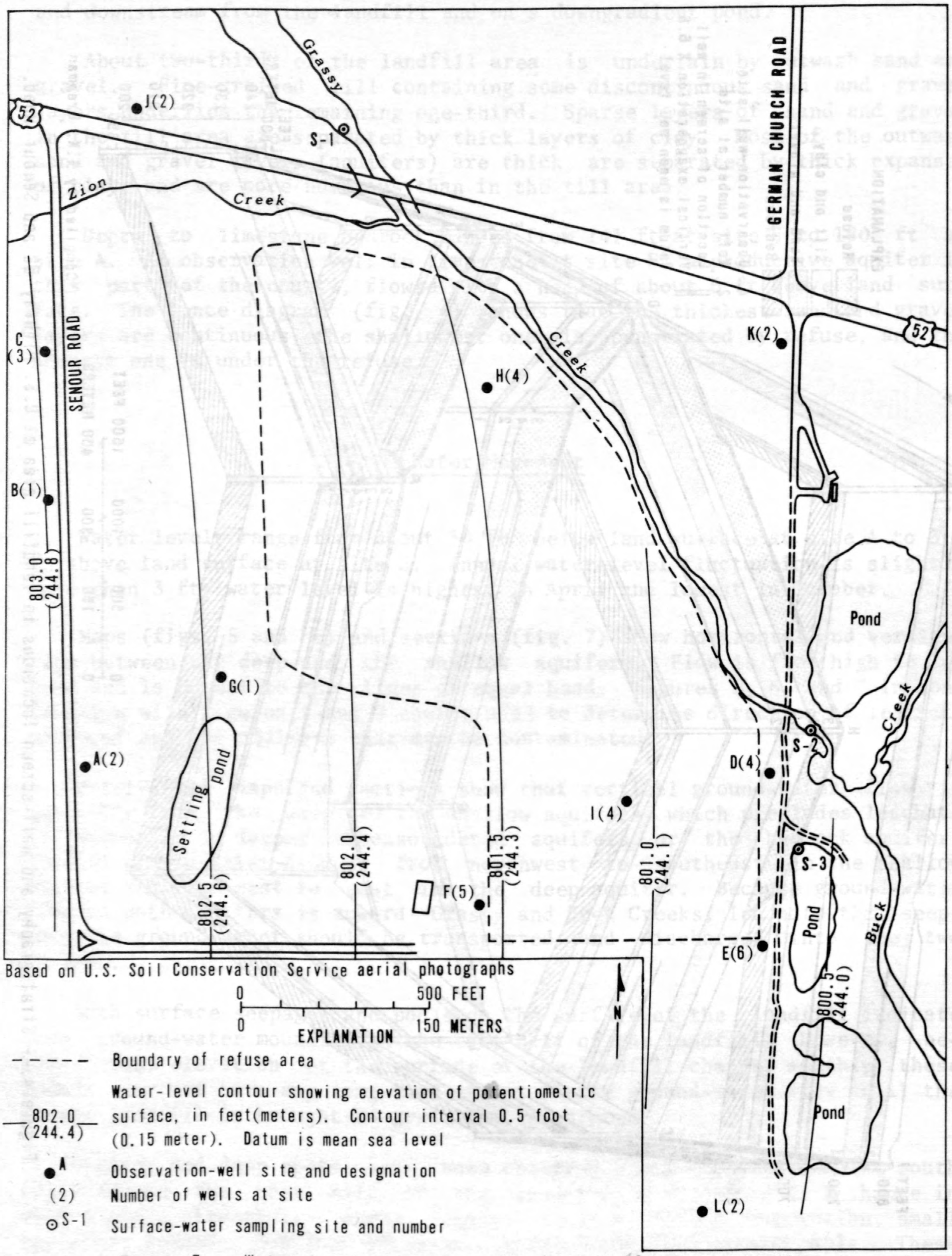


Figure 5.-- Water-level contours in the deep aquifer below landfill area at U.S. Highway 52 and Senour Road, October 1974.

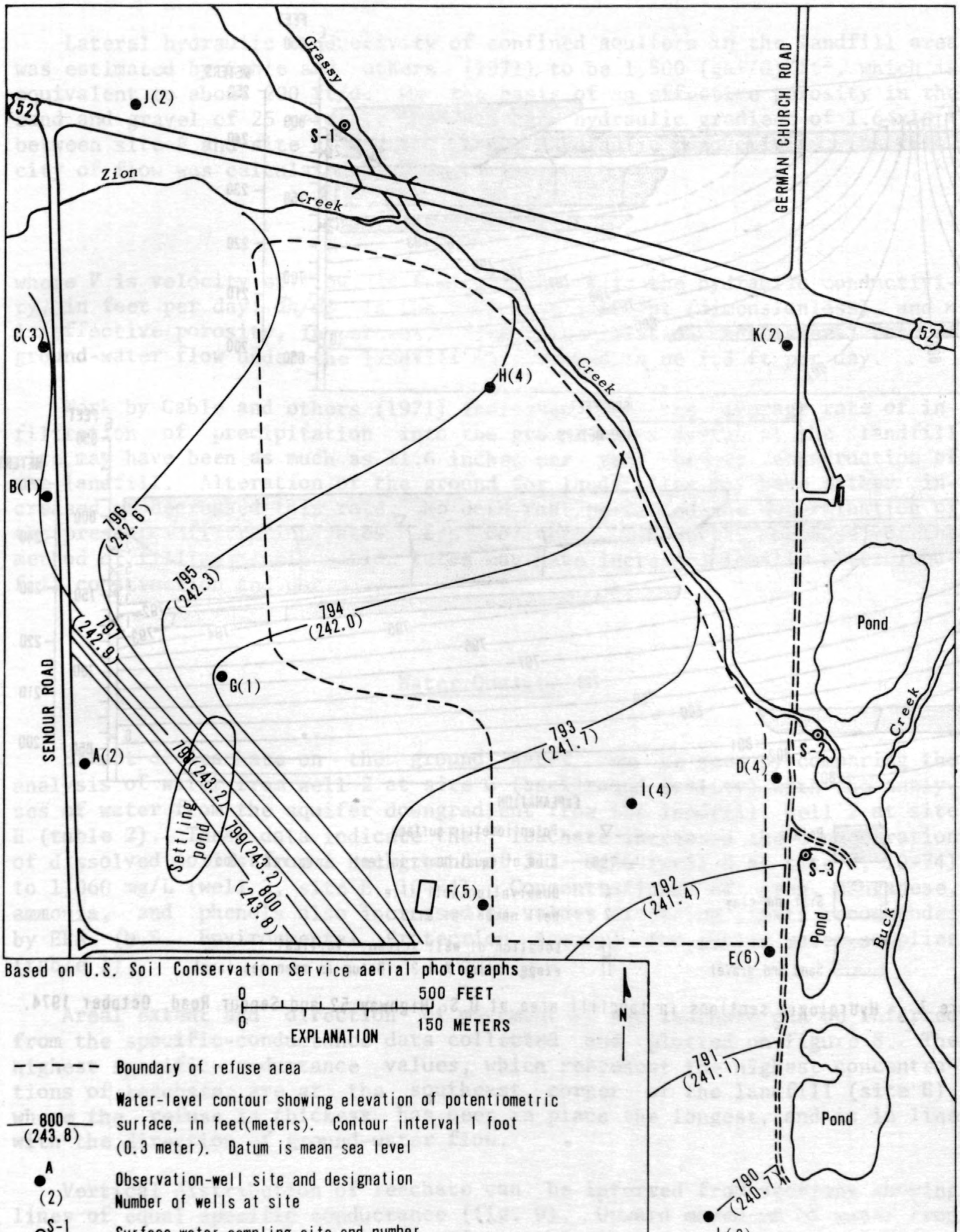


Figure 6.--Water-level contours in the shallow aquifer below landfill area at U.S. Highway 52 and Senour Road, October 1974.

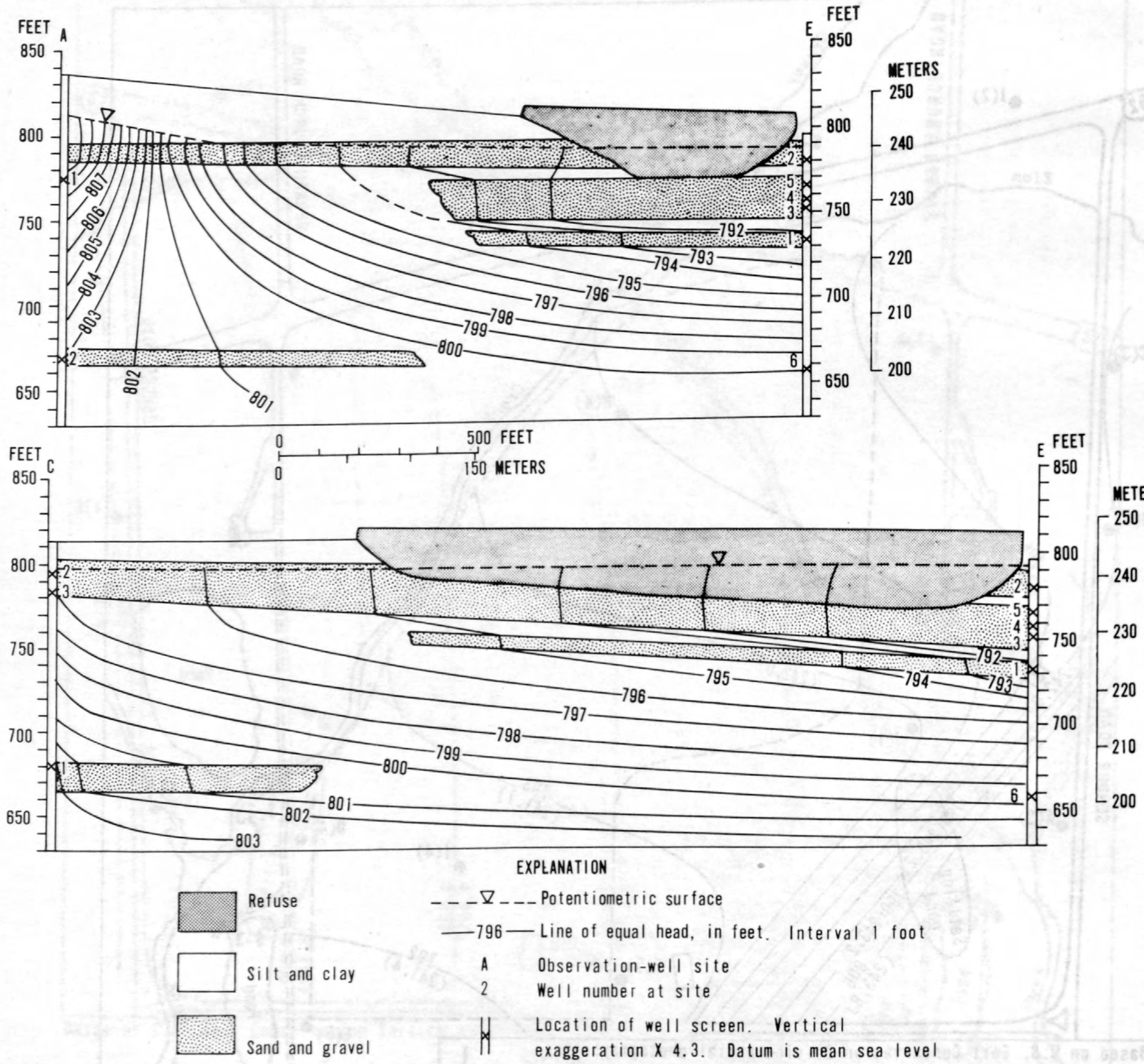


Figure 7.-- Hydrologic sections in landfill area at U.S. Highway 52 and Senour Road, October 1974.

Lateral hydraulic conductivity of confined aquifers in the landfill area was estimated by Cable and others (1971) to be 1,500 (gal/d)/ft^2, which is equivalent to about 200 ft/d. On the basis of an effective porosity in the sand and gravel of 25 percent, the average hydraulic gradient of 1.64×10^{-3} between site F and site E, and the above hydraulic conductivity, the velocity of flow was calculated by Darcy's law:

$$V = \frac{1}{n} K \frac{dh}{dl}$$

where V is velocity of flow, in feet per day; K is the hydraulic conductivity, in feet per day; dh/dl is the hydraulic gradient (dimensionless), and n is effective porosity, in percent. From this relation, the lateral rate of ground-water flow under the landfill is computed to be 1.3 ft per day.

Work by Cable and others (1971) indicates that the average rate of infiltration of precipitation into the ground-water system at the landfill site may have been as much as 11.6 inches per year before construction of the landfill. Alteration of the ground for landfilling may have either increased or decreased this rate. No data that permitted the determination of the present infiltration rates were collected. However, because of the method of filling, infiltration rates may have increased locally after landfill construction and use.

Water Quality

Effect of leachate on the ground water can be seen by comparing the analysis of water from well 2 at site C (background quality) with the analyses of water from the aquifer downgradient from the landfill, well 2 at site E (table 2). These data indicate that leachate increased the concentration of dissolved solids from a background of 311 mg/L (well 2 at site C, 10-74) to 1,060 mg/L (well 2, site E, 10-74). Concentrations of iron, manganese, ammonia, and phenols also increased to values exceeding limits recommended by EPA (U.S. Environmental Protection Agency) for public water supplies (table 1).

Areal extent and direction of movement of the leachate can be inferred from the specific-conductance data collected and plotted on figure 8. The highest specific-conductance values, which represent the highest concentrations of leachate, are at the southeast corner of the landfill (site E), where the refuse is thickest, has been in place the longest, and is in line with the direction of ground-water flow.

Vertical distribution of leachate can be inferred from sections showing lines of equal specific conductance (fig. 9). Upward movement of water from the deep aquifer to the shallow aquifer is indicated by the chemical analysis of water from well 1 at site E (deep aquifer), which shows no indication of leachate contamination, even though water from well 2 at site E

Table 2.--Analyses of water from selected sites on or near landfill at U.S. Highway 52 and Senour Road

[Analyses by U.S. Geological Survey]

Constituents and properties	Site and date of sampling									
	C[1]		I[2]		E[3]	E[4]	L[5]	S-1[6]	S-2[7]	S-3[8]
	4-74	10-74	4-74	10-74	4-74	10-74	10-74	4-74	4-74	11-73
	Constituents and properties, in milligrams per liter									
Iron (Fe)----------	0.04	0.07	[9]110	[9]1.20	0.02	[9]4.30	0.05	0.05	0.04	0.19
Manganese (Mn)------	.017	.04	2.7	.26	.017	[9].07	[9].16	.043	.05	.05
Calcium (Ca)--------	74	71	260	120	44	130	80	66	63	63
Magnesium (Mg)------	24	22	40	27	24	95	36	21	20	22
Chloride (Cl)-------	13	14	120	62	3.8	200	13	25	24	45
Sulfate (SO_4)-------	33	30	7.4	8.9	5.9	8.9	59	46	45	34
Dissolved solids----	314	311	1,470	582	302	1,060	368	302	347	343
Hardness, Ca, Mg (total)----------	280	270	810	410	210	720	350	250	240	250
Alkalinity (as $CaCO_3$)--------	230	130	894	489	286	796	349	189	190	212
Ammonia (as nitrogen)---------	.01	.15	[9]19	[9]15	[9].52	[9]3.1	.36	.41	.32	[9].54
Phosphorus (P) (total)----------	.41	.96	.01	.24	.05	.32	.23	.17	.16	.38
COD (chemical oxygen demand)----	16	120	810	66	0	88	56	20	4	33
MBAS (methylene blue active substance)-	0	------	[9]2.8	------	------	------	------	------	------	.0
TOC (total organic carbon)----------	0	18	------	------	0	26	2.9	------	------	8.0
Phenols------------	.000	.000	[9].790	[9].032	------	[9].003	.000	------	------	[9].002
Fluoride (F)--------	.2	------	.2	------	------	------	------	------	------	------
Silica (SiO_2)-------	6.8	------	12	------	------	------	------	------	------	------

Constituents, in micrograms per liter

Arsenic (As)	0	-------	18	-------	------	---------	-------	------	------	-------
Beryllium (Be)	0	-------	0	-------	------	---------	-------	------	------	-------
Cadmium (Cd)	0	-------	0	-------	------	---------	-------	------	------	-------
Chromium (Cr)	0	-------	2	-------	------	---------	-------	------	------	-------
Cobalt (Co)	0	-------	0	-------	------	---------	-------	------	------	-------
Copper (Cu)	15	-------	1	-------	------	---------	-------	------	------	-------
Lead (Pb)	5	-------	4	-------	------	---------	-------	------	------	-------
Silver (Ag)	0	-------	1	-------	------	---------	-------	------	------	-------
Zinc (Zn)	180	-------	90	-------	------	---------	-------	------	------	-------
Mercury (Hg)	0.0	-------	.1	-------	------	---------	-------	------	------	-------
Nickel (Ni)	10	-------	0	-------	------	---------	-------	------	------	-------

[1]Observation well 2 at site C; 21 ft deep; upgradient of landfill.

[2]Observation well 4 at site I; 51 ft deep; on landfill; (below refuse).

[3]Observation well 1 at site E; 66 ft deep; downgradient of landfill.

[4]Observation well 2 at site E; 21 ft deep; downgradient of landfill.

[5]Observation well 2 at site L; 15 ft deep; 600 ft downgradient of landfill.

[6]Surface-water site S-1; Grassy Creek (upstream).

[7]Surface-water site S-2; Grassy Creek (downstream).

[8]Surface-water site S-3; pond; downgradient of landfill.

[9]Value exceeds limits recommended by EPA for public water supplies (table 1).

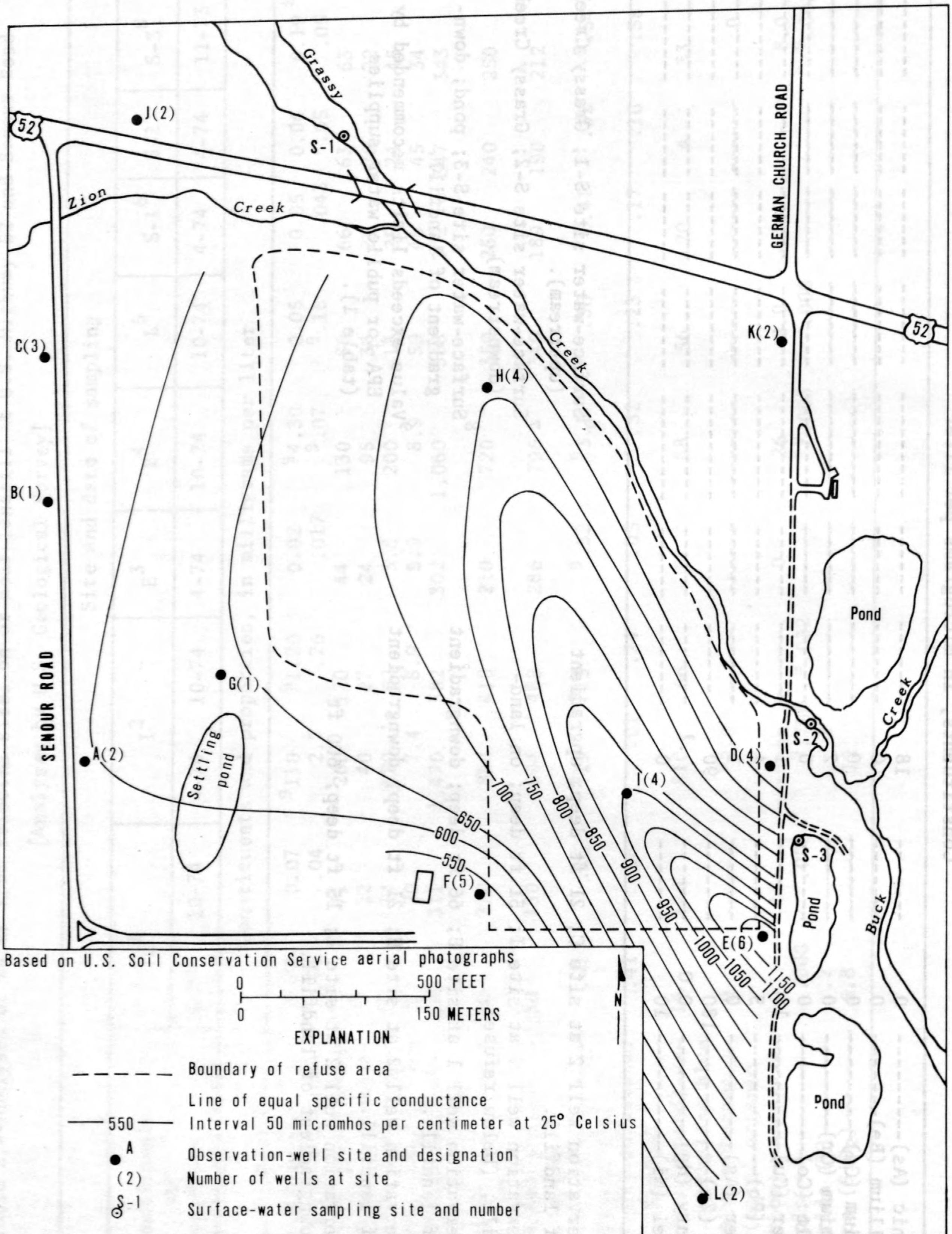


Figure 8.-- Specific conductance of water in the shallow aquifer below landfill area at U.S. Highway 52 and Senour Road, October 1974.

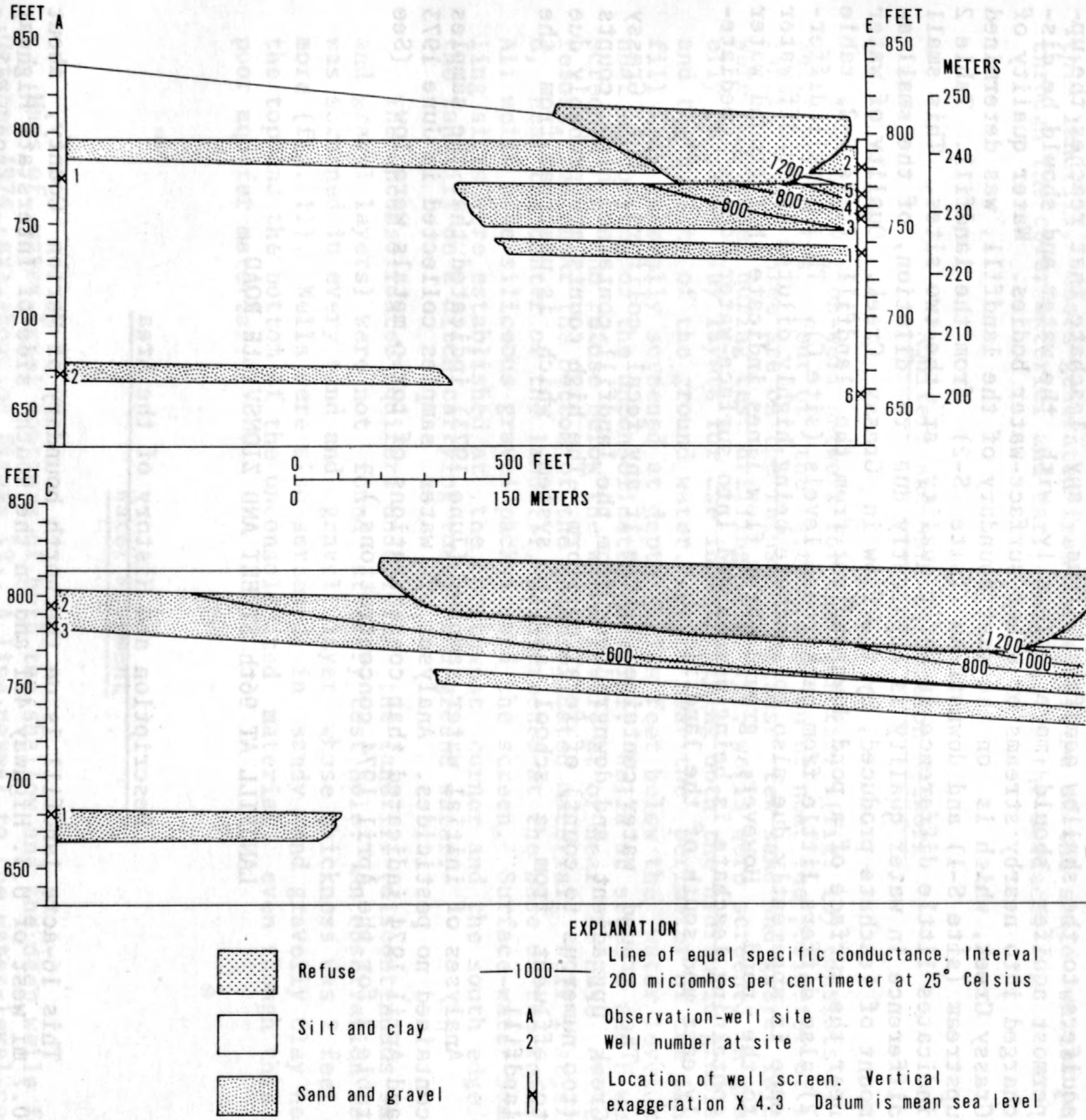


Figure 9.-- Sections showing distribution of specific conductance in landfill area at U.S. Highway 52 and Senour Road, October 1974.

(shallow aquifer) has a higher specific conductance and, by inference, a higher concentration of leachate than water from any other well sampled.

Head differences between aquifers at various depths indicate that the vertical movement of ground water in the landfill area is from the deeper aquifers to the shallow aquifers. Thus, any leachate that reaches the uppermost aquifer should move laterally with the water and should be discharged into nearby streams or other surface-water bodies. Water quality of Grassy Creek, which is on the east boundary of the landfill, was determined upstream (site S-1) and downstream (site S-2) from the landfill. Table 2 indicates little difference in water quality at the two sites. This small difference in water quality is apparently due to dilution, of the small amount of leachate produced, by the flow in Grassy Creek. Quality of water near the surface of a pond downgradient from the landfill (site S-2, table 2) also differs little from background levels (site C). This small difference is apparently due also to leachate being highly diluted by runoff water to the pond. However, ground-water flow lines indicate that ground water containing leachate is being discharged into surface-water bodies immediately east and south of the landfill.

The ground water contained little if any fecal coliform, but Grassy Creek upgradient and downgradient from the landfill contained high counts (too numerous to count) of fecal coliform. The high counts are probably due to effluent from a school septic system, which is upstream from the landfill.

Analyses of initial water samples (June 1973) indicated that the samples contained no pesticides. Analyses of water samples collected in June 1973 and April 1974 indicated that concentrations of toxic metals were low. (See table 2 for the April 1974 concentrations.)

LANDFILL AT 96th STREET AND ZIONSVILLE ROAD

Description and History of the Area

This 16-acre landfill is on the north boundary of Marion County, about 0.7 mi west of U.S. Highway 421 and on the south side of Interstate Highway 465 (fig. 1). The landfill is on a till plain, whose altitude (890 ft) is nearly the highest in the county. Till, from the surface (885 ft above mean sea level) to bedrock (720 ft above mean sea level), underlies the area. The till, composed mostly of clay and silt, also contains some sand and gravel layers, cobbles, and boulders, but the overall vertical hydraulic conductivity of the area is low (table 9). Thus, pools of water collect on the surface during wet periods.

The 35-ft deep fill area was created when dirt was stripped from it to be used in building overpasses for the interstate highway system. In the late 1960's, the pit was opened as a landfill. Refuse was spread in layers, and each layer was covered with dirt (silty clay loam) from the adjoining land to the east, now a lake. Since its closing in early 1973, the landfill has been landscaped and has been seeded with grass. Vegetation, however, is very sparse. The landfill is now about 10 ft higher than the surrounding land surface. Approximately $7.8 \times 10^5 yd^3$ of solid waste has been buried at this landfill. Gases generated from decomposition of the solid wastes pass through the cover material and carry leachate to the surface.

Aquifers and Data-Collection Network

The observation-well network for the landfill (fig. 10) consists of 16 wells at 7 sites. Four of the sites are on or near the perimeter of the landfill, and three are on the refuse. Because few sand and gravel layers were penetrated during test drilling (fig. 11), wells were screened in gravelly or sandy clay layers for use in determining both the hydraulic gradient and the quality of the ground water. Wells near the perimeter of the landfill were generally screened at depths a few feet below the water level and near the bottom of the unconsolidated material. Wells at sites C and F were screened in the refuse below the water level, at or near the base of the refuse, and near the bottom of the unconsolidated material. Well 1 at site G, near the center of the landfill, was screened at the base of the refuse. All wells have siliceous gravel pack around the screen. Surface-water sampling sites were established at the northwest corner and the south edge of the landfill on a ditch carrying runoff and ground water.

The unconsolidated aquifers underlying the landfill (discontinuous sand and gravel layers) were not found at every test hole. An observation well was screened in every sand and gravel layer whose thickness was 2 feet or more (fig. 11). Wells were also screened in sandy and gravelly clay near the top and the bottom of the unconsolidated material, even though this is poor aquifer material.

Water Movement

Maps of water-level contours of both the shallow and the deep wells for October 1974 are shown on figure 12. A line normal to the water-level contours indicates the direction of horizontal ground-water flow.

Greatest depth to water at the landfill is 60 ft in a deep well, and the smallest, 4 ft in a shallow well. Water levels fluctuate annually from as little as 2.5 ft in the shallow wells to as much as 13 ft in the deep wells.

Water levels in the shallow observation wells indicate ground-water mounding in the refuse; thus, flow within the upper part of the fill area is primarily from the west-central area of the landfill toward the perimeter (fig. 12-A).

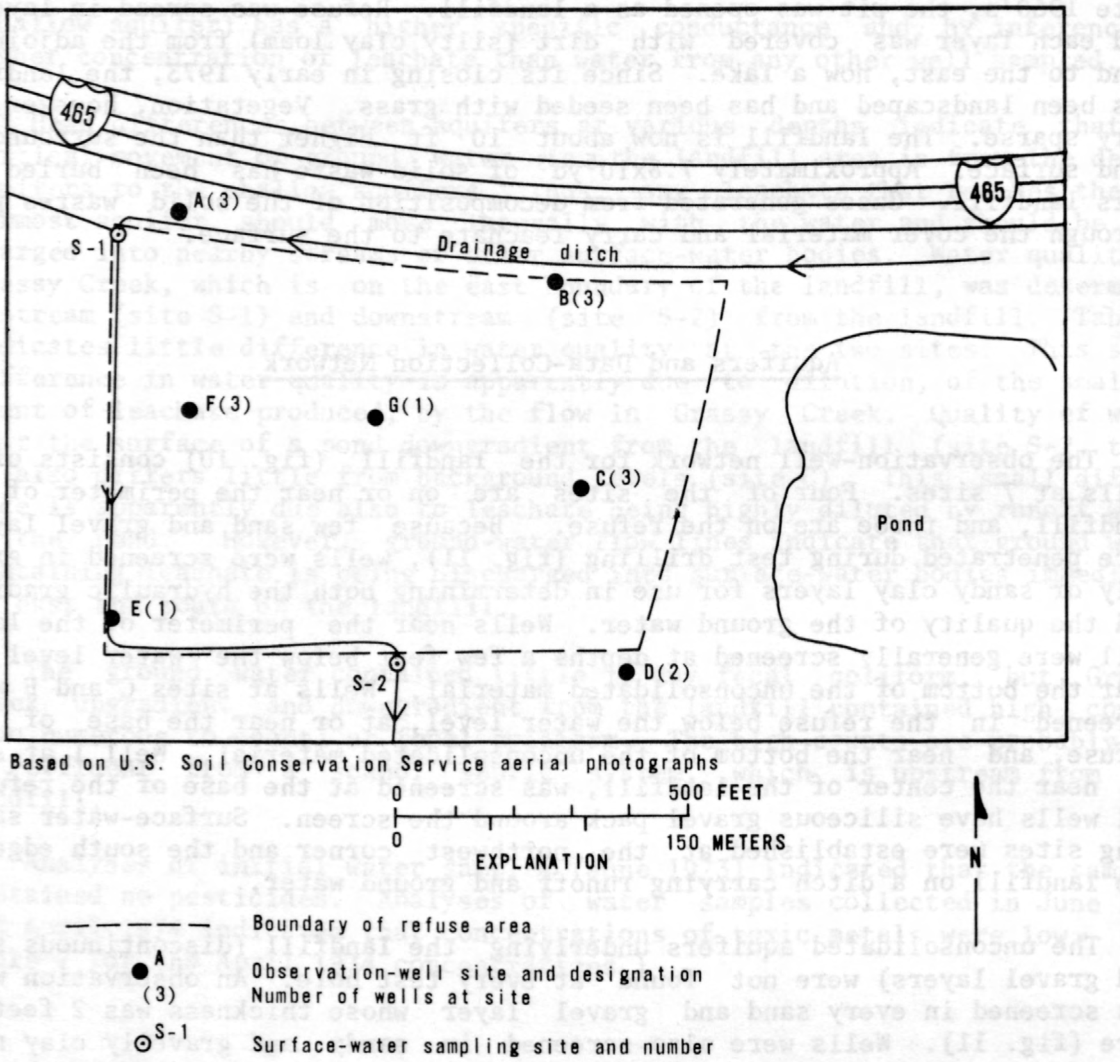


Figure 10.-- Location of well sites in landfill area at West 96th Street and Zionsville Road.

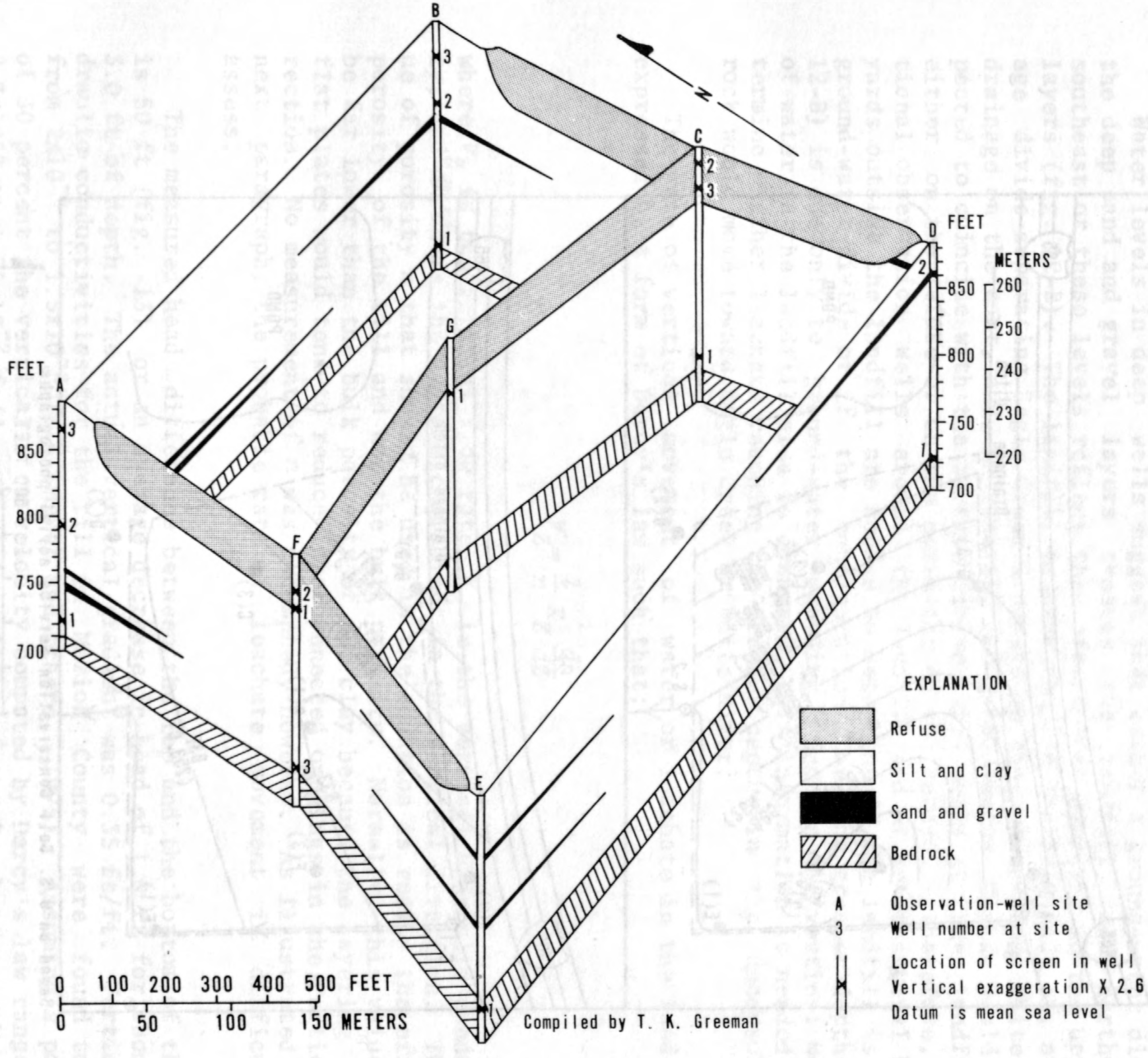


Figure 11.-- Stratigraphy and well-screen locations in landfill area at West 96th Street and Zionsville Road.

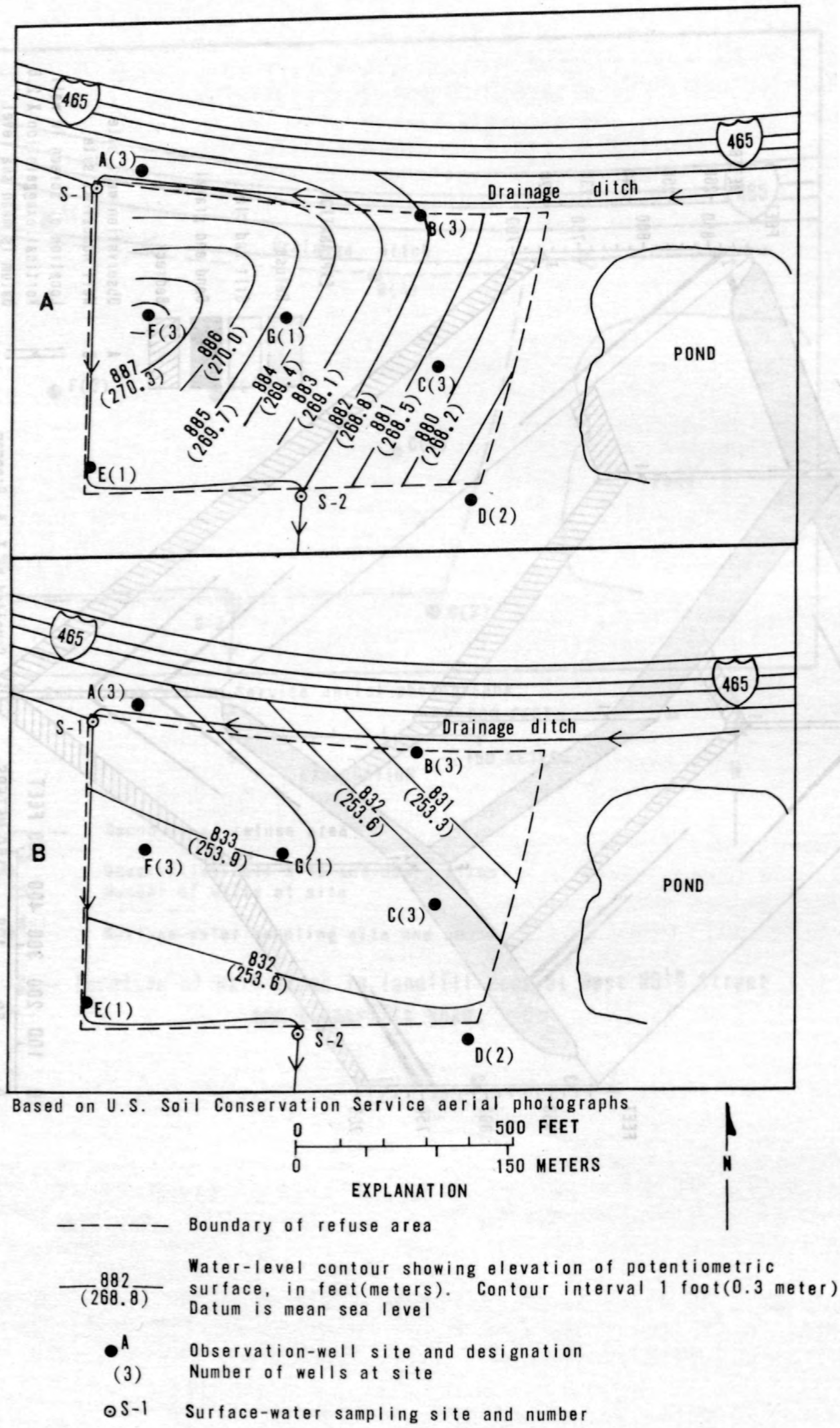


Figure 12.-- Water-level contours in the shallow (A) and deep (B) wells below landfill area at West 96th Street and Zionsville Road, October 1974.

Water levels in deep wells suggest that either a ground-water divide in the deep sand and gravel layers crosses the landfill from northwest to southeast or these levels reflect the effect of mounding in the uppermost layers (fig. 12-B). The landfill is near, but on the east side of, a drainage divide separating Eagle Creek drainage on the west from White River drainage on the east, and, in general, the ground-water divide would be expected to coincide with the surface divide. All wells at the landfill are either on the refuse or on the perimeter of the refuse. Therefore, additional observation wells around the landfill and at least several hundred yards outside the landfill are needed to determine if the landfill is on the ground-water divide or if the configuration for the greater depths (fig. 12-B) is due only to ground-water mounding. Because the vertical movement of water in the landfill area is downward, this information is needed to determine whether leachate reaching the greater depths in the unconsolidated rock would move toward Eagle Creek or White River.

The rate of vertical movement of water or leachate in the landfill is expressed by a form of Darcy's law such that:

$$V_Z = \frac{1}{n} K_Z \frac{dh}{dZ}$$

where V_Z is the vertical flow rate, K_Z is the vertical hydraulic conductivity, and dh/dZ is the hydraulic gradient in the vertical direction. The value of porosity n that should be used in the equation is really the effective porosity of the till and not the bulk porosity. Normally, this value will be far lower than the bulk porosity of the clay because the layering of the flat plates would tend to reduce interconnected openings in the vertical direction. No measurement of n was attempted, however. As illustrated in the next paragraph, the probable rate of leachate movement is difficult to assess.

The measured head difference between the top and the bottom of the till is 50 ft (fig. 13) or an average decrease in head of 1.0 ft for about each 3.0 ft of depth. The actual vertical gradient was 0.35 ft/ft. Vertical hydraulic conductivities for the till in Marion County were found to range from $2x10^{-4}$ to $1.5x10^{-2}$ ft/d (Meyer and others, 1975). Assuming a porosity of 30 percent the vertical flow velocity computed by Darcy's law ranges from $2.3x10^{-4}$ to $1.75x10^{-2}$ ft/d. Thus, traveltime of the leachate to the top of the bedrock would be at least 20 years. However, if the effective porosity of the clay is only 0.003, then the traveltime would only be 71 days.

The lateral hydraulic gradient from site A to site B decreases 1.0 ft in head per 350 ft. Within the till are layers of coarse materials grading from sandy or gravelly clay to fine sand. Hydraulic conductivities are low and, based on studies in similar geohydrologic settings, probably range from about 1 to 54 ft/d. For a porosity of 30 percent and a hydraulic gradient of 0.003 ft/ft, the horizontal velocity of flow ranges from 0.01 to 0.5 ft/d. Distance traveled by water moving at these rates ranges from 3.6 ft to 182 ft per year. Thus, ground-water flow at the landfill is virtually horizontal, and most leachate entering the flow system moves laterally.

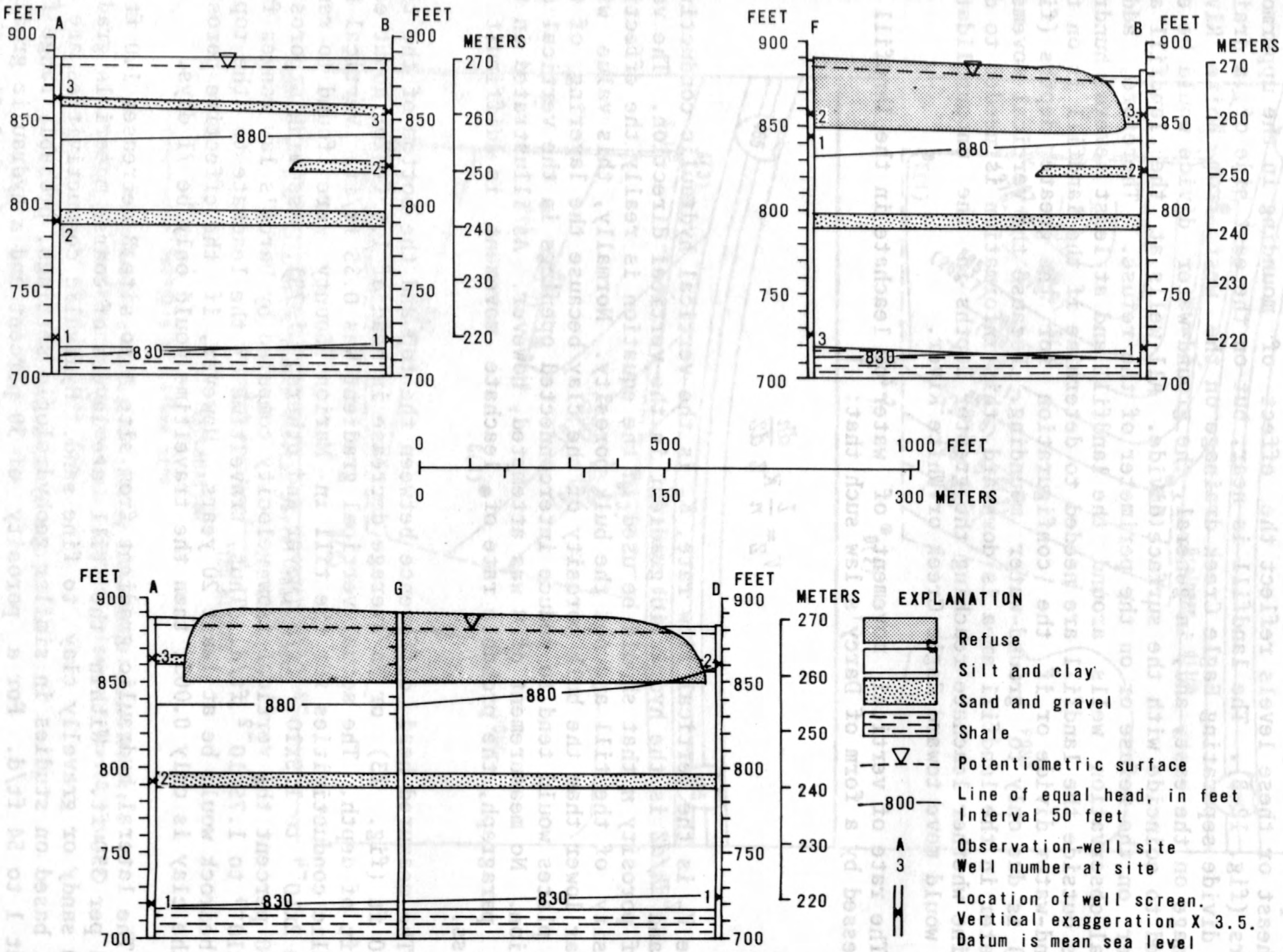


Figure 13.-- Hydrologic sections in landfill area at West 96th Street and Zionsville Road, October 1974.

Water Quality

Effect of leachate on the ground water can be seen by comparing an analysis of the water from well 2 at site A (background quality) with an analysis of the water from the zone under the landfill, well 1 at site F (table 3). These data indicate that leachate increased the concentration of dissolved solids from 342 mg/L to 4,710 mg/L. Concentrations of several chemical constituents in the leachate water exceed limits recommended by EPA for public water supply.

Areal extent and direction of movement of the leachate can be inferred from the specific-conductance data plotted on figure 14. Specific conductance is highest near the center of the landfill. Because of the possibility of sample contamination, the vertical distribution of leachate is more difficult to describe than the horizontal distribution.

Quality of the water just above the bedrock at sites A, D, and E is at or near background levels for the area. However, quality of water at similar depths at sites B, C, and F indicates leachate contamination (fig. 14-B). Age of the landfill and vertical permeabilities of till indicate that water containing leachate has not had time to reach bedrock. Leachate in the ground water indicates that water is moving downward through the backfill at a greater rate than through the till. Further indications of leachate contamination of ground water at various depths are shown in figure 15.

Pesticides were not detected in the initial analyses of ground water from the landfill. Analyses of water samples collected in April 1974 from several sites within the landfill included determination of concentrations of selected metals. Analyses of water from observation well 3 at site A, a shallow well upgradient from the landfill, and well 1 at site F, a well screened at the base of the refuse, are given in table 3. Concentrations of metals were minimal in water from both wells in April 1974.

Seepage from the landfill to the surface and poor surface drainage have caused small pools to develop in the cover material of the landfill. Openings in the cover material are due to escaping gas. Some of these openings are filled with bubbling water, which indicates decay of waste materials below the surface. Three gas samples collected December 14, 1973, had methane contents ranging from 58 to 62 percent and carbon dioxide contents ranging from 35 to 36 percent.

Some of the seepage of leachate to the surface reaches a drainage ditch on the west and the south edges of the fill area (fig. 10). This ditch, which flows most of the year, is the headwater of Oil Creek, which flows into the White River. The effect of leachate on the quality of water in the ditch is minimal during the spring because of high flow but may be detrimental in autumn, when flow is intermittent (sites S-1 and S-2, table 3).

Table 3.--Analyses of water from selected sites on or near landfill at West 96th Street and Zionsville Road

[Analyses by U.S. Geological Survey]

Constituents and properties	A[1]	A[2]	B[3]	B[4]	D[5]	F[6]		S-1[7]	S-2[8]	
	10-74	4-74	4-74	4-74	10-74	4-74	10-74	4-74	4-74	10-74
Constituents and properties, in milligrams per liter										
Iron (Fe)	0.05	0.09	[9]1.0	[9]1.3	[9]2.1	[9]1.80	[9]2.1	0	0.24	[9]0.46
Manganese (Mn)	[9].10	[9].30	[9].53	[9]6.9	[9]3.4	[9].071	.05	.014	[9].30	[9].20
Calcium (Ca)	44	90	75	260	100	120	59	88	73	120
Magnesium (Mg)	15	32	24	120	36	200	170	30	28	170
Chloride (Cl)	5.0	10	62	140	25	[9]1,000	[9]1,200	54	34	[9]680
Sulfate (SO_4)	3.8	64	110	5.0	48	60	17	69	6.7	2.0
Dissolved solids	342	439	657	1,410	487	4,710	4,770	465	504	3,870
Hardness, Ca, Mg (total)	170	360	290	1,100	400	1,100	850	340	330	1,000
Alkalinity (as $CaCO_3$)	311	323	366	1,200	375	4,170	4,290	263	292	1,890
Ammonia (as nitrogen)	[9].54	.09	[9].62	[9]14	[9].54	[9]560	[9]680	.12	[9]11	[9]290
Phosphorus (P) (total)	.20	.65	1.1	.38	.45	1.1	1.8	.03	.05	1.2
COD (chemical oxygen demand)	38	58	60	210	19	880	910	15	200	2,500
MBAS (methylene blue active substance)	----	.4	----	1.1	----	5.3	----	----	----	----
TOC (total organic carbon)	17	2.1	----	.092	7.7	----	360	----	----	----
Phenols	[9].002	.000	----	----	[9].002	[9].39	[9].064	----	----	[9].003
Fluoride (F)	----	.5	----	----	----	.9	----	----	----	----
Silica (SiO_2)	----	20	----	----	----	24	----	----	----	----

Constituents, in micrograms per liter

Arsenic (As)	------	14	-------	-------	------	34	-----	-----	-----	-------
Beryllium (Be)	------	0	-------	-------	------	0	-----	-----	-----	-------
Cadmium (Cd)	------	1	-------	-------	------	0	-----	-----	-----	-------
Chromium (Cr)	------	0	-------	-------	------	10	-----	-----	-----	-------
Cobalt (Co)	------	1	-------	-------	------	0	-----	-----	-----	-------
Copper (Cu)	------	11	-------	-------	------	4	-----	-----	-----	-------
Lead (Pb)	------	1	------	-------	------	0	-----	-----	-----	-------
Mercury (Hg)	------	.2	------	-------	------	.2	-----	-----	-----	-------
Nickel (Ni)	------	------	------	-------	------	0	-----	-----	-----	-------
Silver (Ag)	------	0	------	-------	------	0	-----	-----	-----	-------
Zinc (Zn)	------	10	------	-------	------	10	-----	-----	-----	-------

[1]Observation well 2 at site A; 96 ft deep; perimeter of landfill (native water).

[2]Observation well 3 at site A; 24 ft deep; perimeter of landfill.

[3]Observation well 2 at site B; 62 ft deep; perimeter of landfill.

[4]Observation well 3 at site B; 29 ft deep; perimeter of landfill.

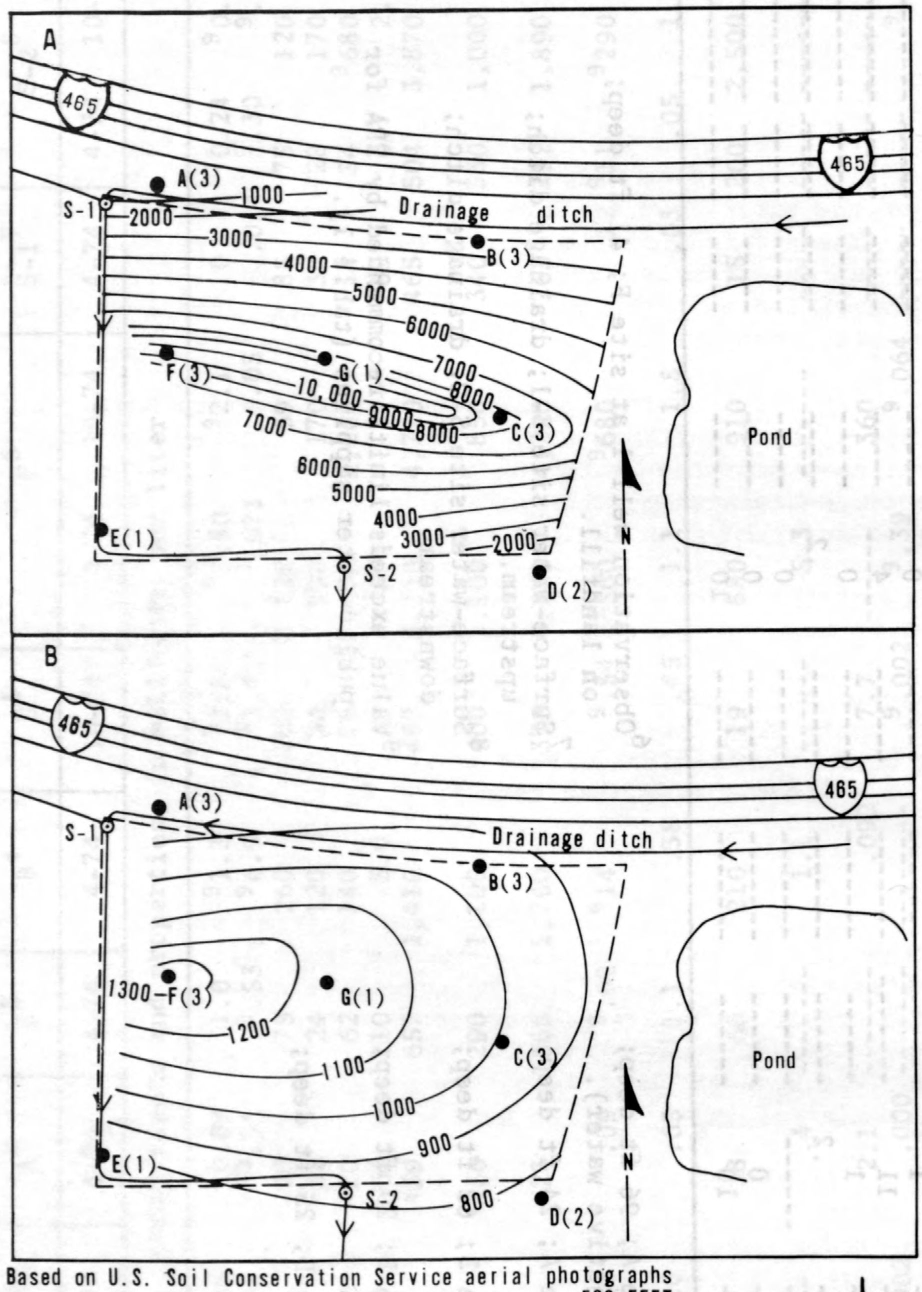
[5]Observation well 2 at site D; 25 ft deep; perimeter of landfill.

[6]Observation well 1 at site F; 41 ft deep; on landfill.

[7]Surface-water site S-1; drainage ditch; upstream.

[8]Surface-water site S-2; drainage ditch; downstream.

[9]Value exceeds limits recommended by EPA for public water supplies (table 1).



EXPLANATION

- - - - - Boundary of refuse area

—1000— Line of equal specific conductance. Interval 100 and 1000 micromhos per centimeter at 25° Celsius

● A Observation-well site and designation

(3) Number of wells at site

S-1 Surface-water sampling site and number

Figure 14.-- Specific conductance of water in the shallow(A) and deep(B) wells below landfill area at West 96th Street and Zionsville Road, October 1974.

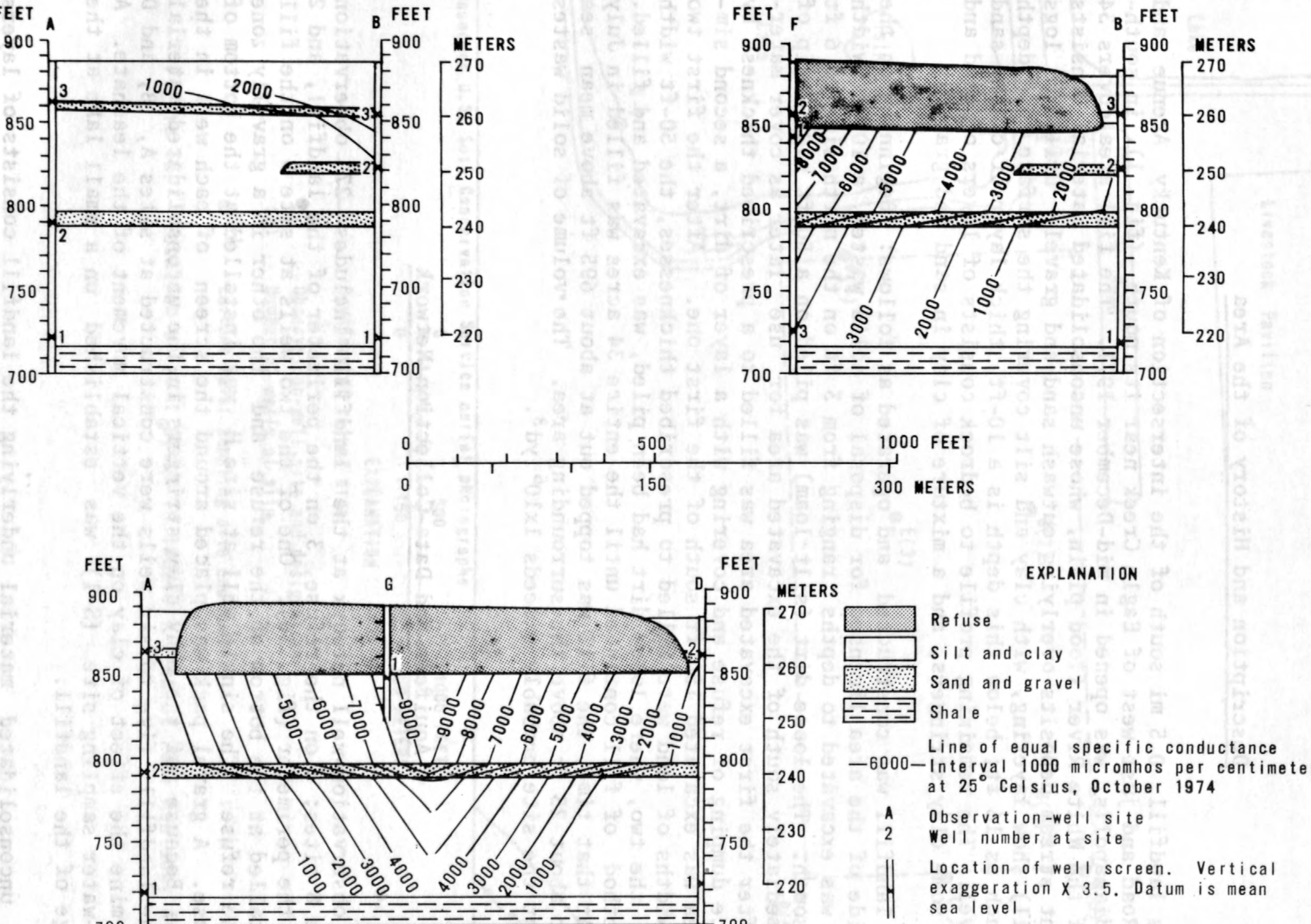


Figure 15.-- Sections showing distribution of specific conductance in landfill area at West 96th Street and Zionsville Road, October 1974.

LANDFILL AT 2561 KENTUCKY AVENUE

Description and History of the Area

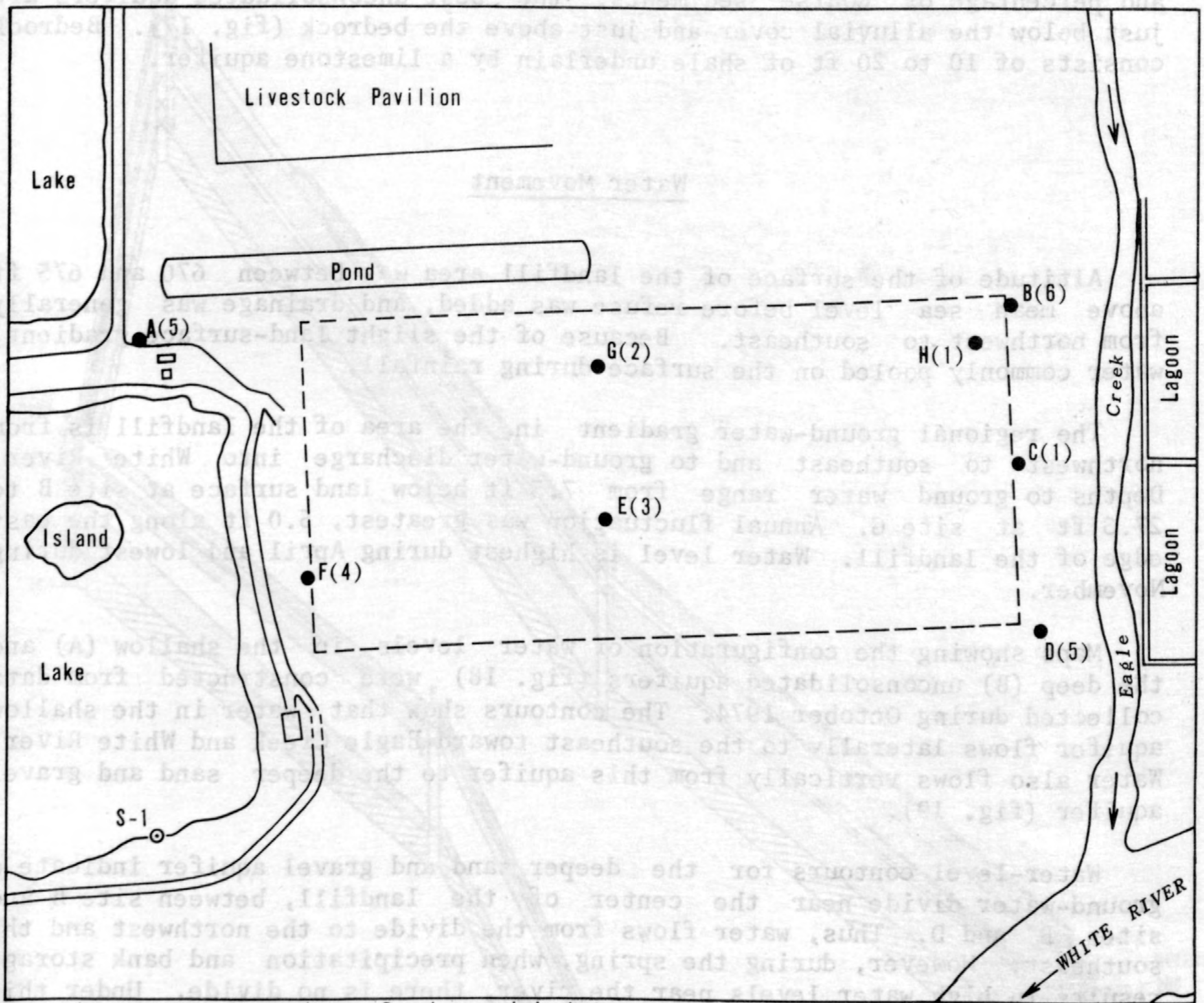
This landfill, 0.5 mi south of the intersection of Kentucky Avenue and Warman Road and just west of Eagle Creek near its mouth (fig. 1), in southwest Indianapolis, was opened in mid-December 1971. The fill area covers 34 acres of the White River flood plain, whose unconsolidated material consists of recent stream deposits overlying outwash sand and gravel. Drillers' logs (table 11) show layering, with clay and silt covering the surface to a depth of as much as 16 ft; below this depth is a 10-ft thick layer of clean sand and gravel. The remaining profile to bedrock consists of layers of sand and gravel, some clay stringers, and a mixture of clay in sand and gravel.

The landfill was constructed and operated as follows: Beginning on the north side of the area licensed for disposal of solid wastes, a 100-ft width of land was excavated to depths ranging from 3 ft on the north side to 6 ft on the south. The loose dirt (silt loam) was piled on a 50-ft wide strip of land immediately south of the excavated area for use later as cover material. After the first excavated area was filled to a prescribed thickness by alternate dumping of refuse and covering with a layer of dirt, a second similar area was excavated 150 ft south of the first one. After the first two 100-ft widths of land were filled to prescribed thicknesses, the 50-ft width between the two, where loose dirt had been piled, was excavated and filled. This method of fill continued until the entire 34 acres was filled in July 1975. At that time, the fill was topped out at about 695 ft above mean sea level or about 25 ft above the surrounding area. The volume of solid wastes buried at the site probably exceeds $1x10^6$ yd^3.

Aquifers and Data-Collection Network

The observation-well network at the landfill includes 27 observation wells at 8 sites; 3 on the refuse, 3 on the perimeter of the landfill, and 2 outside the perimeter (fig. 16). One of the two wells at site G on the fill was installed at the bottom of the refuse and the other in a gravelly zone below the refuse. The single well at site H was installed at the bottom of the refuse. A gravel pack was placed around the screen of each well in the refuse. Because of the many clay stringers in the unconsolidated material below the landfill, five to six wells were constructed at sites A, B, and D to determine the effect of clay on the vertical movement of the leachate. A surface-water sampling site (S-1) was established on a small lake at the west edge of the landfill.

The unconsolidated material underlying the landfill consists of layers of fine sand and sandy, coarse gravel, separated by clay stringers or layers of clay mixed with sand and gravel (table 11). On the basis of thickness



Based on U.S. Soil Conservation Service aerial photographs

0 500 1000 FEET

0 150 300 METERS

N

EXPLANATION

— — — — Boundary of refuse area

● A Observation-well site and designation

(5) Number of wells at site

⊙ S-1 Surface-water sampling site and number

Figure 16.-- Location of well sites in landfill area at 2561 Kentucky Avenue.

and percentage of coarse sediments, the best unconsolidated aquifers are just below the alluvial cover and just above the bedrock (fig. 17). Bedrock consists of 10 to 20 ft of shale underlain by a limestone aquifer.

Water Movement

Altitude of the surface of the landfill area was between 670 and 675 ft above mean sea level before refuse was added, and drainage was generally from northwest to southeast. Because of the slight land-surface gradient, water commonly pooled on the surface during rainfall.

The regional ground-water gradient in the area of the landfill is from northwest to southeast and to ground-water discharge into White River. Depths to ground water range from 7.5 ft below land surface at site B to 27.5 ft at site G. Annual fluctuation was greatest, 5.0 ft along the east edge of the landfill. Water level is highest during April and lowest during November.

Maps showing the configuration of water levels in the shallow (A) and the deep (B) unconsolidated aquifers (fig. 18) were constructed from data collected during October 1974. The contours show that water in the shallow aquifer flows laterally to the southeast toward Eagle Creek and White River. Water also flows vertically from this aquifer to the deeper sand and gravel aquifer (fig. 19).

Water-level contours for the deeper sand and gravel aquifer indicate a ground-water divide near the center of the landfill, between site E and sites B and D. Thus, water flows from the divide to the northwest and the southeast. However, during the spring, when precipitation and bank storage results in high water levels near the river, there is no divide. Under this condition, flow in the deep aquifer is principally toward the northwest.

Although the regional ground-water gradient in the area of the landfill is to the southeast and the White River, the gradient has been reversed locally in the deep aquifer. This reversal is due to heavy ground-water pumping northwest of the landfill. If this pumping should cease or be reduced, the gradient would again be to the southeast. However, if the present rate of pumping continues or is increased, water from the landfill site may reach the pumping wells.

The lateral rate of movement of ground water from the landfill area to the pumping sites is proportional to the amount of water being pumped. Using the hydraulic gradient for October 1974 (0.0013), a lateral hydraulic conductivity of 335 ft/d (Cable and others, 1971), and an effective porosity of 25 percent, the author calculated a velocity of 1.8 ft/d or 689 ft/yr for movement of leachate away from the landfill in October 1974.

The infiltration rate at the landfill is approximately 11 to 12 in/yr (Cable and others, 1971). These figures do not consider the effect of surface compaction or the rate of percolation through the refuse.

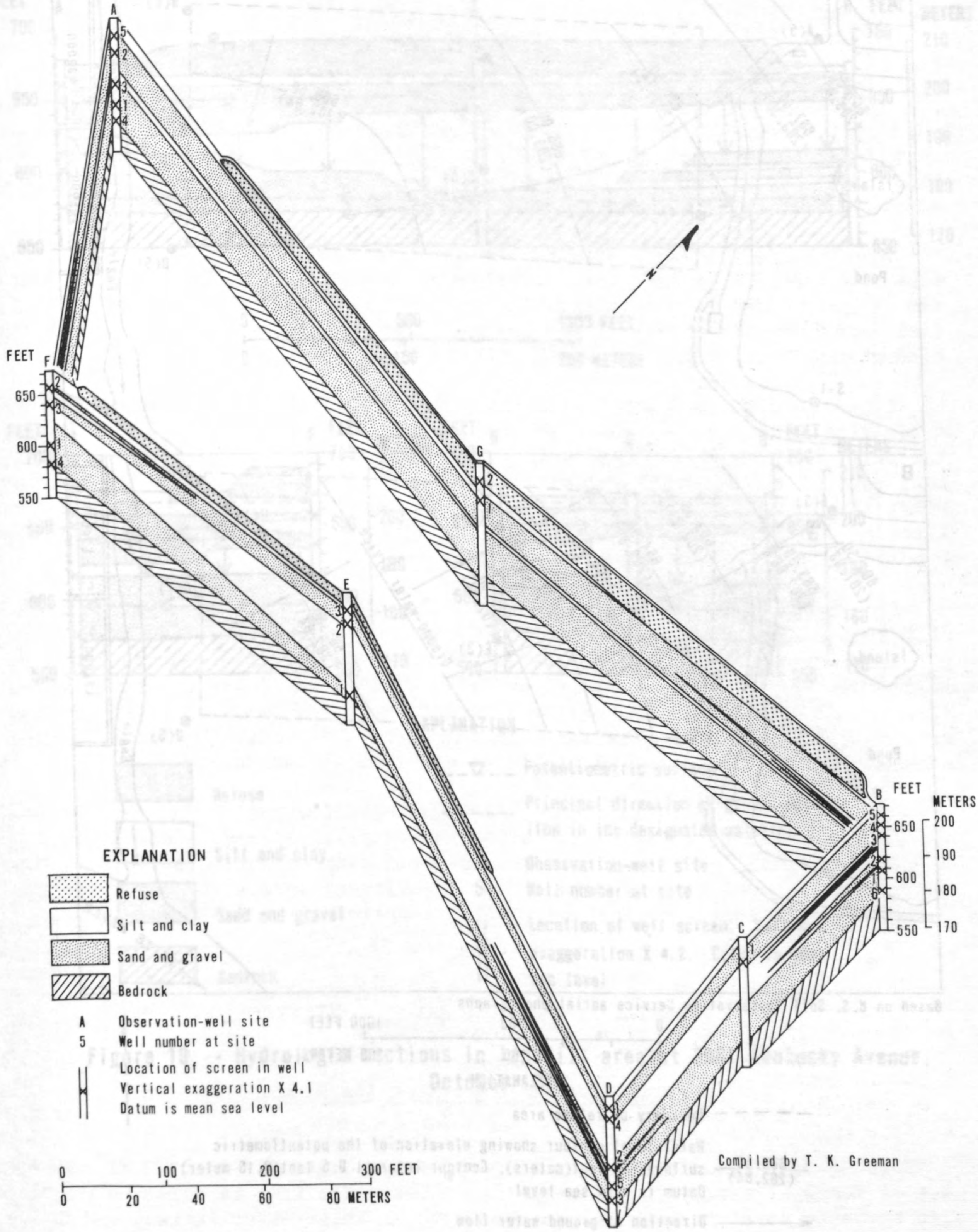


Figure 17.-- Stratigraphy and well-screen locations in landfill area at 2561 Kentucky Avenue.

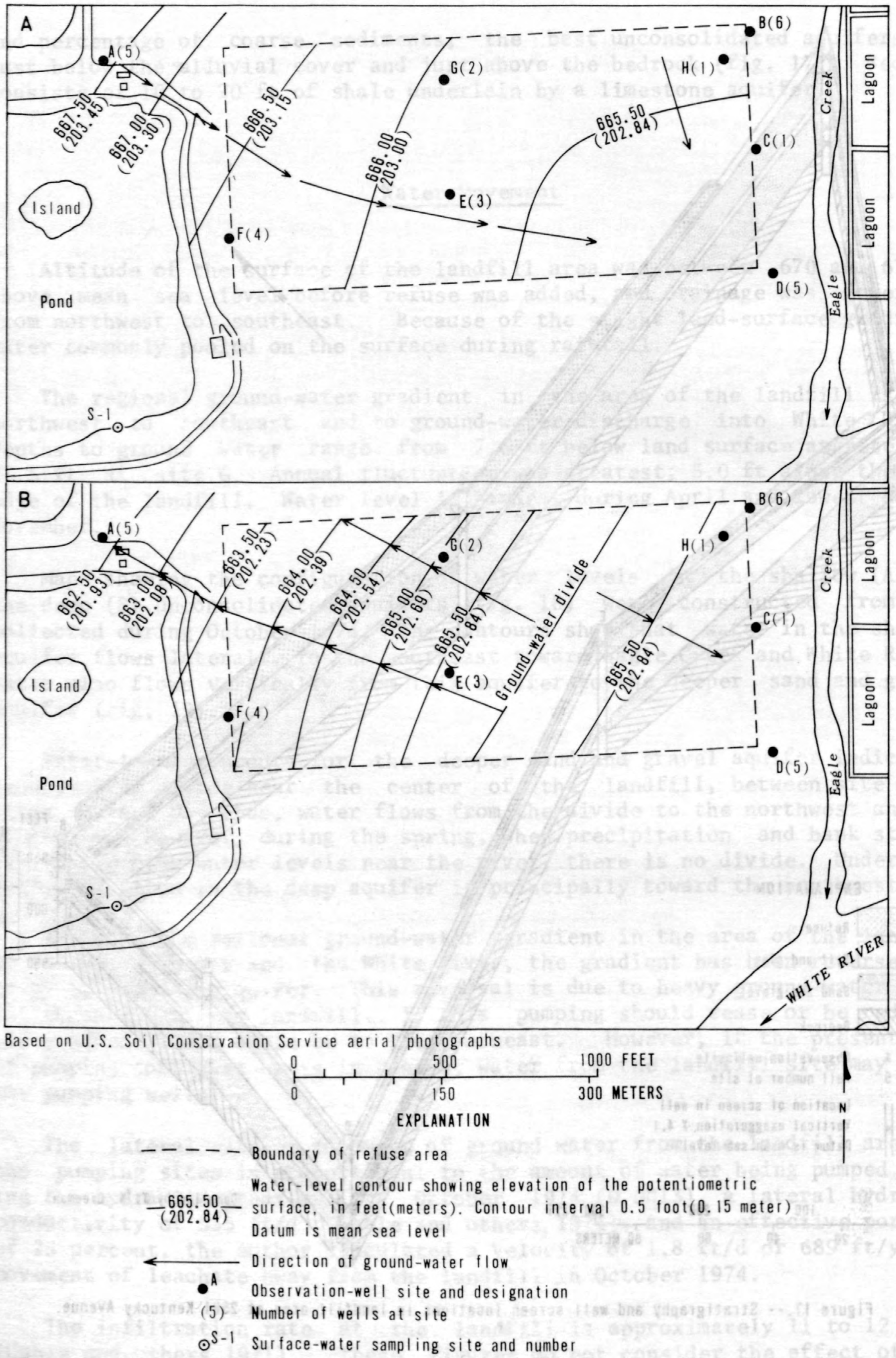


Figure 18 -- Water-level contours in the shallow(A) and deep(B) aquifers below landfill area at 2561 Kentucky Avenue, October 1974.

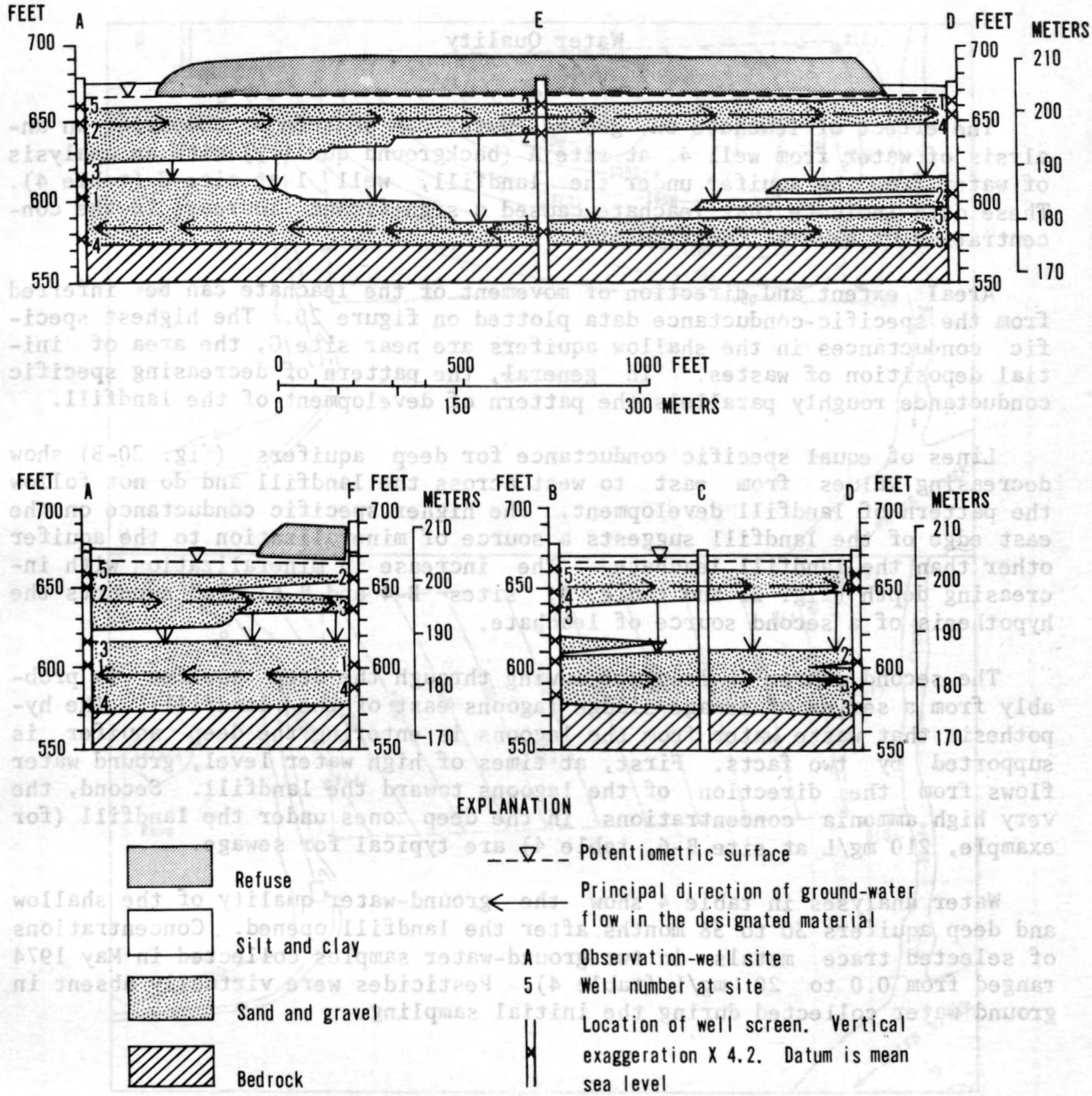


Figure 19.-- Hydrologic sections in landfill area at 2561 Kentucky Avenue, October 1974.

Water Quality

The effect of leachate on ground water can be seen by comparing an analysis of water from well 4 at site A (background quality) with an analysis of water from the aquifer under the landfill, well 1 at site G (table 4). These data indicate that leachate caused a significant increase in the concentration of several constituents.

Areal extent and direction of movement of the leachate can be inferred from the specific-conductance data plotted on figure 20. The highest specific conductances in the shallow aquifers are near site G, the area of initial deposition of wastes. In general, the pattern of decreasing specific conductance roughly parallels the pattern of development of the landfill.

Lines of equal specific conductance for deep aquifers (fig. 20-B) show decreasing values from east to west across the landfill and do not follow the pattern of landfill development. The higher specific conductance on the east edge of the landfill suggests a source of mineralization to the aquifer other than the landfill leachate. The increase in mineralization with increasing depth (fig. 21 and table 4, sites B-4 and B-6) also supports the hypothesis of a second source of leachate.

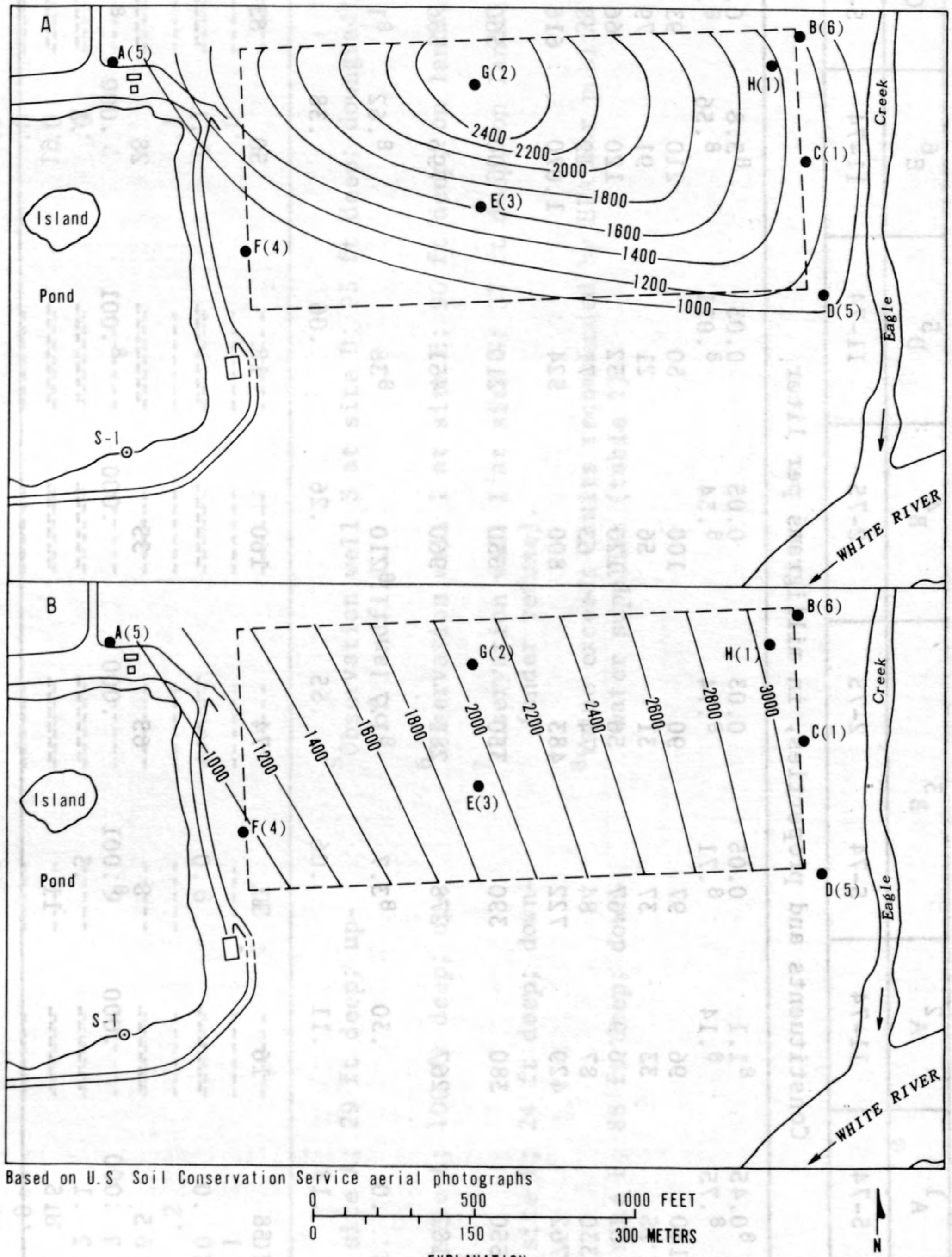
The second source of leachate moving through the deep aquifer is probably from a series of sewage-sludge lagoons east of the landfill. The hypothesis that waste water from the lagoons is entering the deep aquifer is supported by two facts. First, at times of high water level, ground water flows from the direction of the lagoons toward the landfill. Second, the very high ammonia concentrations in the deep zones under the landfill (for example, 210 mg/L at site B-6, table 4) are typical for sewage.

Water analyses in table 4 show the ground-water quality of the shallow and deep aquifers 30 to 38 months after the landfill opened. Concentrations of selected trace metals in two ground-water samples collected in May 1974 ranged from 0.0 to 20 mg/L (table 4). Pesticides were virtually absent in ground water collected during the initial sampling.

LANDFILL AT 800 WEST RAYMOND STREET

Description and History of the Area

This 56-acre landfill, on the flood plain of White River, is 2 mi southwest of Monument Circle in Indianapolis. The landfill is bordered on the east by White River Parkway and on the south by White River Parkway and Raymond Street. Well logs (table 12) show some clay layers or lenses at nearly all test holes. However, poorly sorted sand and gravel are the predominant materials of the unconsolidated deposits. No sharp delineation exists between the alluvial cover and the underlying outwash sands and gravels.



EXPLANATION

Boundary of refuse area

—1000— Line of equal specific conductance. Interval 200 micromhos per centimeter at 25° Celsius

● A Observation-well site and designation

(5) Number of wells at site

⊙ S-1 Surface-water sampling site and number

Figure 20.-- Specific conductance of water in the shallow(A) and deep(B) aquifers below landfill area at 2561 Kentucky Avenue, October 1974.

Table 4.--Analyses of water from selected sites on or near landfill at 2561 Kentucky Avenue

[Analyses by U.S. Geological Survey]

Constituents and properties	Site and date of sampling							
	A[1]	A[2]	B[3]		B[4]	D[5]	E[6]	G[7]
	5-74	11-74	5-74	2-75	2-75	11-74	11-74	5-74
Constituents and properties, in milligrams per liter								
Iron (Fe)------------	[8]0.45	[8]1.1	0.05	0.03	0.05	0.03	[8]3.8	0.05
Manganese (Mn)-------	[8].75	[8].14	[8].71	[8].74	[8].34	[8].021	[8].56	[8].22
Calcium (Ca)---------	180	96	97	90	100	50	210	93
Magnesium (Mg)------	25	33	37	31	56	21	91	79
Chloride (Cl)--------	31	6.9	67	56	120	52	120	66
Sulfate (SO_4)--------	330	87	84	74	63	71	19	38
Dissolved solids-----	762	429	722	483	800	524	1,070	616
Hardness, Ca, Mg (total)------------	550	380	390	350	530	210	900	560
Alkalinity (as $CaCO_3$)---------	182	267	278	281	960	451	796	536
Ammonia (as nitrogen)----------	.0	.30	[8]3.7	[8]1.7	[8]210	[8]38	[8].62	[8]1.0
Phosphorus (P) (total)------------	.18	.11	.06	.55	.26	.06	.38	.27
COD (chemical oxygen demand)----	38	16	11	74	160	18	50	63
MBAS (methylene blue active substance)--	.0	------	.0	------	------	-------	.1	------
TOC (total organic carbon)------------	5	------	8	65	35	-------	28	------
Phenols--------------	.000	.000	[8].001	.000	.000	[8].001	.000	[8].033
Fluoride (F)---------	.1	------	.3	------	------	-------	.3	------
Silica (SiO_2)--------	8.5	------	11	------	------	-------	19	------

Constituents, in micrograms per liter								
Arsenic (As)	0.0	------	0.0	------	------	-------	10	------
Beryllium (Be)	.0	------	.0	------	------	-------	.0	------
Cadmium (Cd)	.0	------	-----	------	------	-------	.0	------
Chromium (Cr)	.0	------	-----	------	------	-------	.0	------
Cobalt (Co)	3	------	-----	------	------	-------	.0	------
Copper (Cu)	3	------	6	------	------	-------	7	------
Lead (Pb)	9	------	-----	------	------	-------	4	------
Mercury (Hg)	.2	------	-----	------	------	-------	.1	------
Nickel (Ni)	10	------	9	------	------	-------	9	------
Silver (Ag)	1	------	-----	------	------	-------	.0	------
Zinc (Zn)	10	------	20	------	------	-------	8	------

[1] Observation well 2 at site A; 29 ft deep; up-gradient of landfill.

[2] Observation well 4 at site A; 100 ft deep; up-gradient of landfill.

[3] Observation well 4 at site B; 24 ft deep; down-gradient of landfill.

[4] Observation well 6 at site B; 88 ft deep; down-gradient of landfill.

[5] Observation well 3 at site D; 95 ft deep; downgradient of landfill.

[6] Observation well 1 at site E; 90 ft deep; on landfill.

[7] Observation well 1 at site G; 37 ft deep; on landfill; (under refuse).

[8] Value exceeds limits recommended by EPA for public water supplies (table 1).

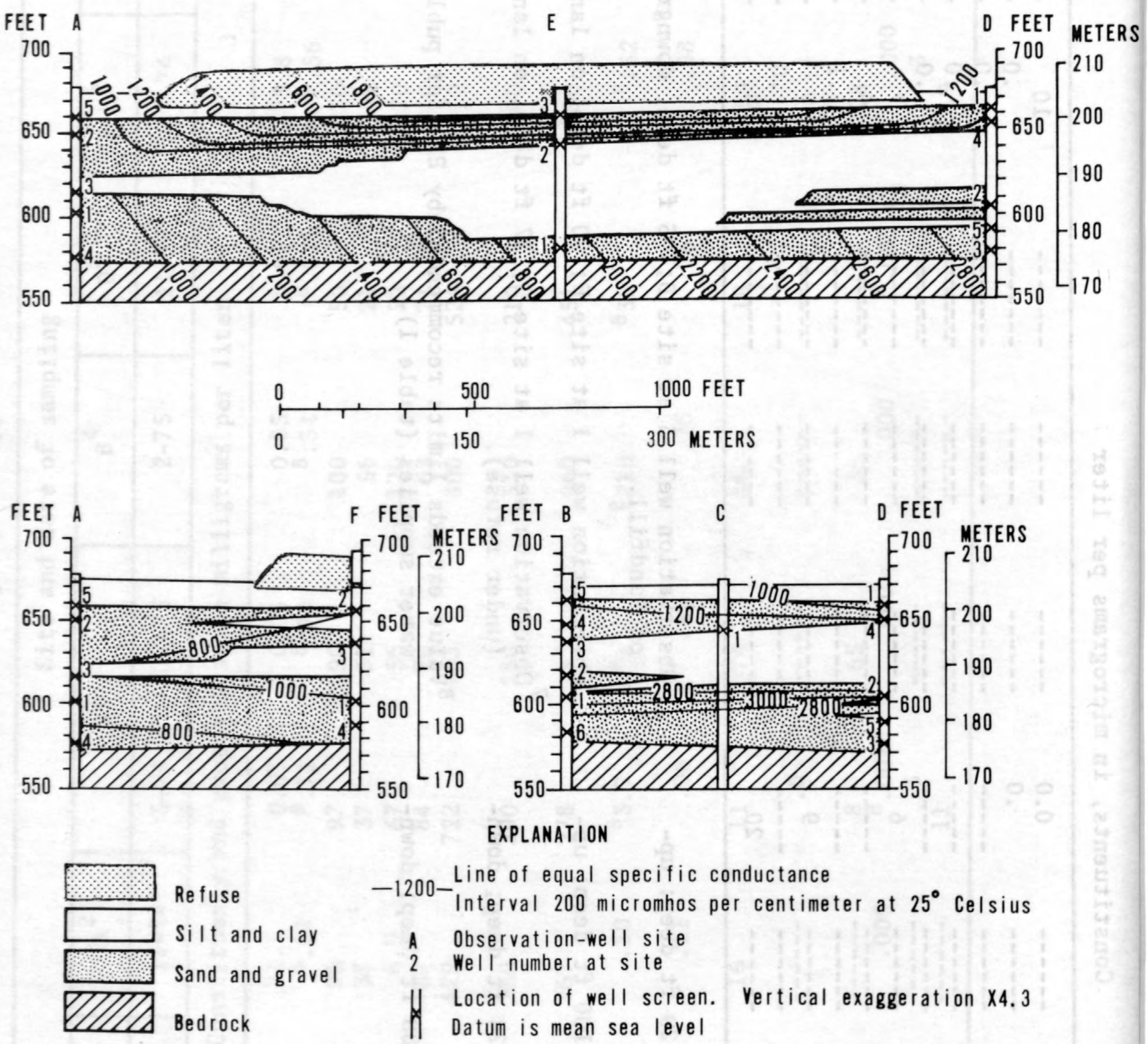


Figure 21.-- Sections showing distribution of specific conductance in landfill area at 2561 Kentucky Avenue, October 1974.

The landfill is a former gravel pit that filled with water before the late 1960's when it was drained and designated as a landfill for receiving domestic, commercial, and industrial types of solid waste. The pit area was enlarged at this time, and the earth material (sandy loam soil) that was removed was piled along the perimeter of the landfill. The earth material was later used to cover the refuse during landfill operations. The refuse was usually left exposed for a period of time before covering was applied.

The landfill was closed near the end of 1973 and was covered with additional soil. The surface is now near the original altitude of 680 ft. Approximately 3.6x10 yd^3 of refuse has been buried in the landfill. The surface of the landfill has been landscaped and has been seeded to grass.

Aquifers and Data-Collection Network

Twenty-five observation wells, constructed at eight sites (fig. 22), were used to establish the ground-water flow system and to monitor the water quality in the unconsolidated material at the landfill. Six of the sites are on or near the perimeter of the landfill, and two sites are on the fill. A gravel pack was placed around the screen of each well in the fill. Several observation wells, constructed north of the landfill area for another study, were used to help establish the ground-water gradient in the landfill area. A surface-water-quality site, S-1, was established on a small lake (former gravel pit) south of the landfill.

Unconsolidated material around and underlying the fill consists primarily of poorly sorted sands and gravels. The sands and gravels are divided into two aquifers of nearly equal thickness by a thin but nearly continuous layer of clay (fig. 23). Refuse lies in the zone of the shallow aquifer and overlies the deep aquifer. Because the clay layer is thin in most places, and is absent along the east side of the landfill area, the two aquifers can be considered hydrologically as one. Depth to limestone bedrock ranges from 80 to 90 ft.

Water Movement

Topography, direction of stream flow, and natural points of discharge indicate that the ground-water gradient in the landfill area is toward the southeast. However, water-level measurements show that the gradient is toward the north. This change in direction is due to drawdowns caused by pumping at two industrial well fields directly north of the landfill. Pumping at these well fields not only draw water from the landfill area but also may draw recharge from the White River, which may subsequently pass under the fill area to the pumping centers.

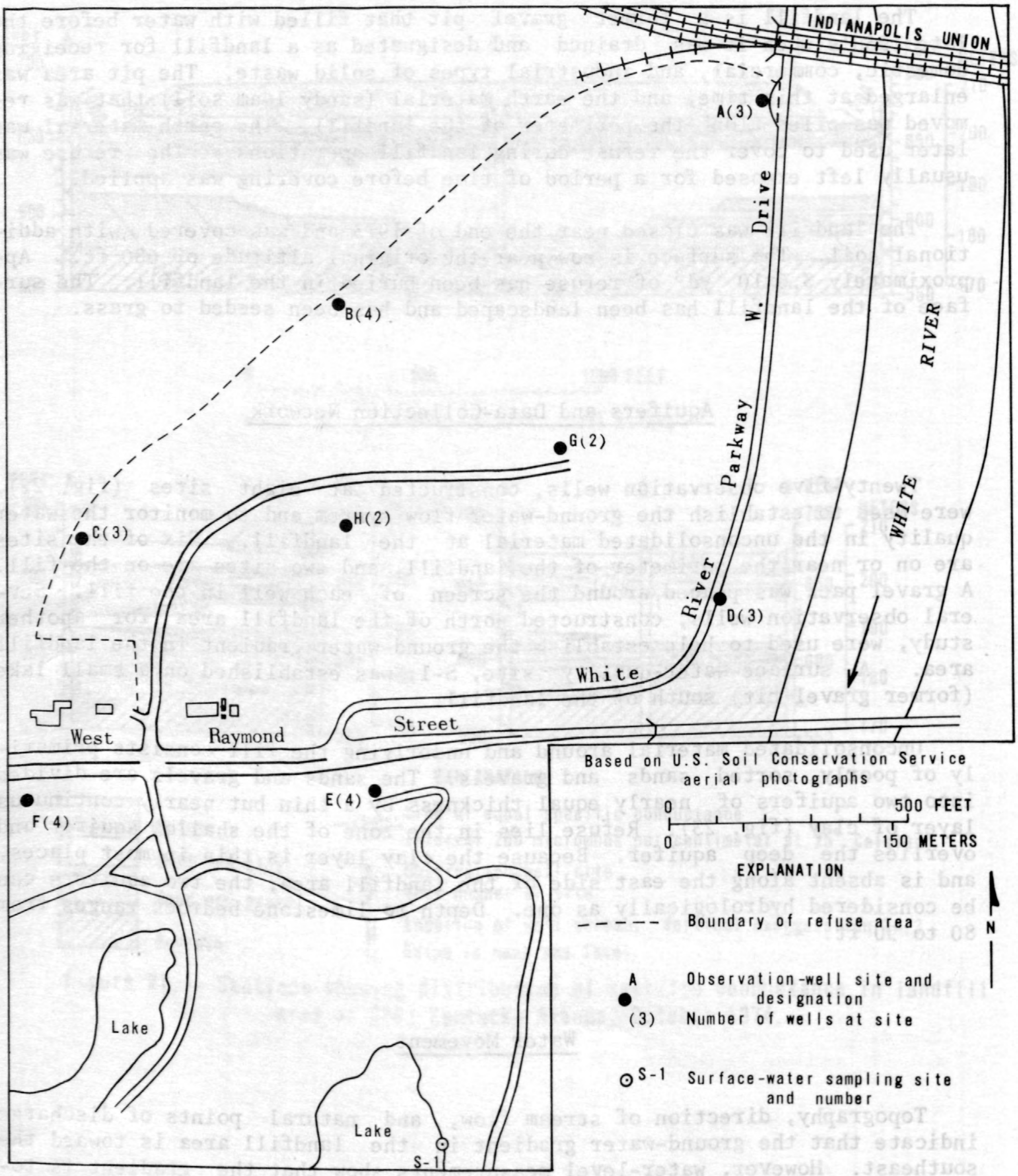


Figure 22.-- Location of well sites in landfill area at 800 West Raymond Street.

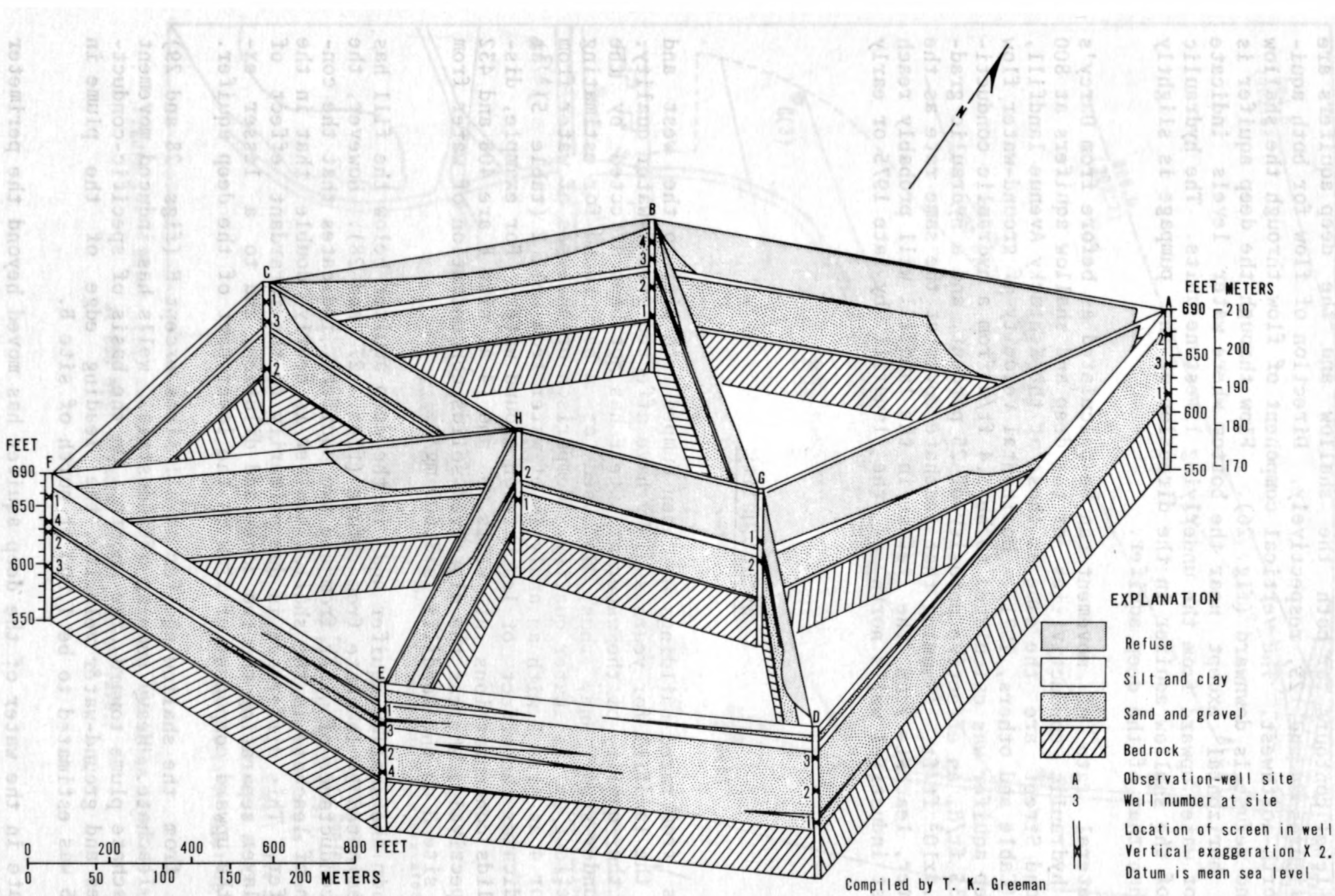


Figure 23.-- Stratigraphy and well-screen locations in landfill area at 800 West Raymond Street.

Water-level contours for both the shallow and the deep aquifers are shown in figures 24 and 25, respectively. Direction of flow for both aquifers is north-northwest. The vertical component of flow through the shallow aquifer and refuse is downward (fig. 26). Flow through the deep aquifer is virtually horizontal except near the bottom where water levels indicate movement of water upward from the underlying limestone units. The hydraulic gradient of the shallow aquifer in the direction of the pumpage is slightly greater than that of the deep aquifer.

The lateral rate of movement can be calculated as before from Darcy's law. The hydraulic conductivities of the deep and shallow aquifers at 800 West Raymond Street are the same as those at the Kentucky Avenue landfill, 335 ft/d (Cable and others, 1971). Horizontal velocity of ground-water flow in the deep aquifer was calculated to be 3.4 ft/d from a hydraulic conductivity of 335 ft/d, an effective porosity of 25 percent, and a hydraulic gradient of 2.4×10^3 ft/ft. Assuming that leachate moves at the same rate as the ground water, leachate from the refuse in the landfill will probably reach the nearest industrial wells north of the landfill by late 1975 or early 1976.

Water Quality

Debris from razed buildings has been dumped into pits to the west and south of the landfill for years and may have affected ground-water quality. However, the quality of the water at site F has not been affected by the landfill under study and, thus, is used as a background for estimating leachate effect on the water quality. Comparison of analyses of water from wells 3 or 4 at site F with an analysis of water from well 2 (table 5) at site H indicates the effect of leachate on ground water. For example, dissolved-solids concentrations at wells 3 and 4 at site F are 408 and 432 mg/L, respectively, whereas the dissolved-solids concentration of water from well 2 at site H on the landfill is 8,600 mg/L.

Water in the shallow aquifer and in the deep aquifer below the fill has been contaminated by leachate from refuse (figs. 27 and 28). However, the specific conductance of water from the two aquifers indicates that the concentration of leachate in the shallow aquifer is nearly double that in the deep aquifer. This difference is due primarily to the retardant effect of the clay layer separating the two zones and dilution, and to a lesser extent, to the upward component of flow in the lower part of the deep aquifer.

Water from the shallow aquifer at all sites except F (figs. 28 and 29) contained leachate. Heavy pumping of industrial wells has induced movement of the leachate plume toward the north. On the basis of specific-conductance values and ground-water velocity, the leading edge of the plume in March 1975 was estimated to be 1,500 ft north of site B.

Leachate in the water of the deep aquifer has moved beyond the perimeter of the refuse at sites B (north) and E (south) (fig. 28). Several times

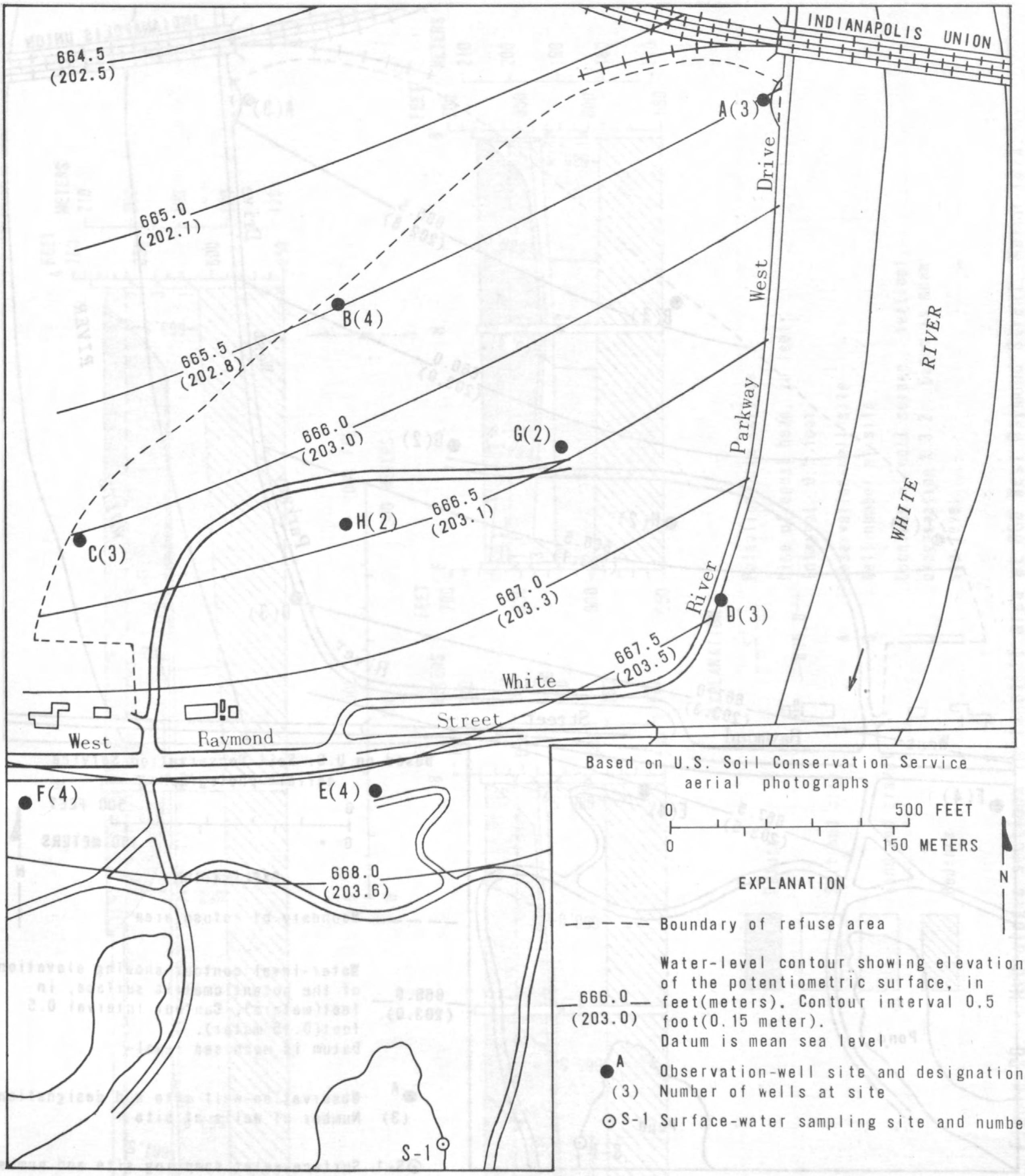


Figure 24.-- Water-level contours in the shallow aquifer below landfill area at 800 West Raymond Street, March 1975.

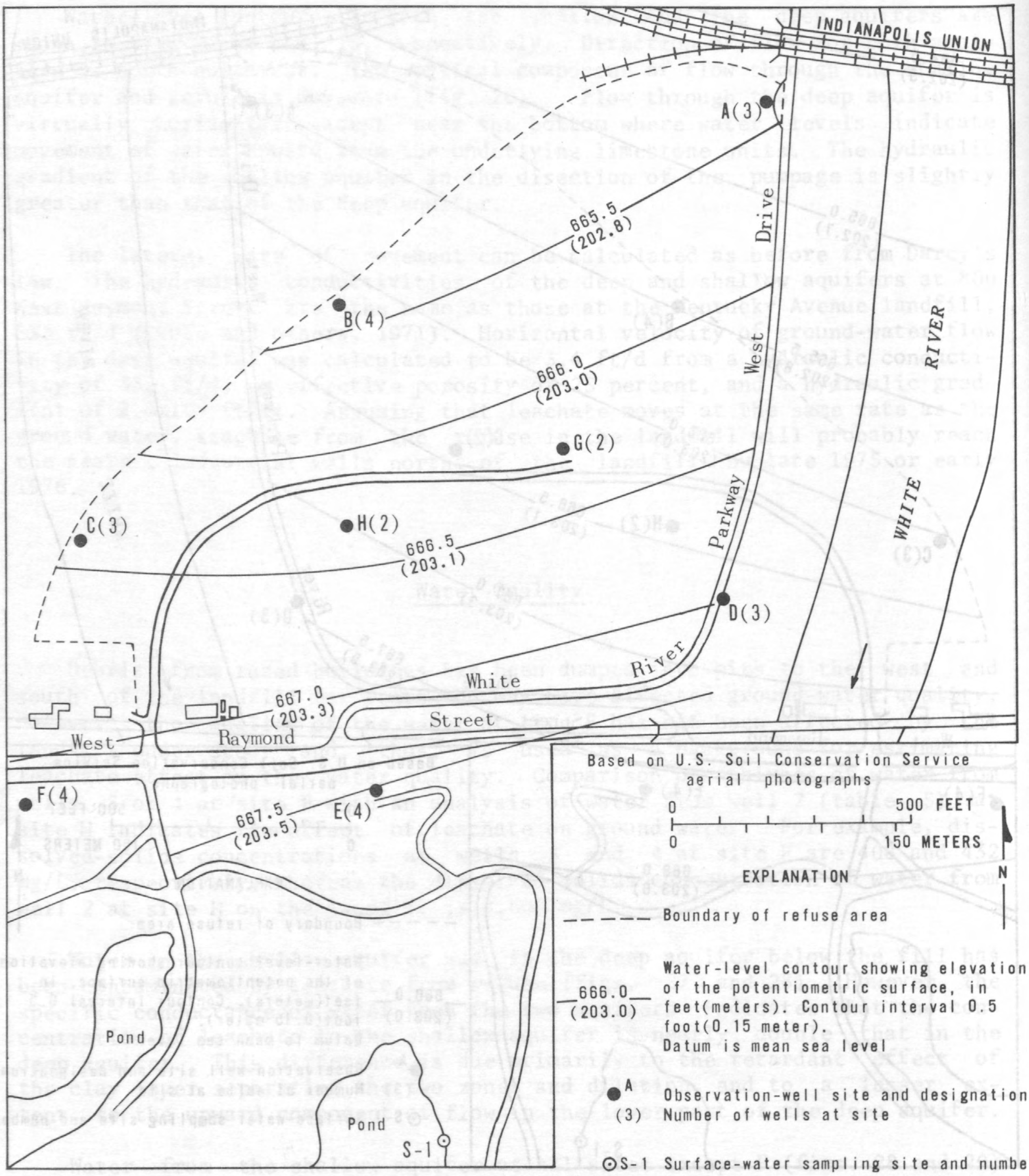


Figure 25.-- Water-level contours in the deep aquifer below landfill area at 800 West Raymond Street, March 1975.

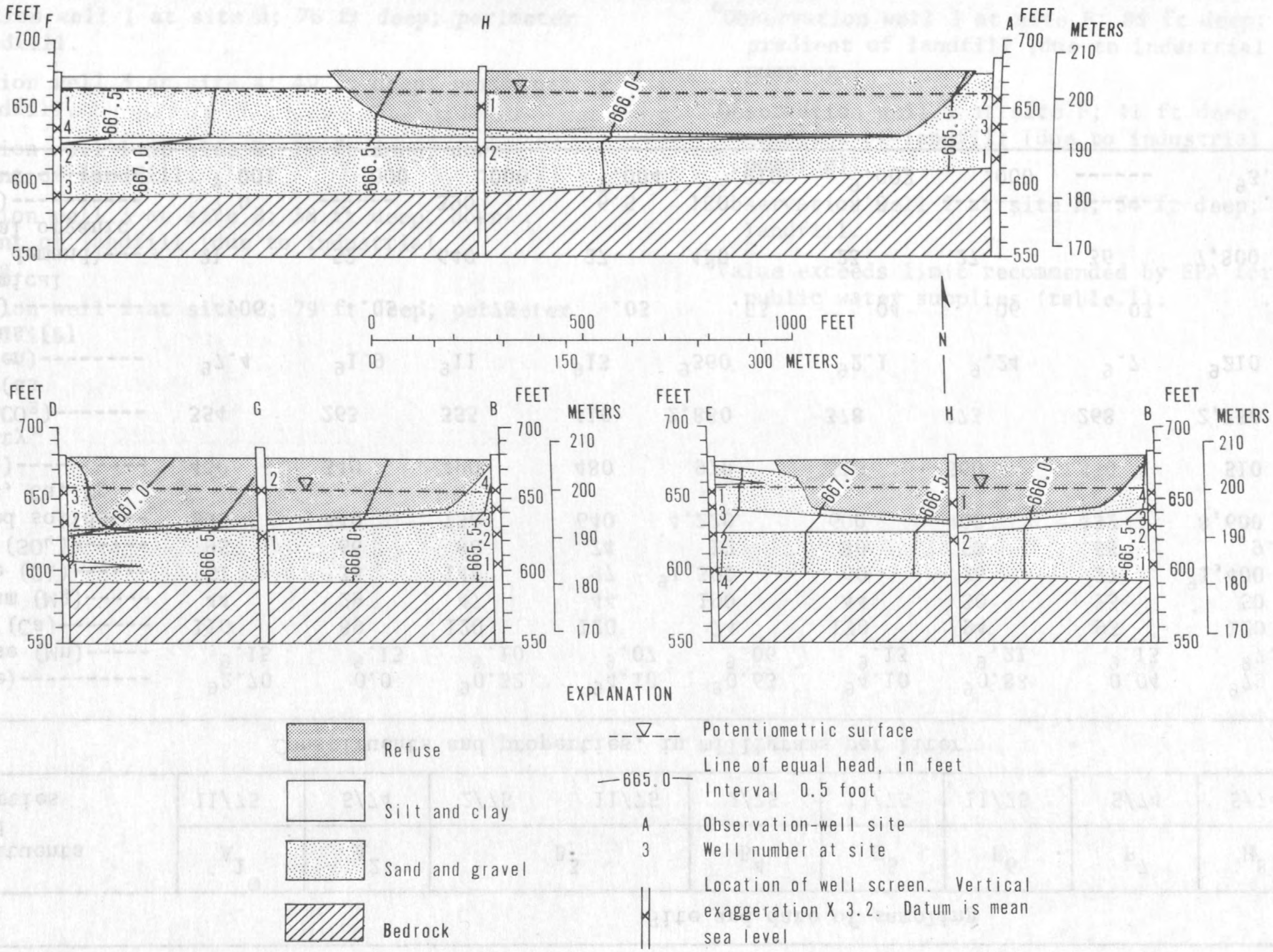


Figure 26.-- Hydrologic sections in landfill area at 800 West Raymond Street, March 1975.

Table 5.--Analyses of water from selected sites on or near landfill at 800 West Raymond Street

[Analyses by U.S. Geological Survey]

Constituents and properties	Site and date of sampling								
	A[1]	A[2]	B[3]		B[4]	C[5]	F[6]	F[7]	H[8]
	11/75	5/74	2/75	11/75	2/75	11/75	11/75	5/74	5/74
	Constituents and properties, in milligrams per liter								
Iron (Fe)----------	[9]2.70	0.0	[9]0.32	[9]4.10	[9]0.63	[9]4.10	[9]0.88	0.04	[9]79
Manganese (Mn)-----	[9].15	[9].13	[9].10	[9].07	[9].06	[9].13	[9].21	[9].13	[9]7.5
Calcium (Ca)-------	110	89	120	120	74	130	94	93	120
Magnesium (Mg)-----	44	29	47	44	190	44	30	23	50
Chloride (Cl)------	51	38	140	97	[9]1,300	60	26	27	[9]1,400
Sulfate (SO_4)------	95	66	88	74	12	80	53	55	9.7
Dissolved solids---	595	440	736	640	4,220	600	408	432	8,600
Hardness, Ca, Mg (total)----------	460	340	490	480	970	510	360	330	510
Alkalinity (as $CaCO_3$)-------	354	263	353	410	2,880	378	273	268	2,730
Ammonia (as nitrogen)--------	[9]7.4	[9]1.9	[9]11	[9]13	[9]360	[9]2.1	[9].24	[9].7	[9]210
Phosphorus (P) (total)----------	.06	.05	.73	.05	.53	.04	.06	.03	.18
COD (chemical oxygen demand)---	21	52	640	27	410	23	27	36	7,800
TOC (total organic carbon)----------	7.0	------	390	6.5	180	8.8	------	------	.73
Phenols------------	[9].001	.000	.000	[9].004	[9].010	[9].002	.000	------	[9]3.0

[1]Observation well 1 at site A; 76 ft deep; perimeter of landfill.

[2]Observation well 3 at site A; 49 ft deep; perimeter of landfill.

[3]Observation well 1 at site B; 77 ft deep; down-gradient of landfill.

[4]Observation well 3 at site B; 38 ft deep; down-gradient of landfill (due to industrial pumping.

[5]Observation well 2 at site C; 79 ft deep; perimeter of landfill.

[6]Observation well 3 at site F; 85 ft deep; up-gradient of landfill (due to industrial pumping.

[7]Observation well 4 at site F; 41 ft deep; up-gradient of landfill (due to industrial pumping).

[8]Observation well 2 at site H; 34 ft deep; on landfill.

[9]Value exceeds limit recommended by EPA for public water supplies (table 1).

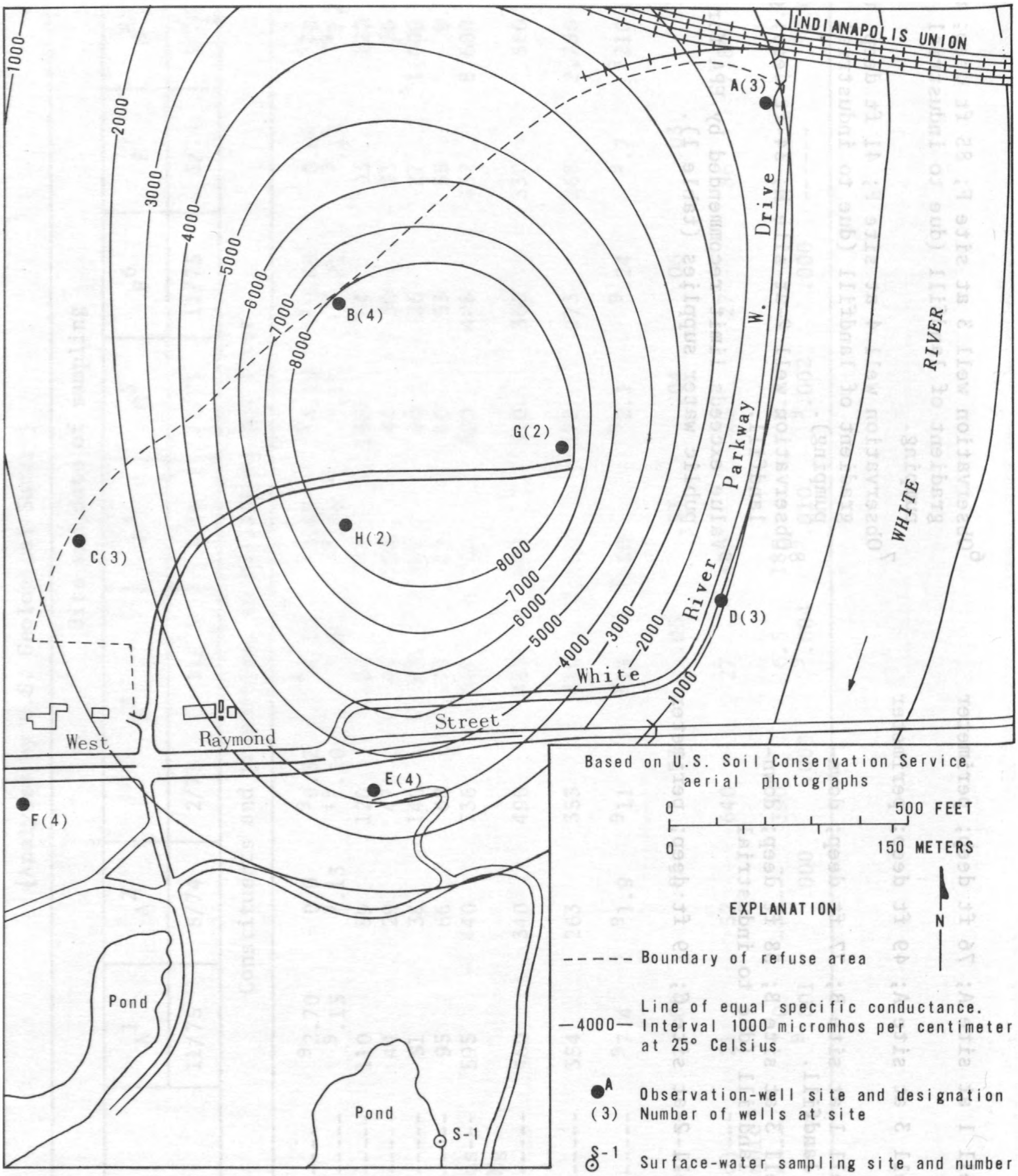


Figure 27.-- Specific conductance of water in the shallow aquifer below landfill area at 800 West Raymond Street, March 1975.

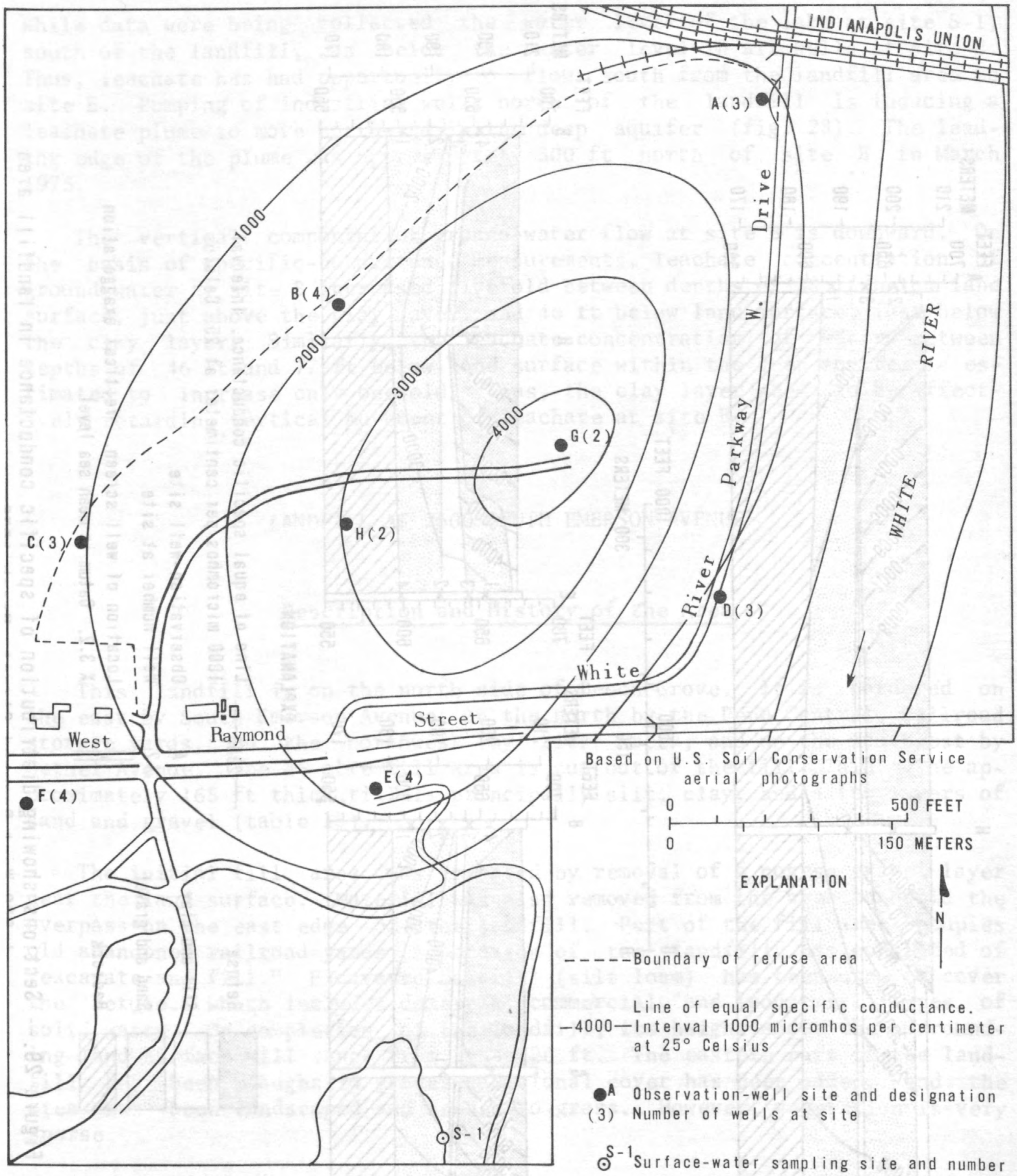


Figure 28.-- Specific conductance of water in the deep aquifer below landfill area at 800 West Raymond Street, March 1975.

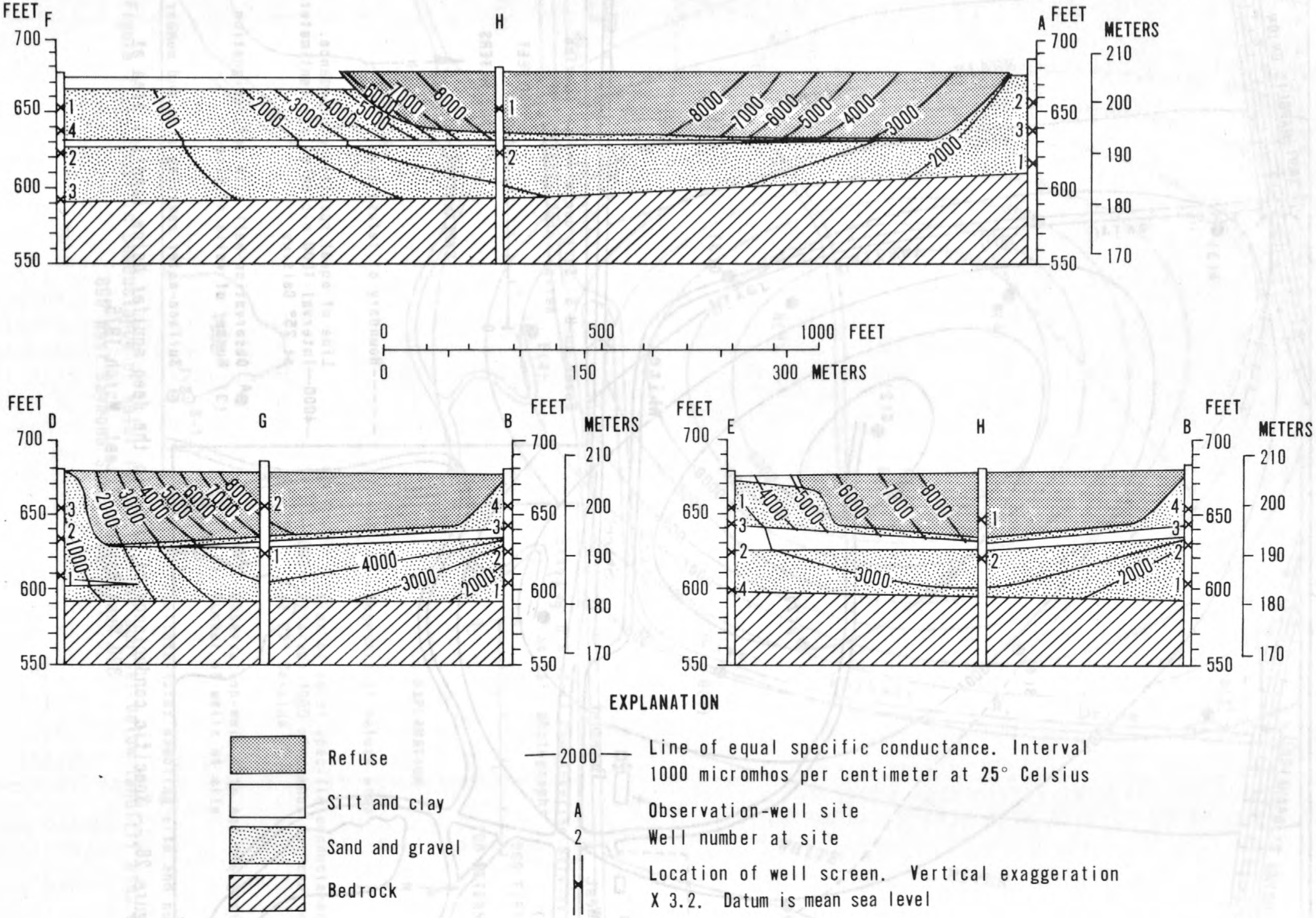


Figure 29.-- Sections showing distribution of specific conductance in landfill area at 800 West Raymond Street, March 1975.

while data were being collected the water level of the lake at site S-1, south of the landfill, was below the water level in all wells at site E. Thus, leachate has had opportunity to flow south from the landfill area to site E. Pumping of industrial wells north of the landfill is inducing a leachate plume to move northward in the deep aquifer (fig. 28). The leading edge of the plume was approximately 300 ft north of site B in March 1975.

The vertical component of ground-water flow at site B is downward. On the basis of specific-conductance measurements, leachate concentration of ground water at site B increased fivefold between depths of 38 ft below land surface, just above the clay layer, and 46 ft below land surface, just below the clay layer. Similarly, the leachate concentration of water between depths of 46 ft and 77 ft below land surface within the deep aquifer is estimated to increase only onefold. Thus, the clay layer seems to be effectively retarding vertical movement of leachate at site B.

LANDFILL AT 2600 SOUTH EMERSON AVENUE

Description and History of the Area

This landfill is on the north side of Beech Grove. It is bordered on the east by South Emerson Avenue, on the north by the Penn Central Railroad storage yards, on the northwest by Lick Creek, and on the southwest by Bethel Avenue. The 45-acre fill area is cut out of the till plain. The approximately 165 ft thick till is principally silt, clay, and a few layers of sand and gravel (table 13).

The initial fill area was created by removal of a coarse gravel layer near the land surface. Material was also removed from the area to build the overpass on the east edge of the landfill. Part of the fill area occupies old abandoned railroad yards. Operation of the landfill has consisted of "excavate and fill." Excavated material (silt loam) has been used to cover the refuse, which includes domestic, commercial, and industrial types of solid waste. On completion of the landfill, its height above the surrounding land surface will range from 15 to 20 ft. The eastern part of the landfill has been brought to grade, additional cover has been added, and the area has been landscaped and seeded to grass. However, vegetation is very sparse.

The landfill was scheduled to reach capacity by the end of 1975. If the schedule is met, approximately $1x10^6$ yd^3 of refuse will have been buried at the landfill by that time.

Aquifers and Data-Collection Network

Nineteen observation wells were constructed at eight sites around and on the landfill (fig. 30). Because the regional ground-water gradient was assumed to be west toward White River and the local gradient northwest toward Lick Creek, wells were constructed at site G for upgradient sampling and at sites C and D for downgradient sampling. A well was constructed in nearly every sand and gravel layer penetrated at sites A, B, E, and F, which are on the perimeter of the landfill. Gravel-packed wells were constructed in and at the base of the refuse at site H to obtain leachate samples and determine if ground-water mounding occurs. A surface-water sampling site (S-1) was established on Lick Creek just upstream of the discharge ditch from Jones Chemical Company.

The landfill area is underlain by till containing both continuous and discontinuous sand and gravel layers. These sparse and usually very thin layers are separated by thick expanses of clay-dominant material (fig. 31). Production from the sand and gravel aquifers that were penetrated during test drilling is very low. Thus, the limestone aquifer underlying the till is needed as a source of water for some industries.

Water Movement

The original topography of the landfill area was dish-shaped on three sides: highest along the east, northeast, and southwest sides; low through the middle; and lowest along the northwest side at the creek. The decrease in altitude from Emerson Avenue to Lick Creek is 30 ft. Because landfilling has changed the topography, overland flow is now away from the fill area to drainage ways that eventually carry it to Lick Creek.

Depth to water ranged from 10 ft in a shallow well at site D to 80 ft in a deep well at site G. Water levels fluctuated annually from 2 ft in a shallow well to 10 ft in a deep well. Head difference between the deep and the shallow wells was approximately 55 ft.

The water-level configuration for both the deep and the shallow aquifers is shown in figures 32 and 33, respectively. Flow in the shallow aquifer is toward Lick Creek. Although ground-water mounding is apparent, its effect on water flow in the shallow aquifer is limited to a very small area near site H and does not change the general flow pattern. Flow in the deep aquifer is toward the southwest, which is the general direction of the regional gradient of the area. The vertical component of flow in both the shallow and the deep aquifers is downward (fig. 34).

The measured vertical hydraulic gradient was 0.76 ft/yr in a positive direction downward. Thus, assuming values of vertical hydraulic conductivity and effective porosity equal to those discussed for the landfill at the 96th Street and Zionsville Road, one finds that the potential vertical rate

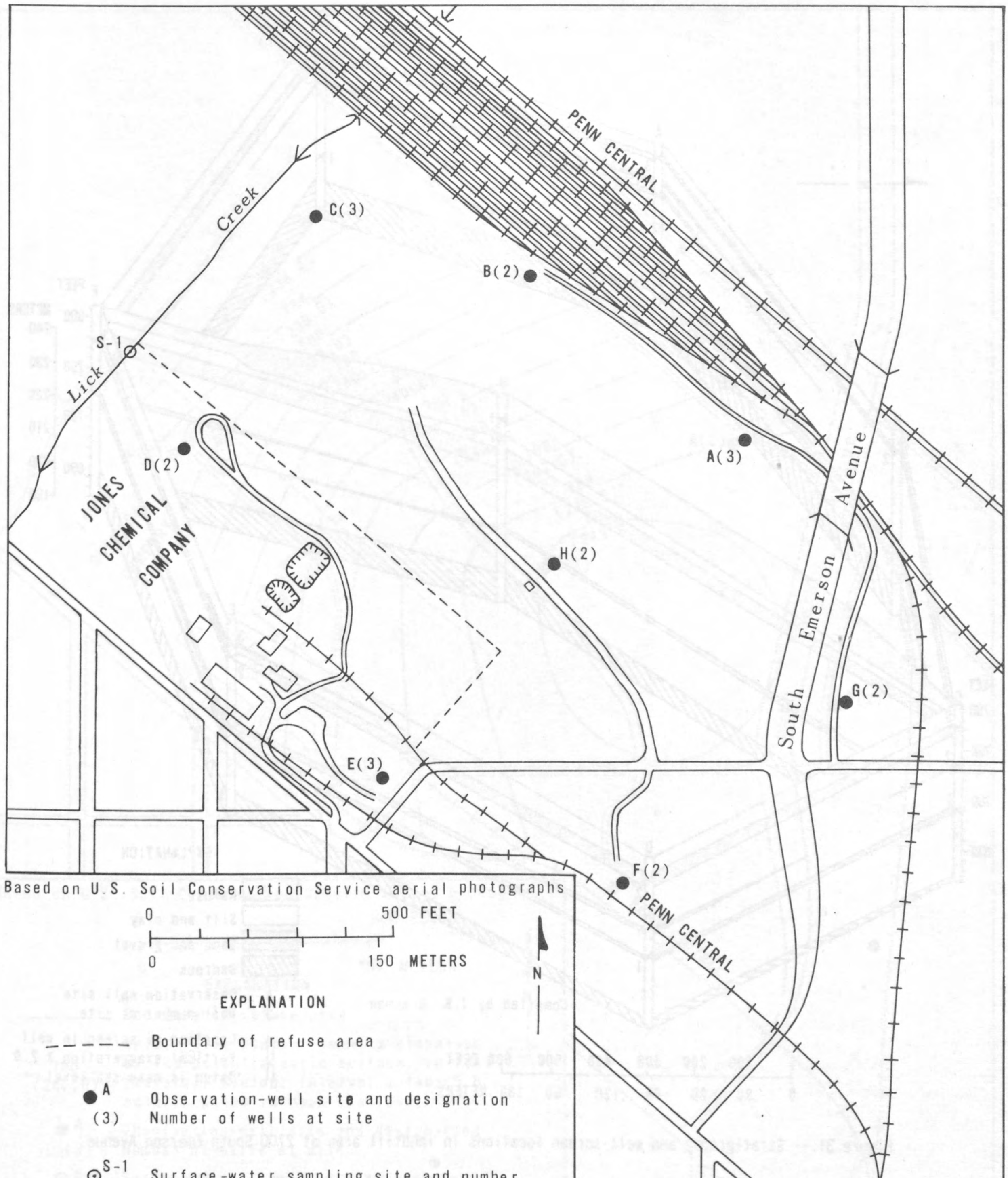


Figure 30.-- Location of well sites in landfill area at 2700 South Emerson Avenue.

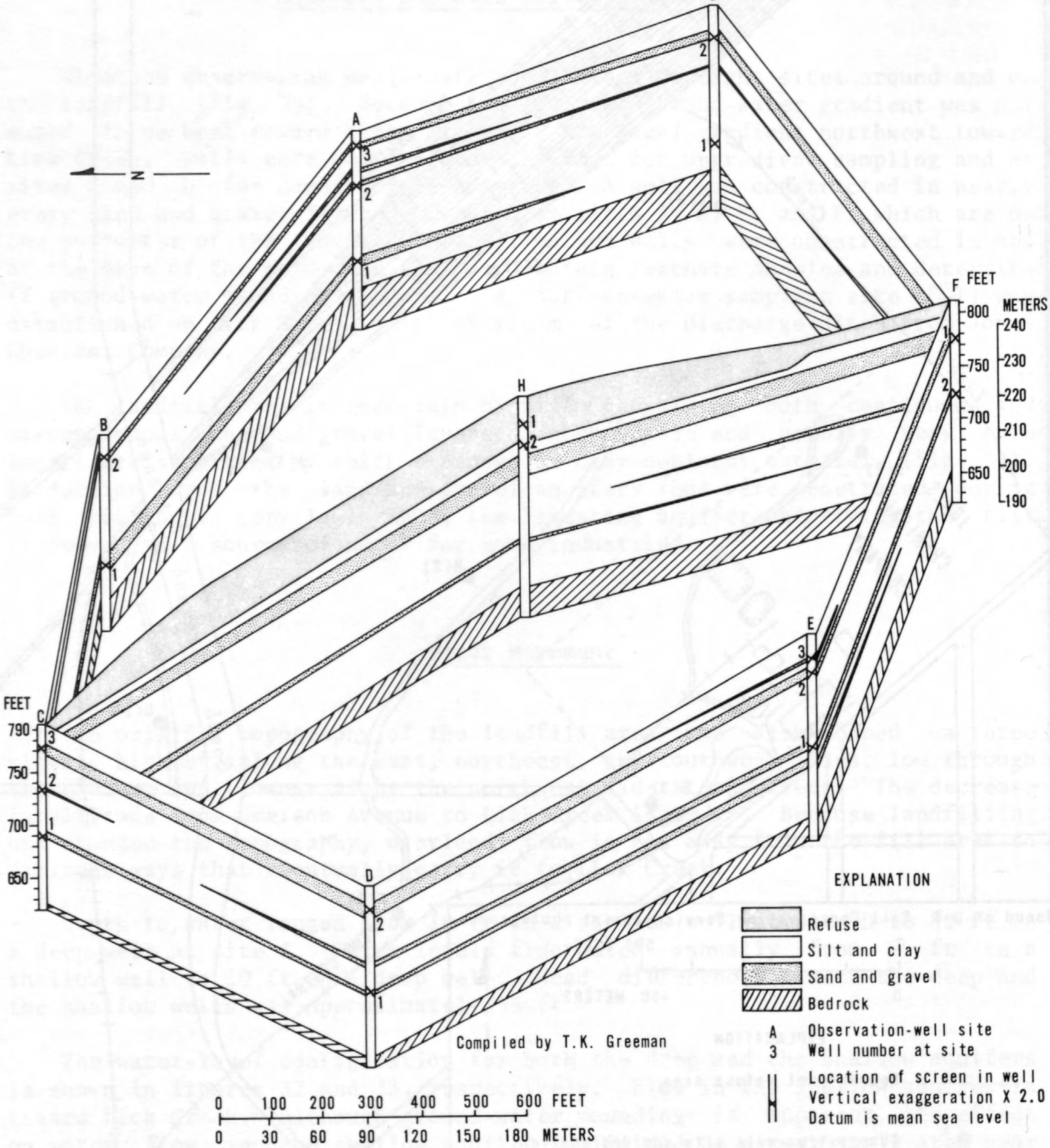


Figure 31.-- Stratigraphy and well-screen locations in landfill area at 2700 South Emerson Avenue.

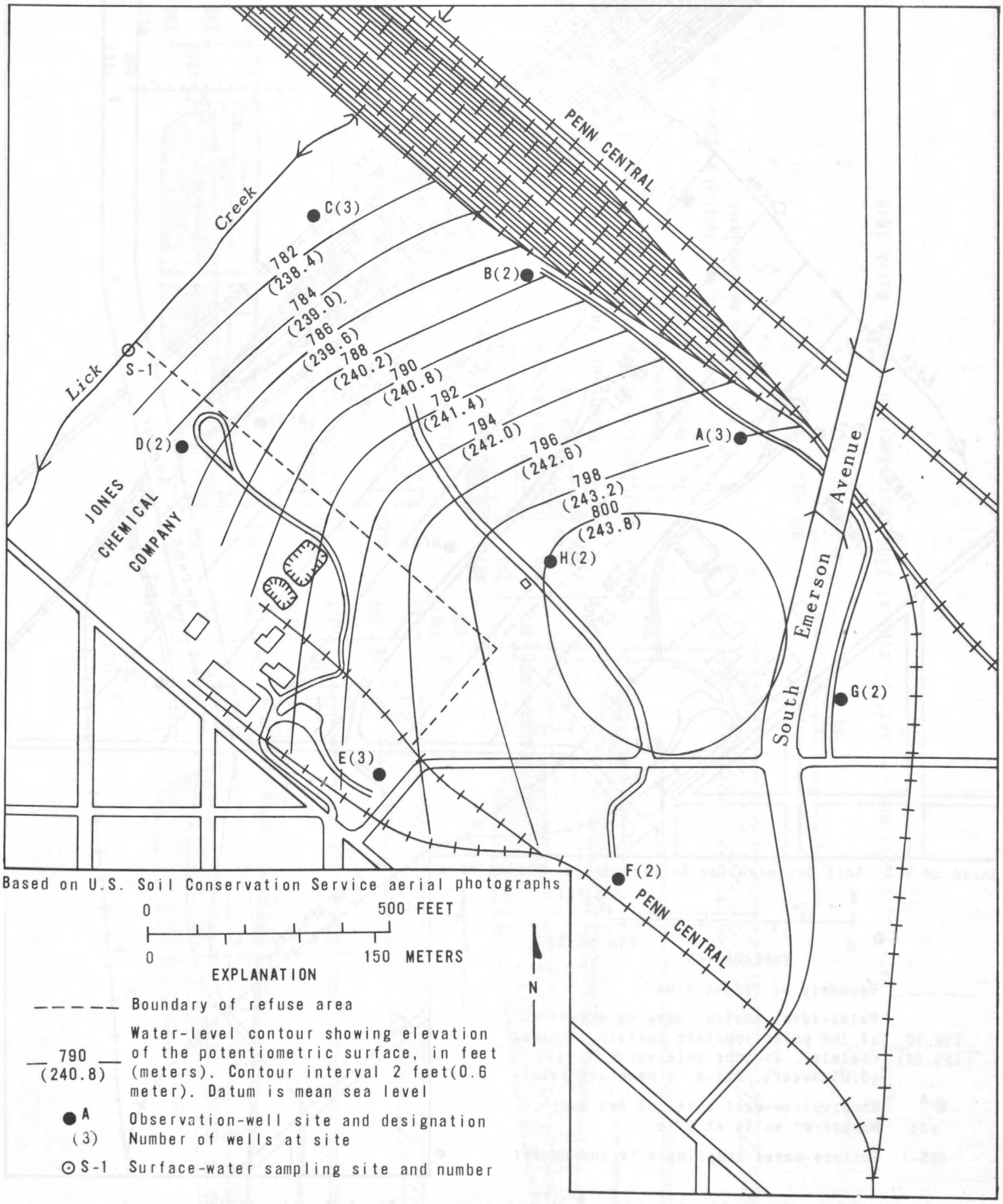


Figure 32.-- Water-level contours in the shallow aquifer below landfill area at 2700 South Emerson Avenue, March 1975.

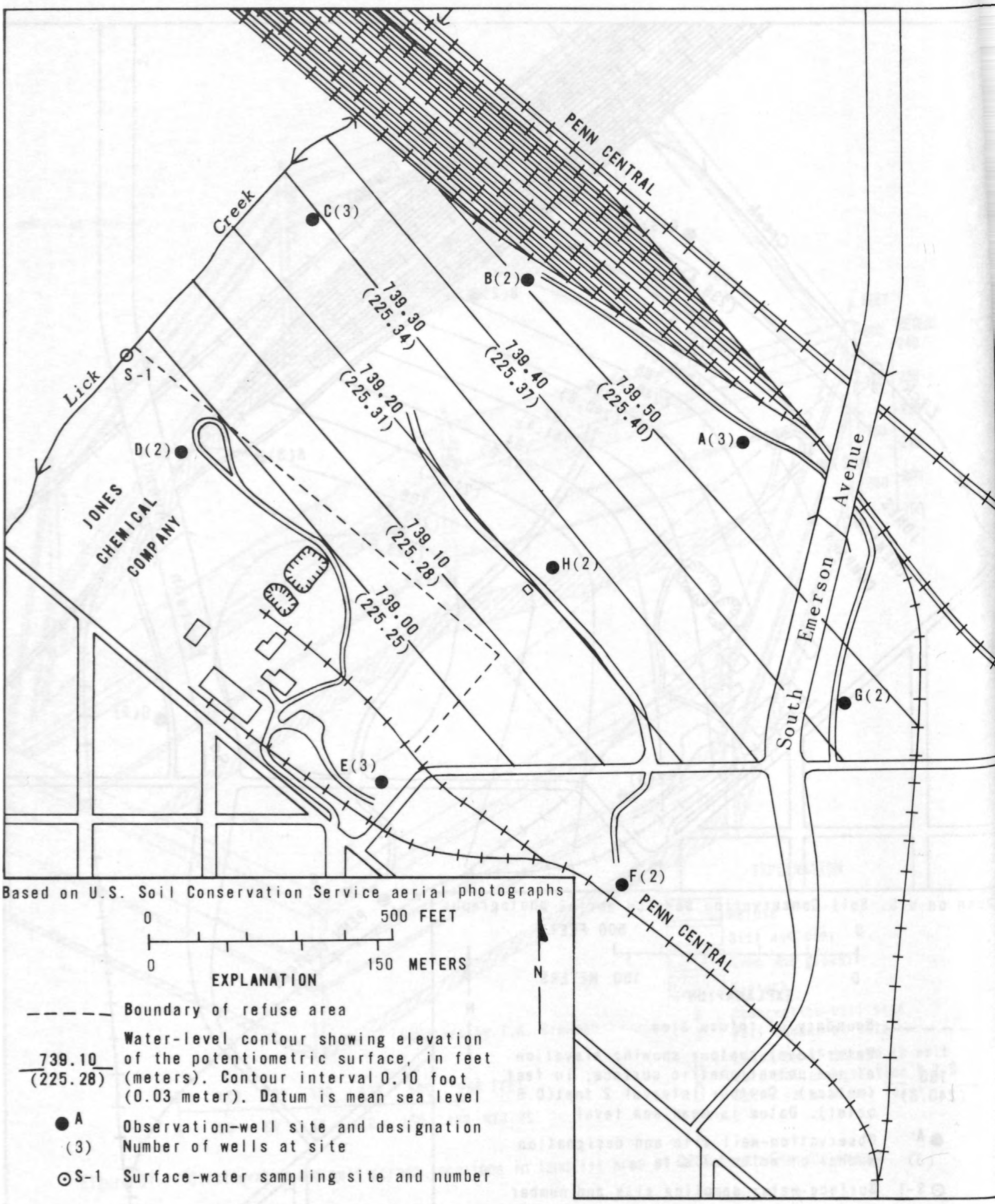


Figure 33.-- Water-level contours in the deep aquifer below landfill area at 2700 South Emerson Avenue, March 1975.

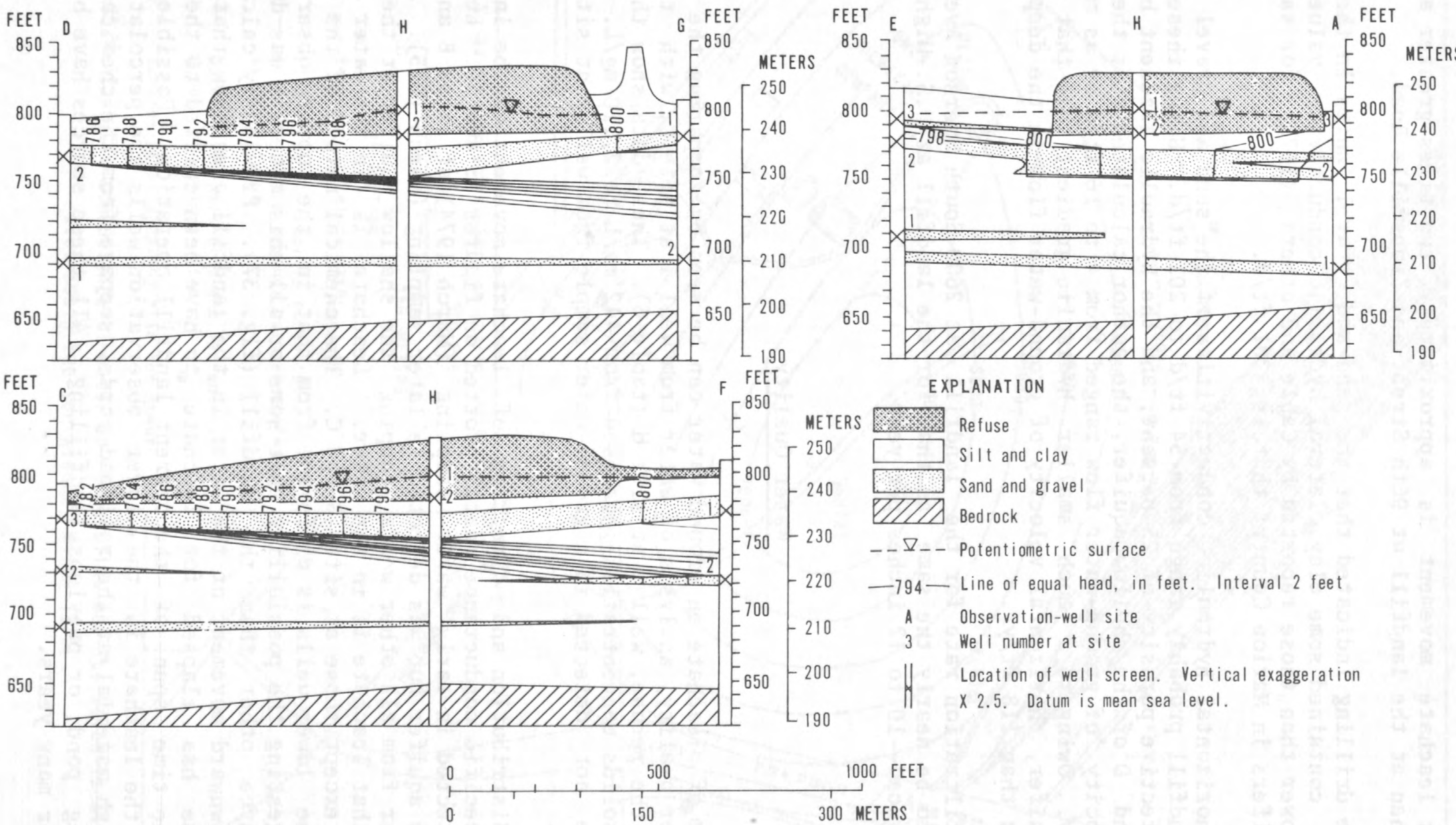


Figure 34.-- Hydrologic sections in landfill area at 2700 South Emerson Avenue, March 1975.

of water or leachate movement is approximately two times greater at this landfill than at the landfill at 96th Street and Zionsville Road.

Because drilling indicated that the sand and gravel units in the landfill area contained some clay, lateral hydraulic conductivity values are probably lower than those reported by Cable and others (1971) for sand and gravel aquifers in Marion County; that is, 201 ft/d.

Thus, horizontal hydraulic conductivities of the sand and gravel layers at the landfill probably range from 54 ft/d to 201 ft/d. Using these values, an effective porosity of 25 percent, and the hydraulic gradient between sites H and D of the shallow aquifer, the author calculated that the horizontal velocity of ground-water flow ranged from 4 to 16 ft/d or as much as 5,690 ft/yr. Owing to a much smaller hydraulic gradient than that of the shallow aquifer, horizontal velocity of ground-water flow in the deep aquifer is less than 118 ft/yr.

The infiltration rate for the landfill at 2600 South Emerson Avenue is estimated to be nearly the same as that for the landfill at U.S. Highway 52 and Senour Road--10 to 12 inches per year.

Water Quality

Effect of leachate on ground water can be seen by comparing the background water quality, analysis of water from well 1 at site C, with that of water from the refuse, well 2 at site H (table 6). These data show that the dissolved-solids concentration increased from 442 mg/L to 2,110 mg/L. Pesticides were not detected in a ground-water sample from well 2 at site H in March 1974.

Areal distribution and direction of leachate movement can be inferred from the specific conductance data plotted on figures 35 and 36. Leachate was not detected in early water sampling (March 1974) at sites B and C in the shallow aquifer but was detected in later sampling (March 1975). Analyses of water from all other wells tapping the shallow aquifer at the landfill show that leachate is in the water. Leachate is in the water of all deep wells except those at sites B and C. The chemical nature of the leachate in the lower wells is different from that in the upper observation wells, suggesting the possibility that some or all this material was derived from a source other than the landfill (fig. 37). Previously calculated rates of downward movement of the water in the landfill area show that sufficient time has elapsed for leachate to have been carried to the lower wells in the time span of the current landfill operation. Possible other sources of the leachate in the lower observation wells are percolation of water through material at the railroad yards, seepage from the chemical company holding pond, or previous landfilling. All these sources have been in the area for many years.

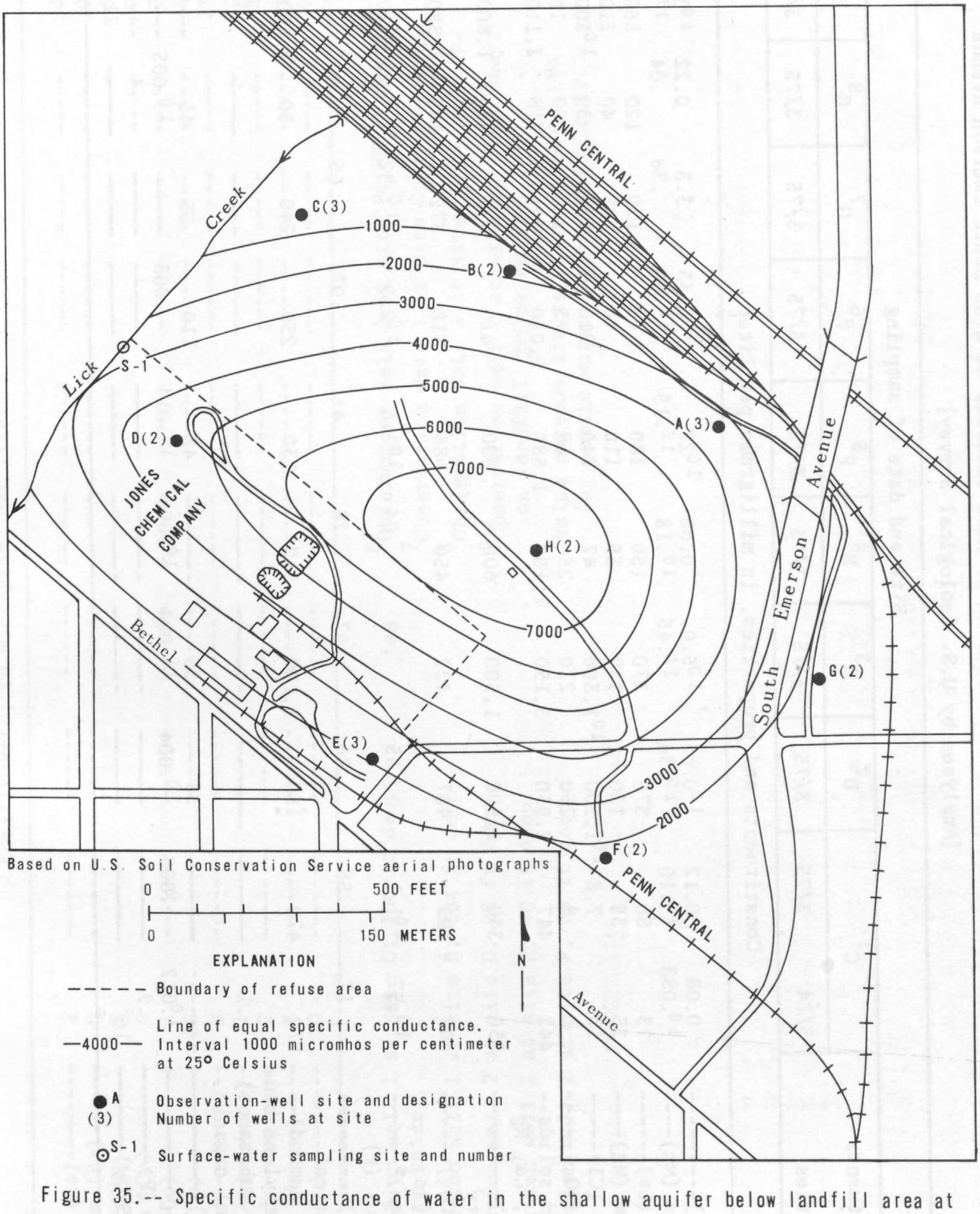


Figure 35.-- Specific conductance of water in the shallow aquifer below landfill area at 2700 South Emerson Avenue, March 1975.

Table 6.--Analyses of water from selected sites on or near landfill at 2700 South Emerson Avenue

[Analyses by U.S. Geological Survey]

Constituents and properties	Site and date of sampling									
	C[1]		D[2]	D[3]	E[4]	F[5]	F[6]	G[7]	G[8]	H[9]
	3/74	3/75	3/75	3/75	3/75	3/75	3/75	3/75	3/75	3/74
Constituents and properties, in milligrams per liter										
Iron (Fe)---------	0.08	0.12	[10]0.63	[10]5.0	0.06	[10]22	[10]0.33	3.3	0.22	[10]3.6
Manganese (Mn)----	[10].083	[10].10	[10].34	[10].45	[10].18	[10].15	[10].08	.38	.04	[10].50
Calcium (Ca)------	73	80	370	370	150	180	85	130	120	360
Magnesium (Mg)----	35	35	130	130	55	110	48	45	40	210
Chloride (Cl)-----	13	7.8	[10]1,100	[10]1,300	47	240	210	120	39	[10]500
Sulfate (SO_4)-----	6	8	250	270	250	68	75	210	200	16
Dissolved solids--	442	447	2,930	3,150	1,100	1,580	1,010	901	718	2,110
Hardness, Ca, Mg (total)---------	330	340	1,500	1,500	600	900	410	510	460	1,800
Alkalinity (as $CaCO_3$)------	409	399	407	422	450	984	518	372	335	1,380
Ammonia (as nitrogen)-------	[10].57	[10]1.1	.05	.49	.04	[10]7.6	[10]2.9	[10].82	.15	[10]10
Phosphorus (P) (total)---------	.17	.58	.76	.67	.28	.41	.97	.65	.47	.54
COD (chemical oxygen demand)--	570	470	150	1,100	310	130	250	240	50	3,800
MBAS (methylene blue active substance)	.1	-------	--------	-------	-------	------	------	-----	-----	[10].6
TOC (total organic carbon)----------	------	-------	33	55	-------	45	110	55	15	------
Phenols------------	[10].012	[10].005	[10].004	[10].004	[10].006	[10].014	.003	-----	[10].005	------
Fluoride (F)--------	.9	-------	------	-------	-------	------	------	-----	.4	------
Silica (SiO_2)-------	16	-------	------	-------	-------	------	------	-----	------	21

Constituents, in micrograms per liter

Arsenic (As)--------	2	-------	------	------	------	------	------	-----	-----	24
Beryllium (Be)------	0	-------	------	------	------	------	------	-----	-----	0
Cadmium (Cd)--------	5	-------	------	------	------	------	------	-----	-----	6
Chromium (Cr)-------	0	-------	------	------	------	------	------	-----	-----	0
Cobalt (Co)---------	1	-------	------	------	------	------	------	-----	-----	7
Copper (Cu)---------	15	-------	------	------	------	------	------	-----	-----	44
Lead (Pb)-----------	8	-------	------	------	------	------	------	-----	-----	23
Silver (Ag)---------	1	-------	------	------	------	------	------	-----	-----	0
Zinc (Zn)-----------	2	-------	------	------	------	------	------	-----	-----	44
Mercury (Hg)--------	5	-------	------	------	------	------	------	-----	-----	1
Nickel (Ni)---------	20	-------	------	------	------	------	------	-----	-----	10

[1]Observation well 1 at site C; 106 ft deep; (native water).

[2]Observation well 1 at site D; 104 ft deep.

[3]Observation well 2 at site D; 28 ft deep.

[4]Observation well 2 at site E; 40 ft deep.

[5]Observation well 1 at site F; 38 ft deep.

[6]Observation well 2 at site F; 87 ft deep.

[7]Observation well 1 at site G; 117 ft deep.

[8]Observation well 2 at site G; 33 ft deep.

[9]Observation well 2 at site H; 46 ft deep; on landfill (below refuse).

[10]Value exceeds limits recommended by EPA for public water supplies (table 1).

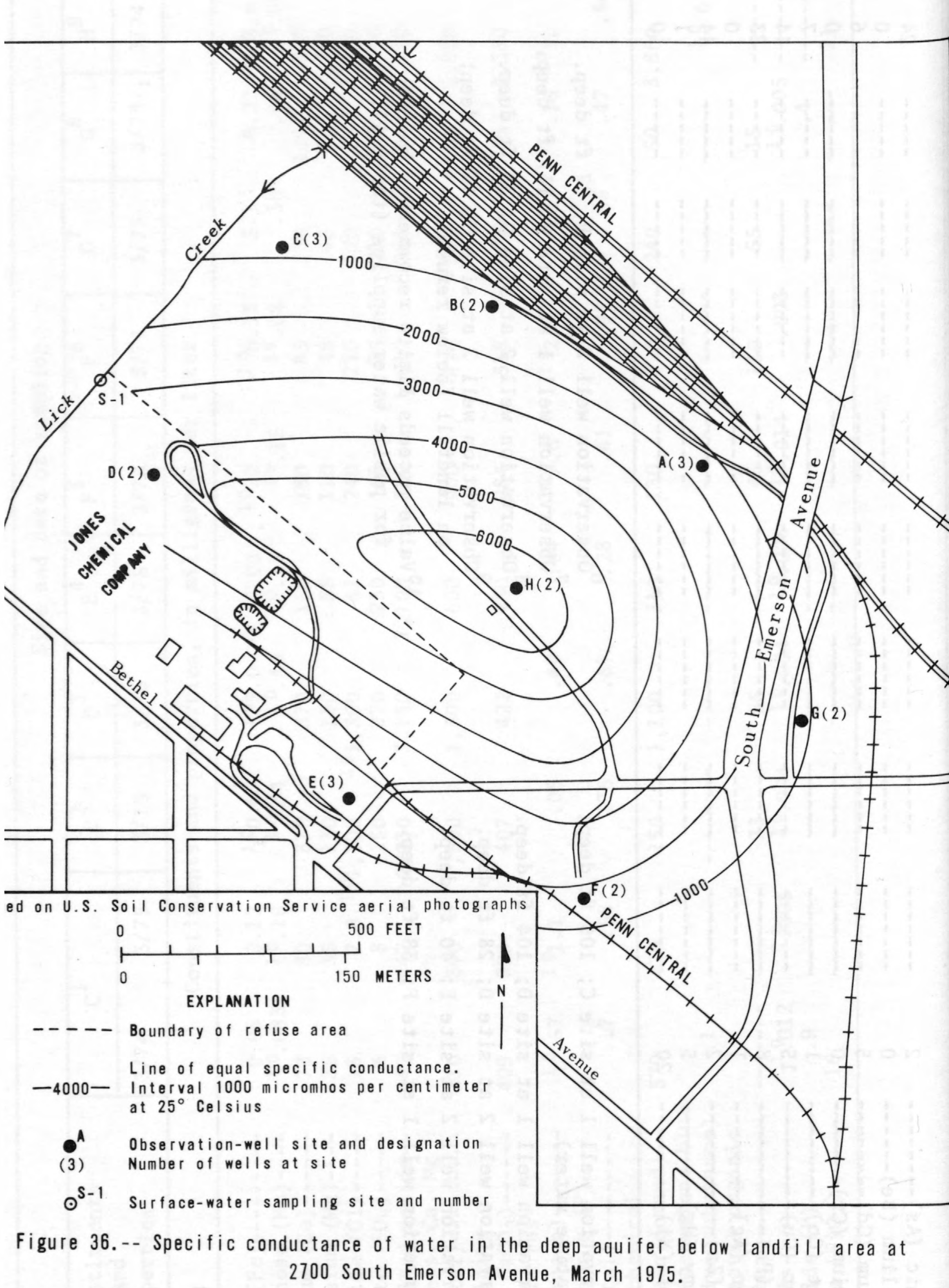


Figure 36.-- Specific conductance of water in the deep aquifer below landfill area at 2700 South Emerson Avenue, March 1975.

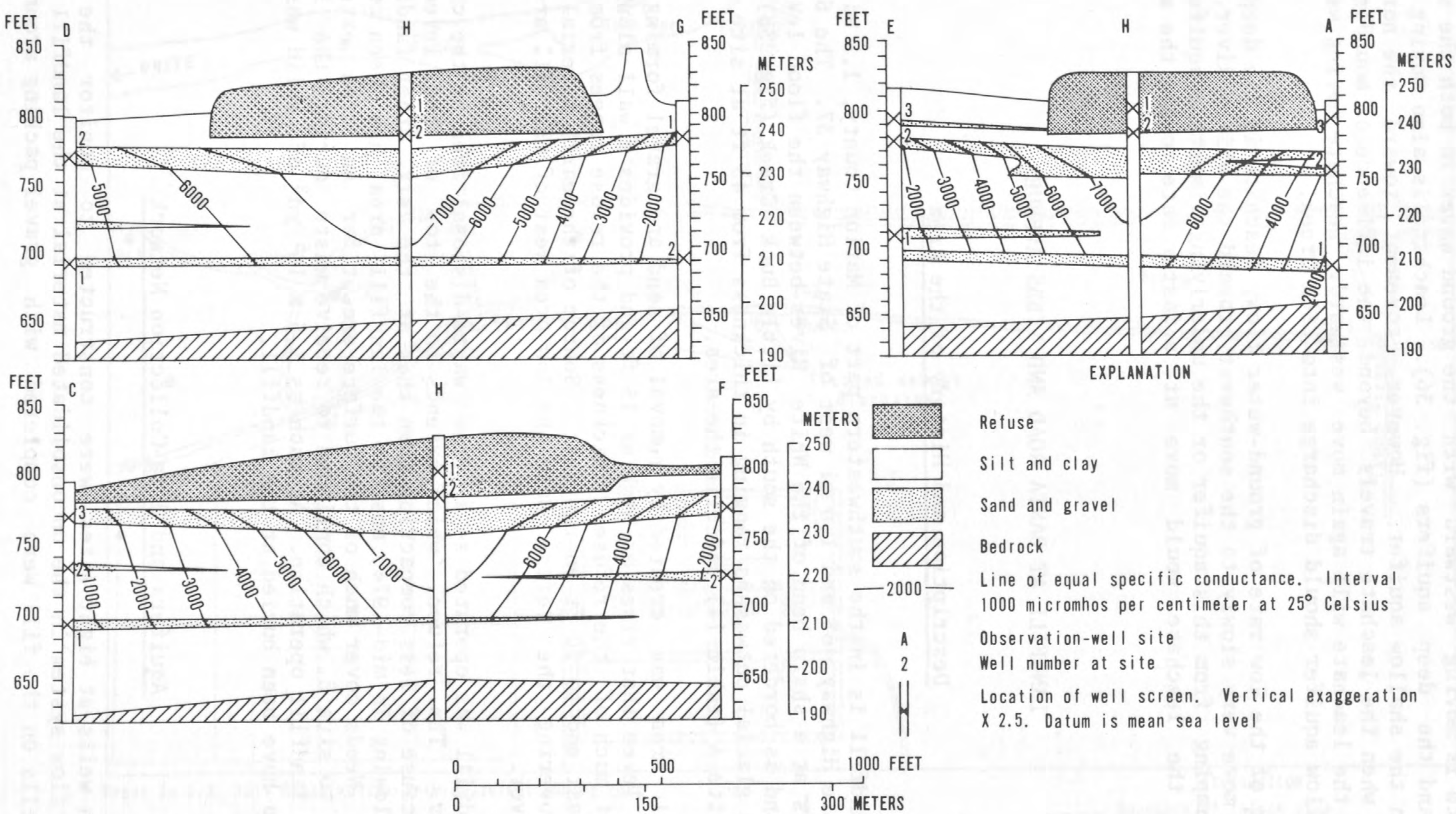


Figure 37.-- Sections showing distribution of specific conductance in landfill area at 2700 South Emerson Avenue, March 1975.

Leachate is moving westward with the ground water in both the shallow (fig. 35) and the deep aquifers (fig. 36). Leachate is also moving northeastward in the shallow aquifer. However, movement toward the northeast will cease when the leachate travels beyond the influence of mounding. At that time, the leachate will again move westward. Leachate moving westward in the shallow aquifer should discharge into Lick Creek.

Because of the low rate of ground-water flow, leachate in the deep aquifer will move very slowly to the southwest, toward the White River. If, however, pumping from this aquifer or the underlying limestone aquifer were increased, the leachate would move at a faster rate toward the area of pumping.

LANDFILL AT BANTA ROAD AND TIBBS AVENUE

Description and History of the Area

This landfill is in the southwestern part of Marion County, 1.5 mi south of Interstate Highway 465 and 1.0 mi west of State Highway 37. The 63-acre fill area is at a sharp bend of the White River between the flood levee and the river and is bordered on the south by Little Buck Creek (fig. 38). Alluvial and glacial outwashes ranging in thickness from 43 ft at site H to 103 ft at site A (table 14) underlie the area.

The fill area was created by removal of sand and gravel forming a pit and by a levee that rises as high as 15 ft and provides a wall along the perimeter of much of the refuse. Thickness of the refuse ranges from 15 ft near the east end to 30 ft on the west. Source of the earth material (silt loam) for covering the refuse was the low area west of the fill area and near the river.

The landfill was operated as a free waste-disposal area by the city of Indianapolis. The refuse, which extends to the top of the levee, is "spongy" because of less compaction than that at the six other landfills. Since its closing in mid-1974, most of the landfill area has been covered with soil. Weeds cover much of the surface except for an area extending from site C to site E, which continued to receive waste during the latter part of the landfill operation. As much as 1.5×10^6 yd^3 of solid waste is estimated to have been buried at the landfill.

Aquifers and Data-Collection Network

Fourteen wells at eight sites were constructed to monitor the water quality and flow system in the unconsolidated material at the landfill (fig. 38). All wells on the fill were completed with gravel packing around the screen.

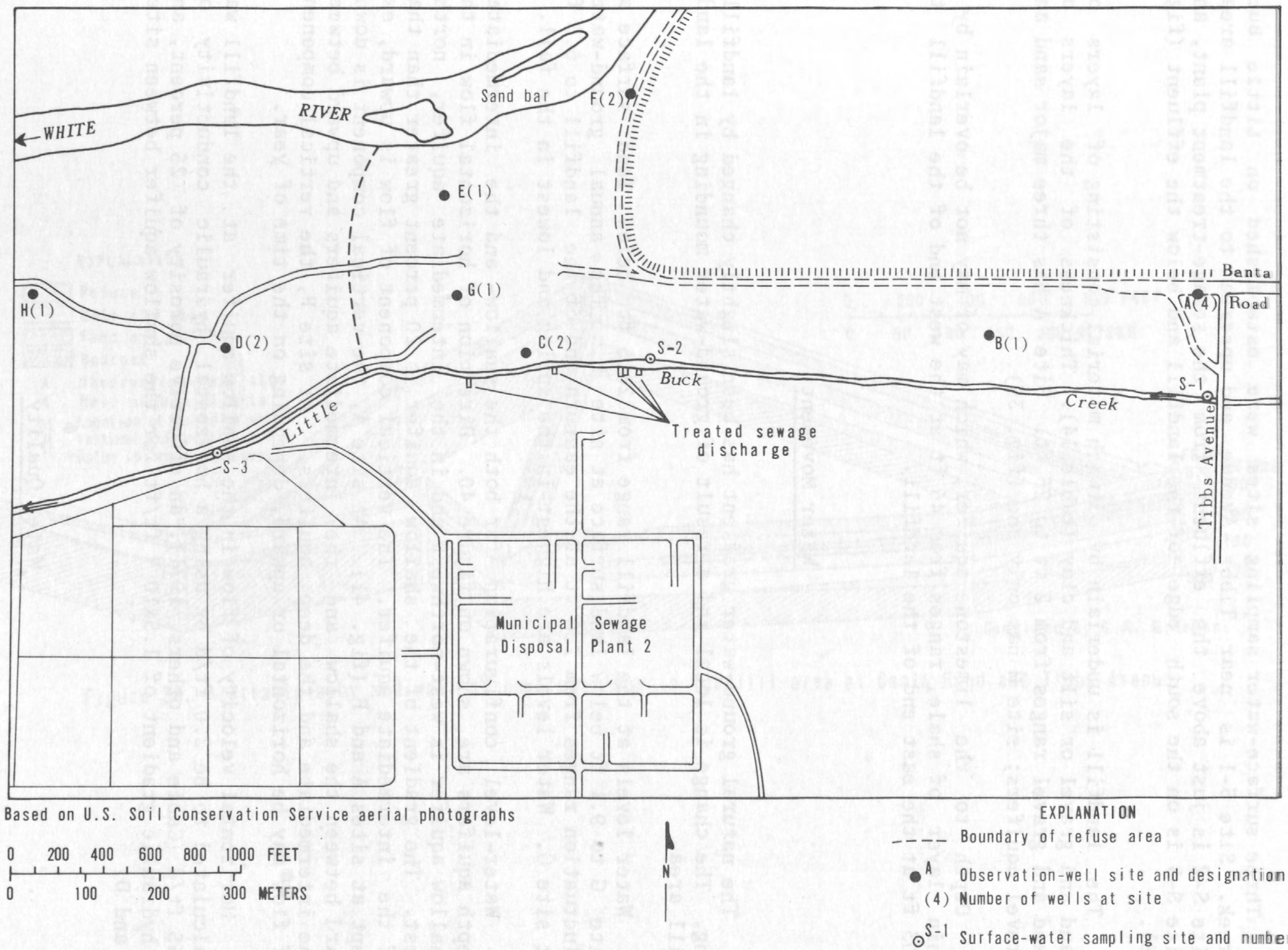


Figure 38.-- Location of well sites in landfill area at Banta Road and Tibbs Avenue.

Three surface-water sampling sites were established on Little Buck Creek. Site S-1 is near Tibbs Avenue and upstream to the landfill area, site S-2 is just above the effluent from the sewage-treatment plant, and site S-3 is on the south edge of the landfill and below the effluent (fig. 38).

The landfill is underlain by outwash material consisting of layers of sand and gravel or silt and clay (table 14). Thickness of the layers of sand and gravel ranges from 2 ft to 25 ft. Site A has three major sand and gravel aquifers; site H has only one (fig. 39).

Depth to the limestone aquifer, which may or may not be overlain by a thin layer of shale, ranges from 46 ft at the west end of the landfill to 103 ft at the east end of the landfill.

Water Movement

The natural ground-water gradient has been slightly changed by landfilling. The change is local and a result of ground-water mounding in the landfill area.

Water levels at the landfill range from 26.5 ft below land surface at site G to 9.1 ft below land surface at site H. The annual ground-water fluctuation ranges from 2.0 ft at the eastern end of the landfill to 6.5 ft at site G. Water levels are highest in the spring and lowest in the fall.

Water-level configuration for both the shallow- and the intermediate-depth aquifers are shown on figure 40. Direction of horizontal flow in the shallow aquifer is west-northwest and in the intermediate aquifer, northwest. The gradient of the shallow aquifer is 20 percent greater than that of the intermediate aquifer. The vertical component of flow is upward, except at sites A and F (fig. 41). At site A, the vertical component is downward between the shallow and the intermediate aquifers and upward between the intermediate and the deep aquifers. At site F, the vertical component of flow may be horizontal or upward, depending on the time of year.

Horizontal velocity of flow in the shallow aquifer at the landfill was calculated to be 2.0 ft/d by using a horizontal hydraulic conductivity of 335 ft/d (Cable and others, 1971), an effective porosity of 25 percent, and a hydraulic gradient of 1.5×10^{-3} ft/ft for the shallow aquifer between sites A and D.

Water Quality

Comparison of the dissolved-solids concentration of background water (well 2 at site A, table 7) with dissolved-solids concentration of water samples collected from all sites on the landfill indicates that leachate

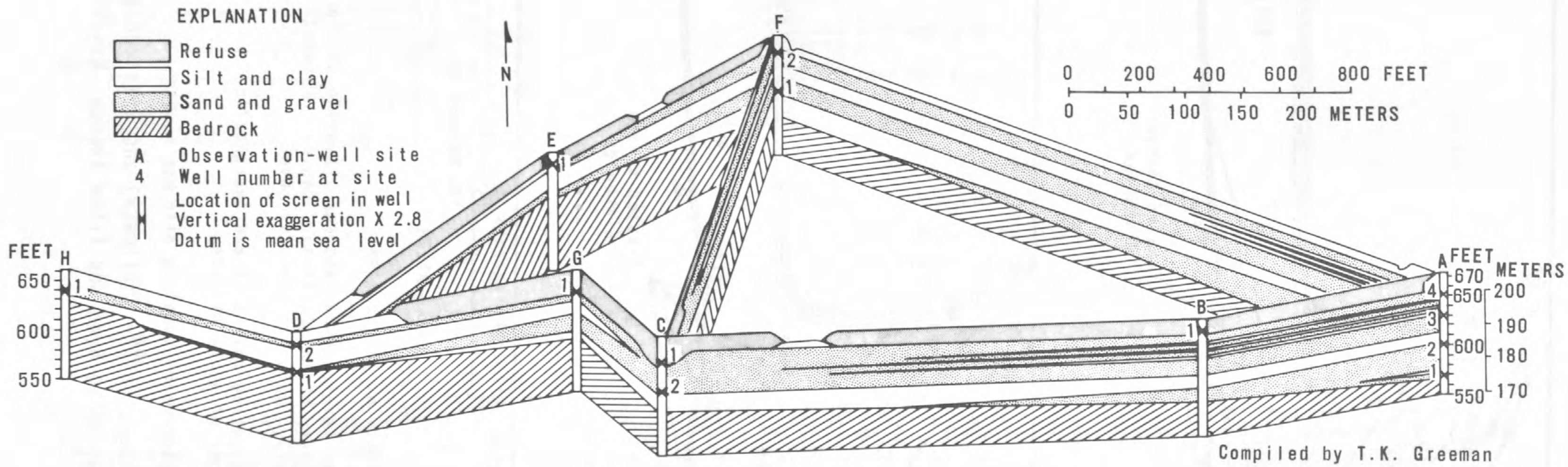


Figure 39.-- Stratigraphy and well-screen locations in landfill area at Banta Road and Tibbs Avenue.

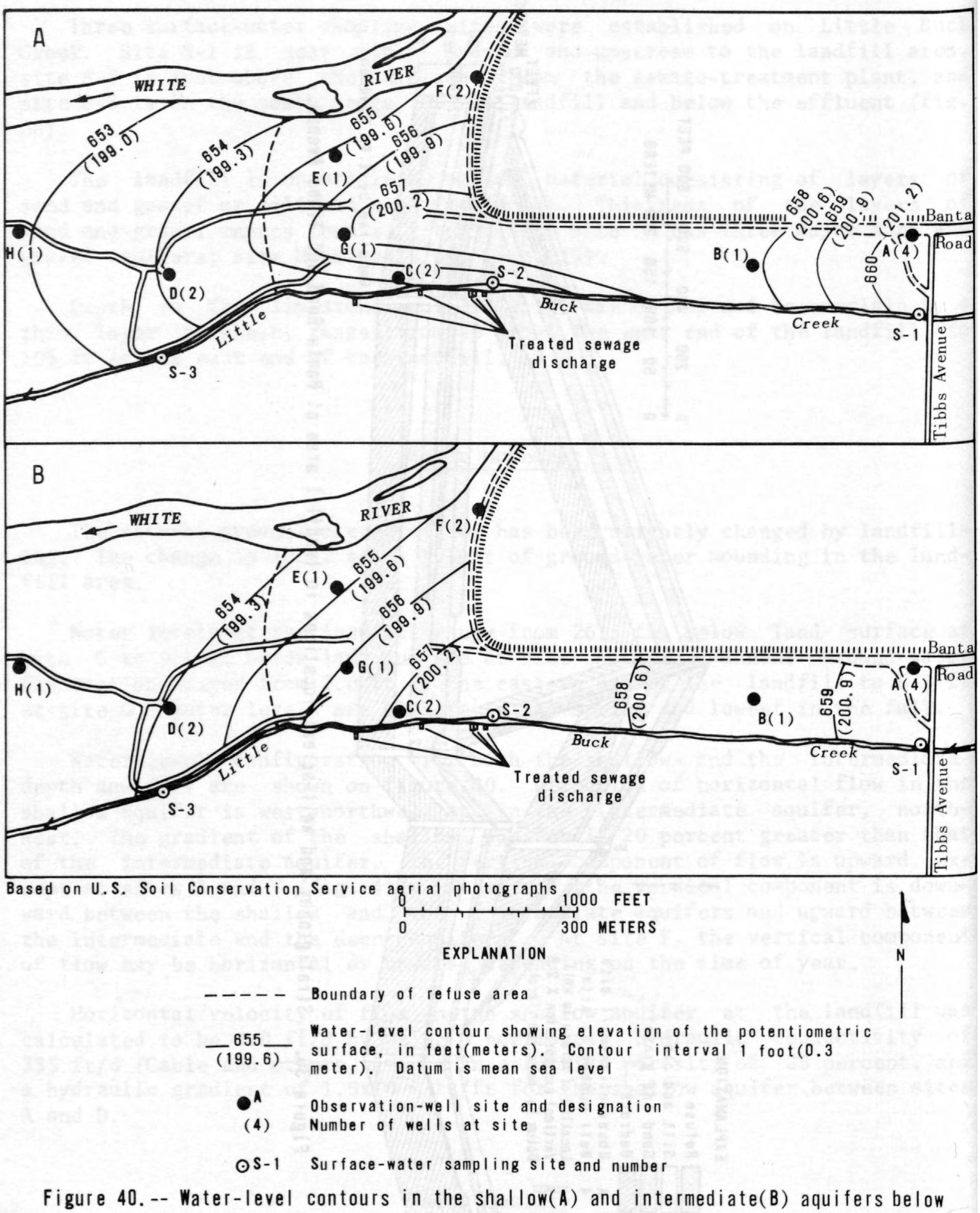


Figure 40.-- Water-level contours in the shallow(A) and intermediate(B) aquifers below landfill area at Banta Road and Tibbs Avenue, March 1975.

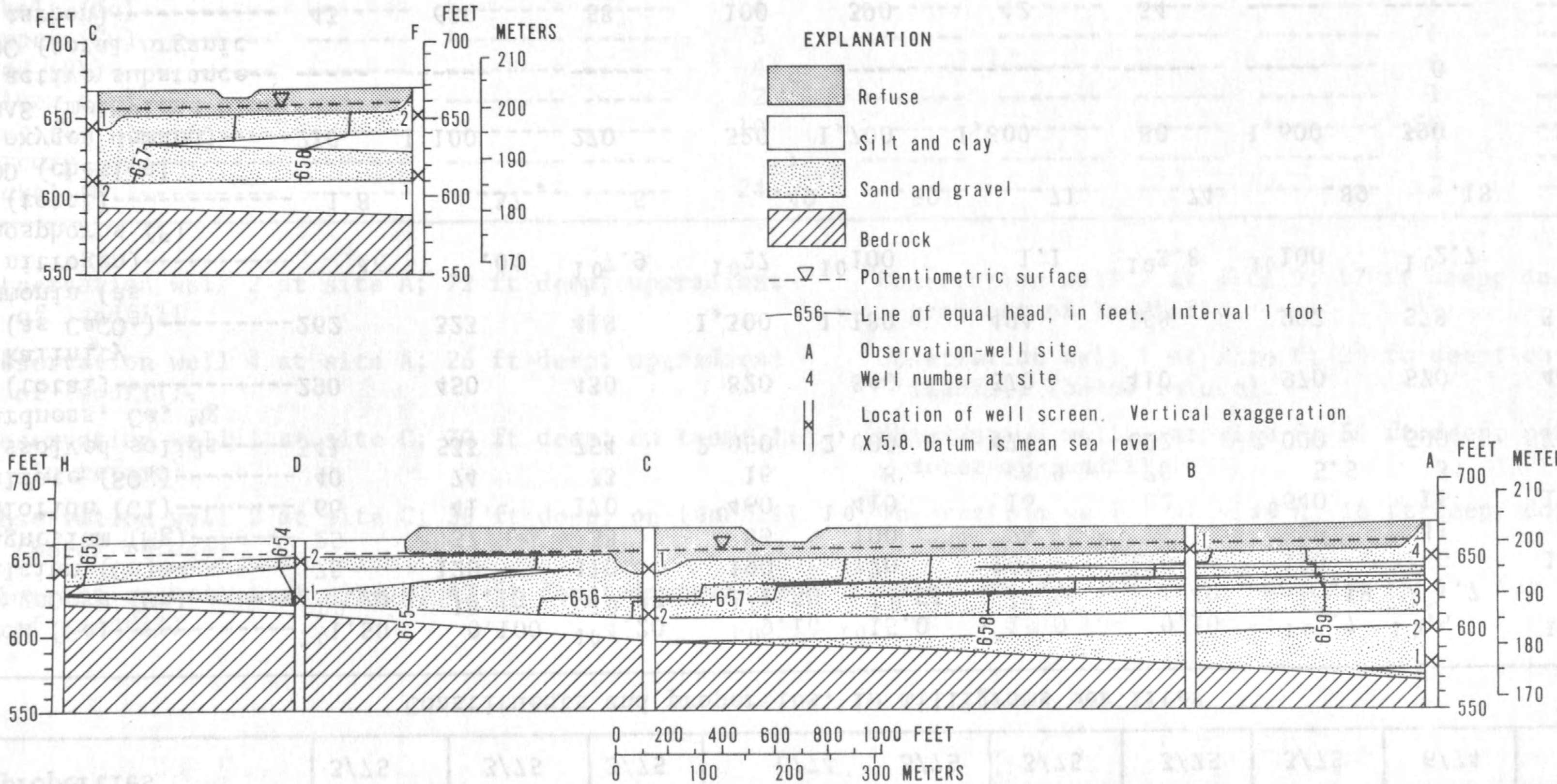


Figure 41.--Hydrologic sections in landfill area at Banta Road and Tibbs Avenue, March 1975.

Table 7.--Analyses of water from selected sites on or near landfill at Banta Road and Tibbs Avenue

[Analyses by U.S. Geological Survey]

Constituents and properties	Site and date of sampling									
	A[1]	A[2]	C[3]	C[4]		D[5]	D[6]	E[7]	F[8]	H[9]
	3/75	3/75	3/75	6/74	3/75	3/75	3/75	3/75	6/74	3/75
Constituents and properties, in milligrams per liter										
Iron (Fe)------------	[10]1.50	0.100	[10]4.20	[10]9.10	[10]15.0	[10]13.0	0.10	[10]1.7	[10]45	[10]5.0
Manganese (Mn)-------	[10].20	[10].15	[10].22	[10]1.50	[10].53	[10].83	[10]1.40	[10].18	[10]1.7	[10].58
Calcium (Ca)---------	75	120	110	190	170	100	110	190	160	130
Magnesium (Mg)-------	25	37	38	83	100	28	33	120	41	33
Chloride (Cl)--------	66	41	170	[10]460	[10]410	16	82	[10]640	16	130
Sulfate (SO_4)--------	40	74	33	16	8	8.9	70	5.5	3	65
Dissolved solids-----	341	533	754	2,050	2,000	474	622	2,000	590	724
Hardness, Ca, Mg (total)------------	290	450	430	820	840	370	410	970	570	460
Alkalinity (as $CaCO_3$)---------	262	323	418	1,300	1,180	404	358	992	578	355
Ammonia (as nitrogen)----------	.46	.04	[10]7.9	[10]27	[10]100	1.1	[10]3.8	[10]100	[10]2.7	.24
Phosphorus (P) (total)------------	1.8	.37	.5	.49	.59	.71	.74	.89	.18	.75
COD (chemical oxygen demand)-----	210	1,100	270	320	1,700	1,800	80	1,600	390	38
MBAS (methylene blue active substance--	-----	------	-----	.5	-----	------	------	-----	0	------
TOC (total organic carbon)-----------	43	680	58	100	390	42	34	-----	------	9.8
Phenols--------------	.0003	.0002	[10].002	[10].038	[10].067	.0003	[10].004	[10].007	------	[10].006
Fluoride (F)---------	-------	--------	------	.7	-------	-------	------	--------	.3	-------
Silica (SiO_2)--------	-------	--------	------	22	-------	-------	------	--------	19	-------

Constituents, in micrograms per liter										
Arsenic (As)	--	--	--	3	--	--	--	--	1	--
Beryllium (Be)	--	--	--	0	--	--	--	--	0	--
Cadmium (Cd)	--	--	--	3	--	--	--	--	2	--
Chromium (Cr)	--	--	--	1	--	--	--	--	0	--
Cobalt (Co)	--	--	--	4	--	--	--	--	3	--
Copper (Cu)	--	--	--	3	--	--	--	--	6	--
Lead (Pb)	--	--	--	4	--	--	--	--	0	--
Silver (Ag)	--	--	--	2	--	--	--	--	1	--
Zinc (Zn)	--	--	--	10	--	--	--	--	30	--
Mercury (Hg)	--	--	--	.3	--	--	--	--	4	--
Nickel (Ni)	--	--	--	24	--	--	--	--	12	--

[1]Observation well 2 at site A; 72 ft deep; upgradient of landfill.

[2]Observation well 4 at site A; 26 ft deep; upgradient of landfill.

[3]Observation well 1 at site C; 30 ft deep; on landfill (in refuse).

[4]Observation well 2 at site C; 30 ft deep; on landfill (below refuse).

[5]Observation well 1 at site D; 42 ft deep; downgradient of landfill.

[6]Observation well 2 at site D; 17 ft deep; downgradient of landfill.

[7]Observation well 1 at site E; 24 ft deep; on landfill (below refuse).

[8]Observation well 1 at site F; 59 ft deep; perimeter of landfill.

[9]Observation well 1 at site H; 16 ft deep; downgradient of landfill.

[10]Value exceeds limits recommended by EPA for public water supplies (table 1).

from the refuse has affected the quality of ground water at all monitoring sites. (See fig. 42.) Only the shallow aquifer at site A, on the upgradient side and on the perimeter of the landfill, has been affected by leachate from a thin layer of refuse extending to near the site. Although site F is on the upgradient side of the landfill and flow lines are parallel to the perimeter of the landfill at the site, leachate has affected the water quality in both the deep and the shallow aquifers. The remaining sites are affected because they are either on or immediately downgradient from the refuse.

Relative concentration of leachate in the shallow aquifer is generally greater than that in the deeper one (fig. 43) because the leachate is diluted and its rate of movement downward is slowed by the layer of silt and clay. However, these conditions do not apply at site C. Data collected at this site show that the leachate concentration of water from the deep well is consistently much greater than that of water from the shallow well. Magnitude of the difference in water quality can be seen by comparing concentrations of chemical constituents in ground water from the two depths (wells 1 and 2 at site C, table 7). History of site C suggests a possible explanation for this difference in water quality. Several years ago, shortly after a fire in the area of this site, the area was excavated to a depth of 40 ft, and new waste was added to the excavated area. Thus, at the 30-ft depth, ground water receives leachate from only the recently emplaced refuse, whereas, at the 69-ft, it receives leachate from much older refuse upgradient from site C as well as from the recently emplaced refuse.

The dominant movement of leachate in the water of all the aquifers is toward the White River (fig. 42). Because the vertical component of flow is upward at site D and the bedrock is less than 40 ft below land surface, leachate is being discharged with the ground water into the White River.

The variation in quality of water in the shallow aquifer is demonstrated by dissolved-solids concentrations at sites A, E, and H (table 7). The relative concentration of leachate in the ground water increases from a low at site A to a high at site E and then begins to decrease as the leachate is diluted in its movement downgradient to discharge into the White River.

Field analyses of water from Little Buck Creek were made at points upstream from the refuse (site S-1), alongside the refuse but upstream from the effluent from the sewage-treatment plant (site S-2), and downstream from the effluent from the sewage-treatment plant (site S-3). The quality of the stream decreases slightly between sites S-1 and S-2. However, the change in stream quality was more pronounced between site S-2 and site S-3, indicating that effluent from the sewage-treatment plant rather than leachate was having the greatest effect on water quality in Little Buck Creek. Magnitude of the change as indicated from the March 1975 sampling was as follows: 5°-C increase in temperature, a 4-mg/L decrease in dissolved-oxygen concentration, and 440-μmhos/cm increase in specific conductance.

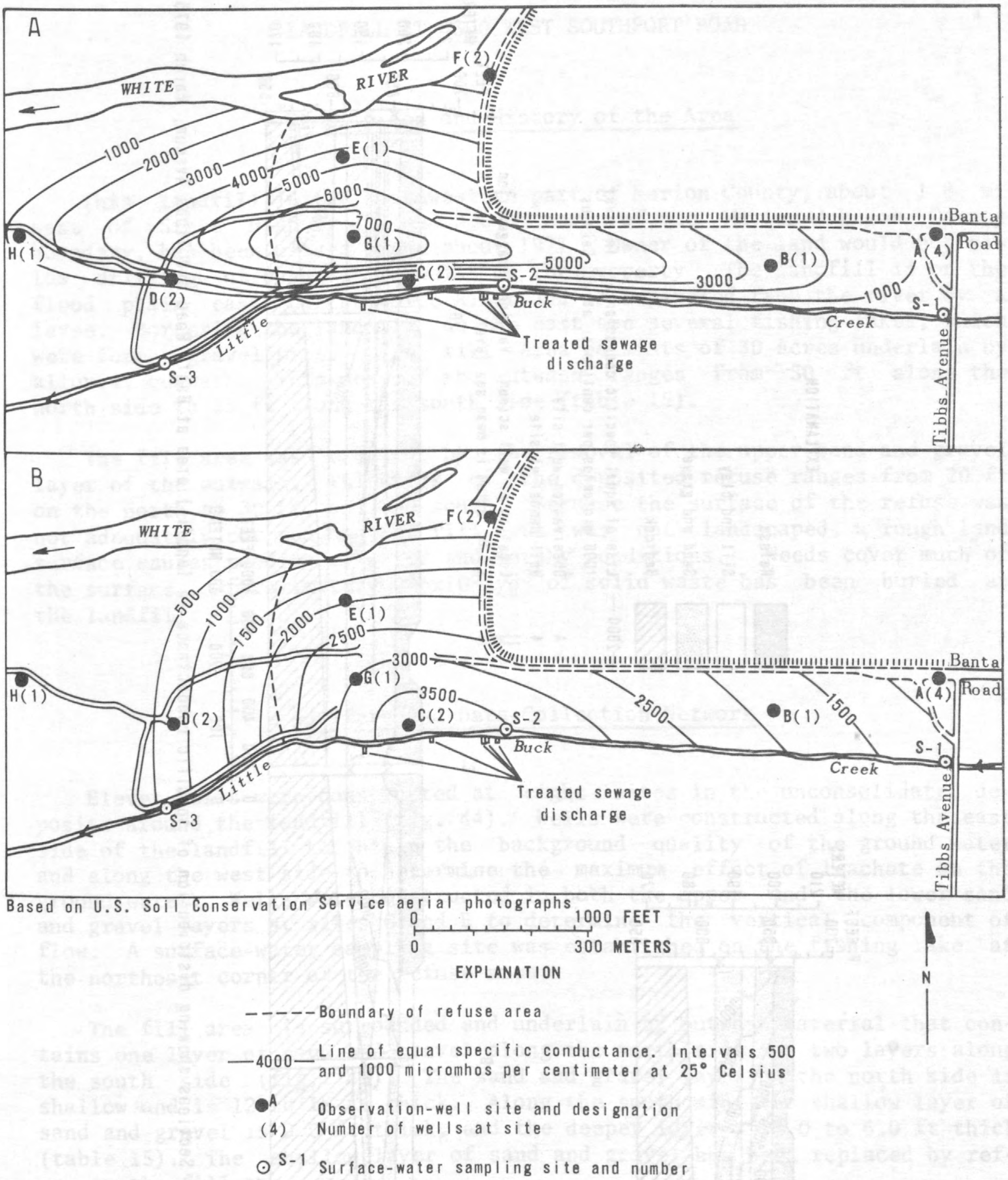


Figure 42.-- Specific conductance of water in the shallow(A) and intermediate(B) aquifers below landfill area at Banta Road and Tibbs Avenue, March 1975.

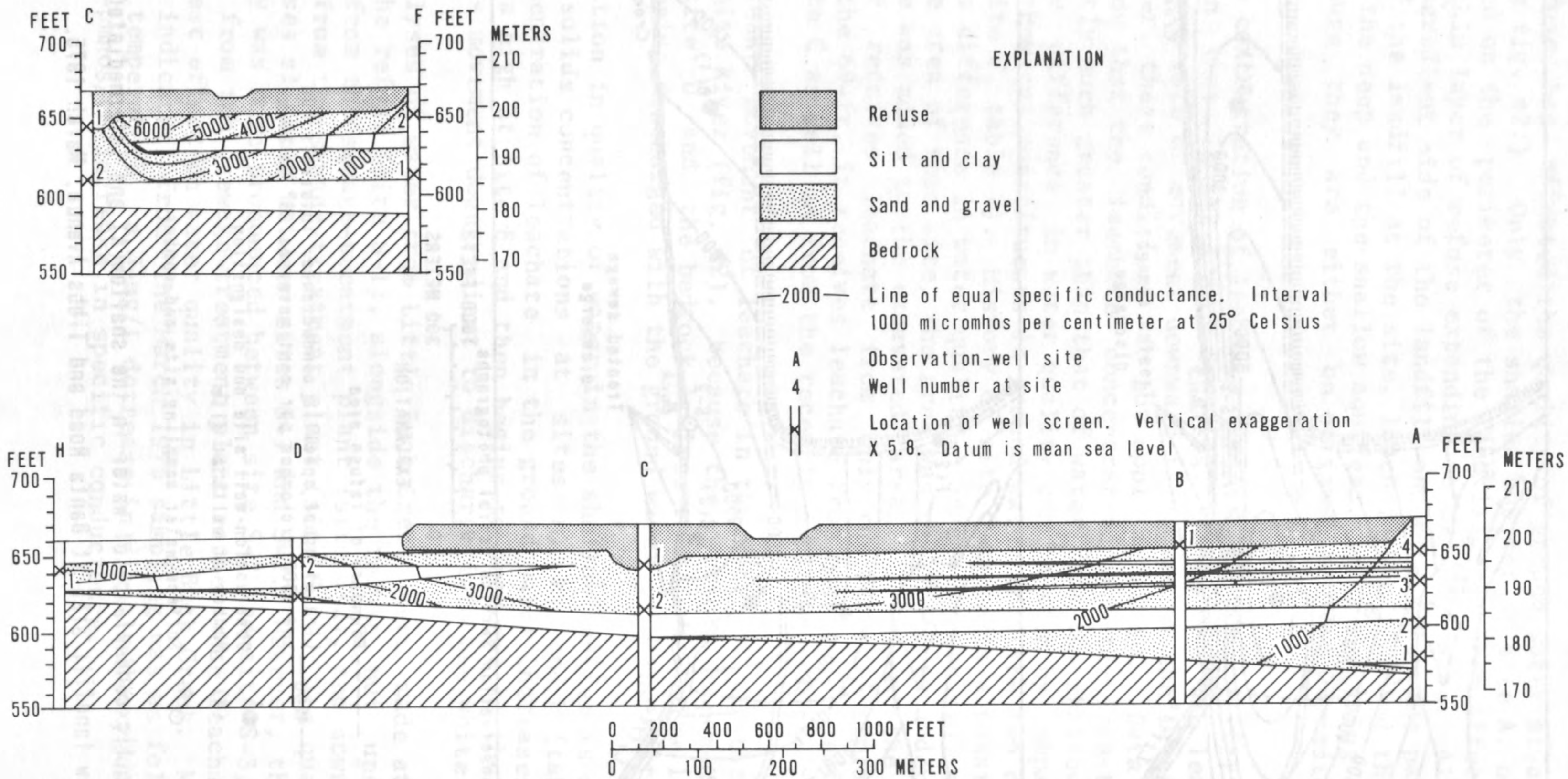


Figure 43.-- Sections showing distribution of specific conductance in landfill area at Banta Road and Tibbs Avenue, March 1975.

LANDFILL AT 4300 WEST SOUTHPORT ROAD

Description and History of the Area

This landfill in the southwestern part of Marion County, about 1.8 mi west of State Highway 37 and 2.0 mi north of the Marion-Johnson County boundary, has been closed since about 1971. Owner of the land would not allow drilling of observation wells on the property. The landfill is on the flood plain east of the White River and is separated from the river by a levee. Bordering the landfill on the east are several fishing lakes, which were former gravel pits. The fill area consists of 30 acres underlain by alluvial outwash. Thickness of the outwash ranges from 50 ft along the north side to 55 ft along the south side (table 15).

The fill area was created by the removal of the upper sand and gravel layer of the outwash. Thickness of the deposited refuse ranges from 20 ft on the north to 30 ft on the south. Because the surface of the refuse was not adequately covered and the fill area was not landscaped, a rough land surface causes ponding of water and marshy conditions. Weeds cover much of the surface. Approximately 9.6×10^5 yd^3 of solid waste has been buried at the landfill.

Aquifers and Data-Collection Network

Eleven wells were constructed at eight sites in the unconsolidated deposits around the landfill (fig. 44). Wells were constructed along the east side of the landfill to obtain the background quality of the ground water and along the west side to determine the maximum effect of leachate on the ground water. Wells were constructed in both the upper and the lower sand and gravel layers at sites G and E to determine the vertical component of flow. A surface-water sampling site was established on the fishing lake at the northeast corner of the refuse area.

The fill area is surrounded and underlain by outwash material that contains one layer of sand and gravel along the north side and two layers along the south side (fig. 45). The sand and gravel layer on the north side is shallow and is 12 to 16 ft thick. Along the south side the shallow layer of sand and gravel is 9.0 ft thick, and the deeper layer is 3.0 to 6.0 ft thick (table 15). The shallow layer of sand and gravel has been replaced by refuse in the fill area.

Depth to the shale bedrock is about 50 ft. The limestone aquifer beneath the shale is a source of ground water in the area.

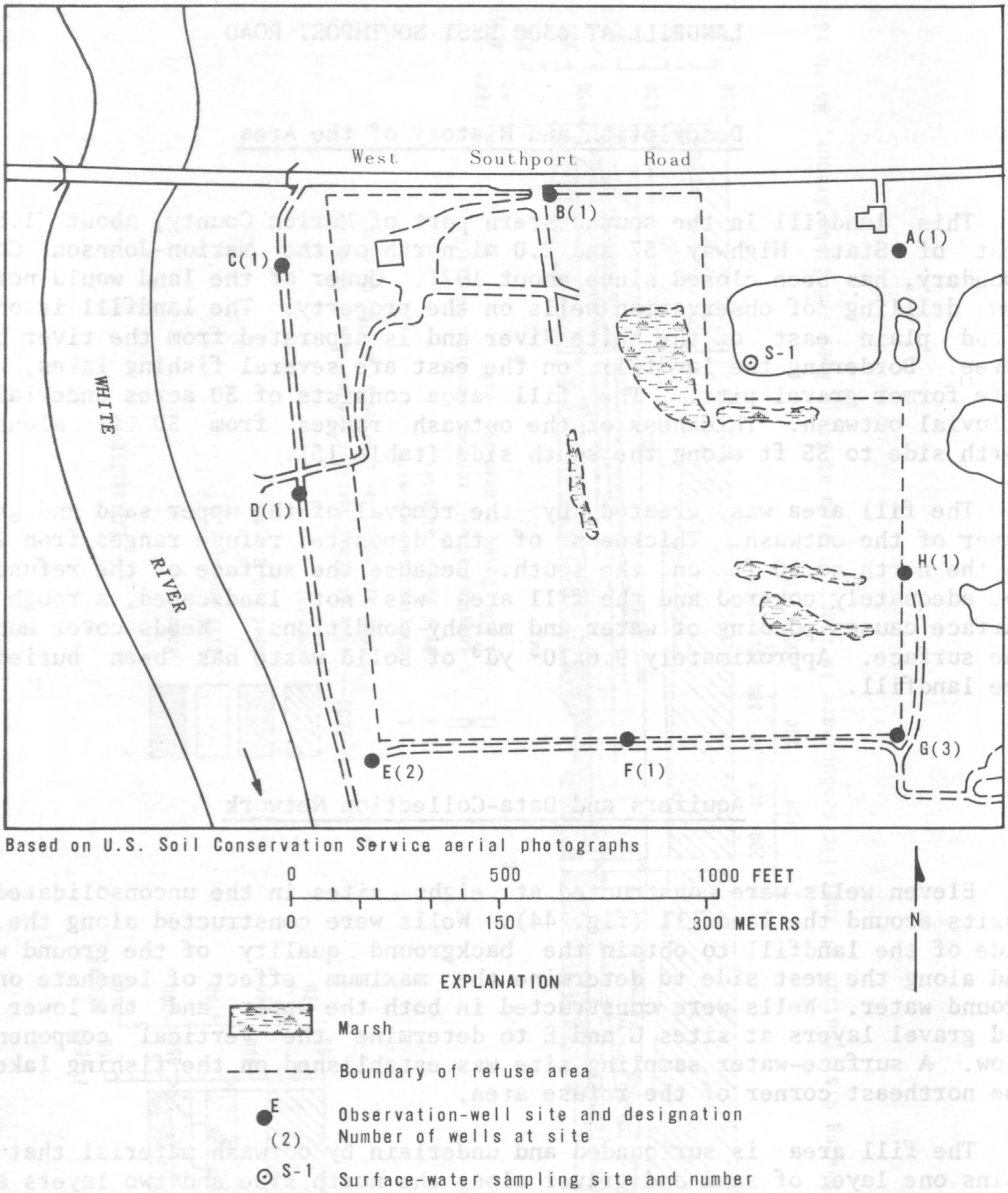


Figure 44.-- Location of well sites in landfill area at 4300 West Southport Road.

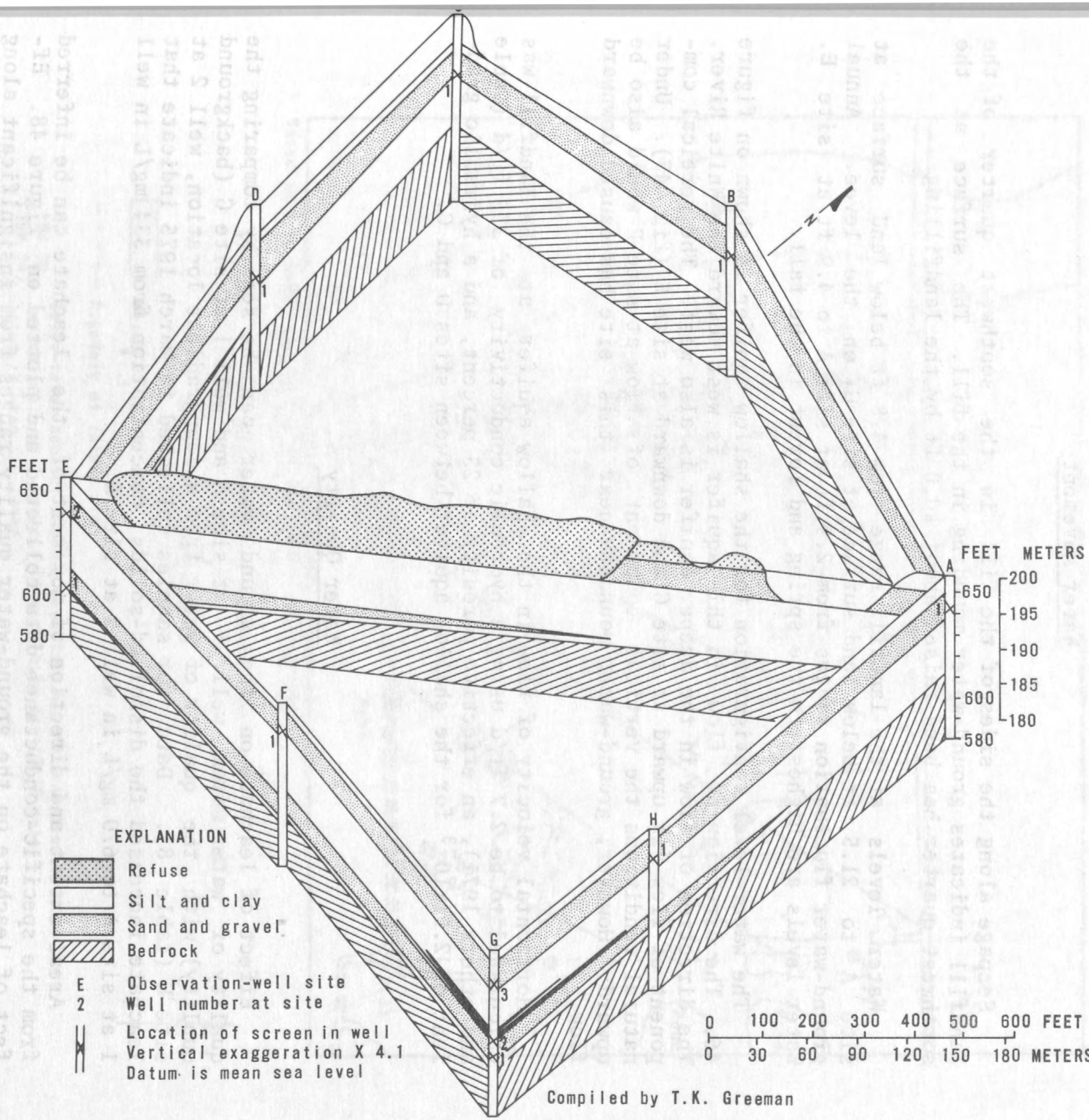


Figure 45.-- Stratigraphy and well-screen locations in landfill area at 4300 West Southport Road.

Water Movement

Seepage along the sides of the fill in the southwest quarter of the landfill indicates ground-water mounding in the fill. The surface at the southwest quarter has been raised about 10.0 ft by the landfilling.

Water levels at the landfill range from 4.8 ft below land surface at site A to 21.5 ft below land surface at site C, on the levee. Annual ground-water fluctuation ranges from 2.9 ft at site A to 4.9 ft at site E. Water levels are highest in the spring and lowest in the fall.

The water-level configuration for the shallow aquifer is shown on figure 46. The direction of flow in this aquifer is west toward the White River. The direction of flow in the deeper aquifer is also west. The vertical component of flow is upward at site G and downward at site E (fig. 47). Under natural conditions the vertical component of flow at site E would also be upward. However, ground-water mounding near this site has caused downward flow.

Horizontal velocity of flow in the shallow aquifer at the landfill was calculated to be 2.7 ft/d using a hydraulic conductivity of 335 ft/d (Cable and others, 1971), an effective porosity of 25 percent, and a hydraulic gradient of 2.01×10^{-3} for the shallow aquifer between sites D and G.

Water Quality

Effect of leachate on the ground water can be seen by comparing the quality of water from well 1 at site A and well 1 at site G (background quality) with the quality of water from a downgradient location, well 2 at site E (table 8). Data for samples collected in March 1975 indicate that leachate increased the dissolved-solids concentration from 334 mg/L in well 1 at site A to 670 mg/L in well 2 at site E.

Areal extent and direction of movement of the leachate can be inferred from the specific-conductance data collected and plotted on figure 48. Effect of leachate on the ground-water quality ranges from insignificant along the east and north sides of the landfill, to significant along the south and west sides, where the refuse is thickest. The amount of leachate in the ground water below the fill is apparently due to the quantity of refuse in the landfill rather than to the flow pattern.

Water mounding near site E is causing leachate to move downward from the shallow to the deep aquifer (fig. 49). However, at site G, the deep aquifer is not receiving leachate from above because there is no mounding near this site and the vertical flow is toward the surface. Here, ground-water quality approximates background quality. Thus, with the present flow system, leachate from the landfill refuse should not adversely affect the ground-water quality below the east edge of the landfill. In addition, leachate in

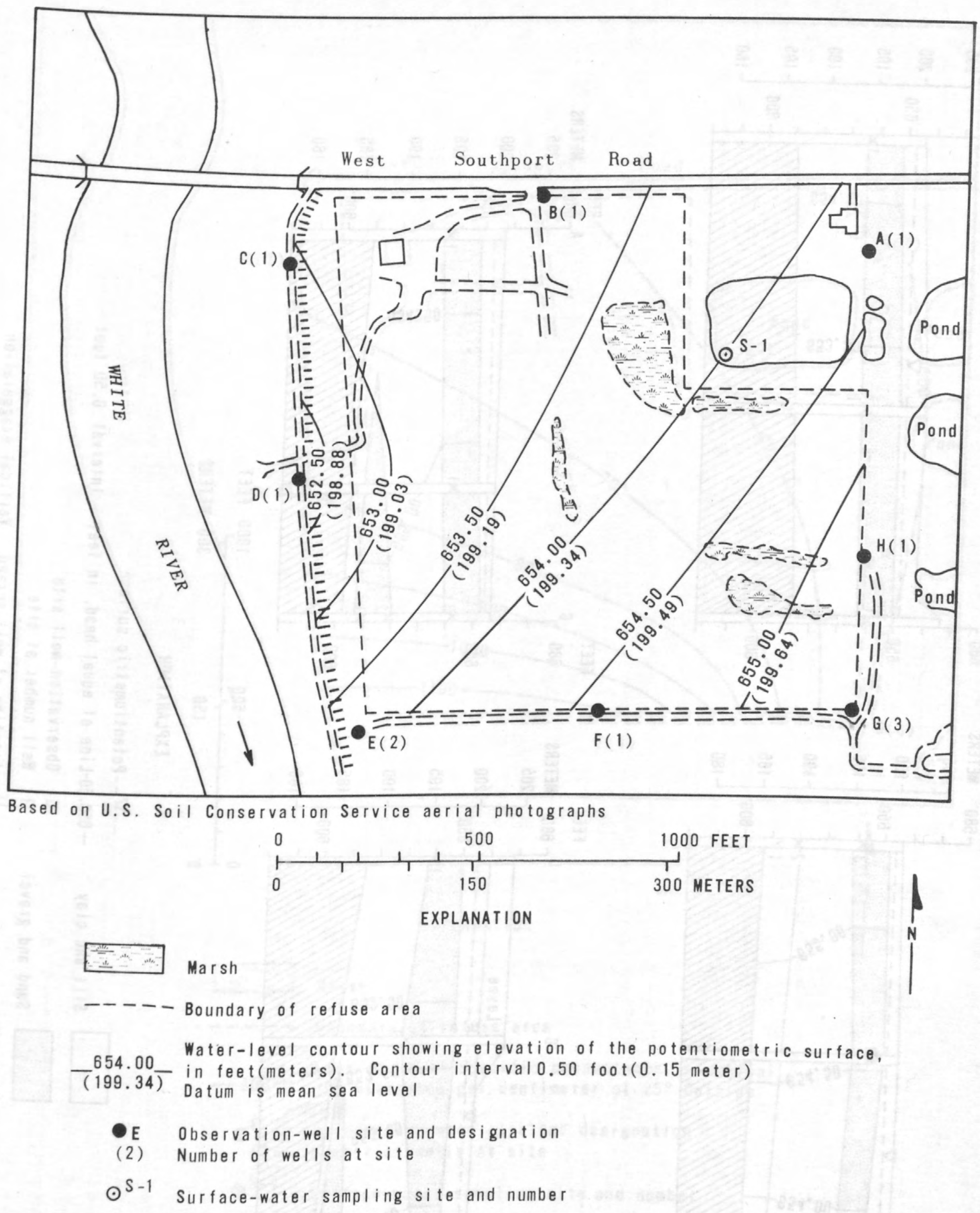


Figure 46.-- Water-level contours in the shallow aquifer below landfill area at 4300 West Southport Road, March 1975.

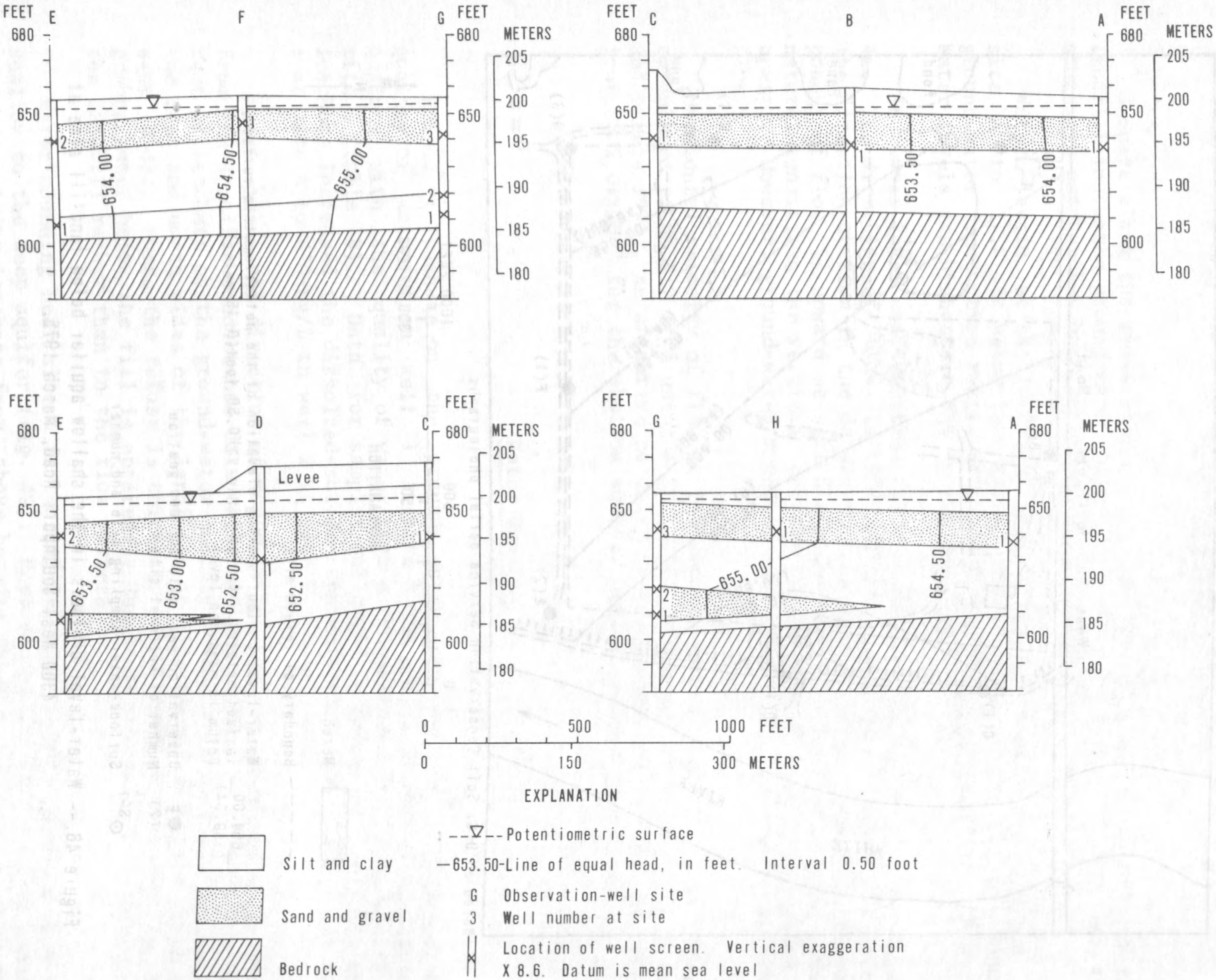


Figure 47.-- Hydrologic sections in landfill area at 4300 West Southport Road, March 1975.

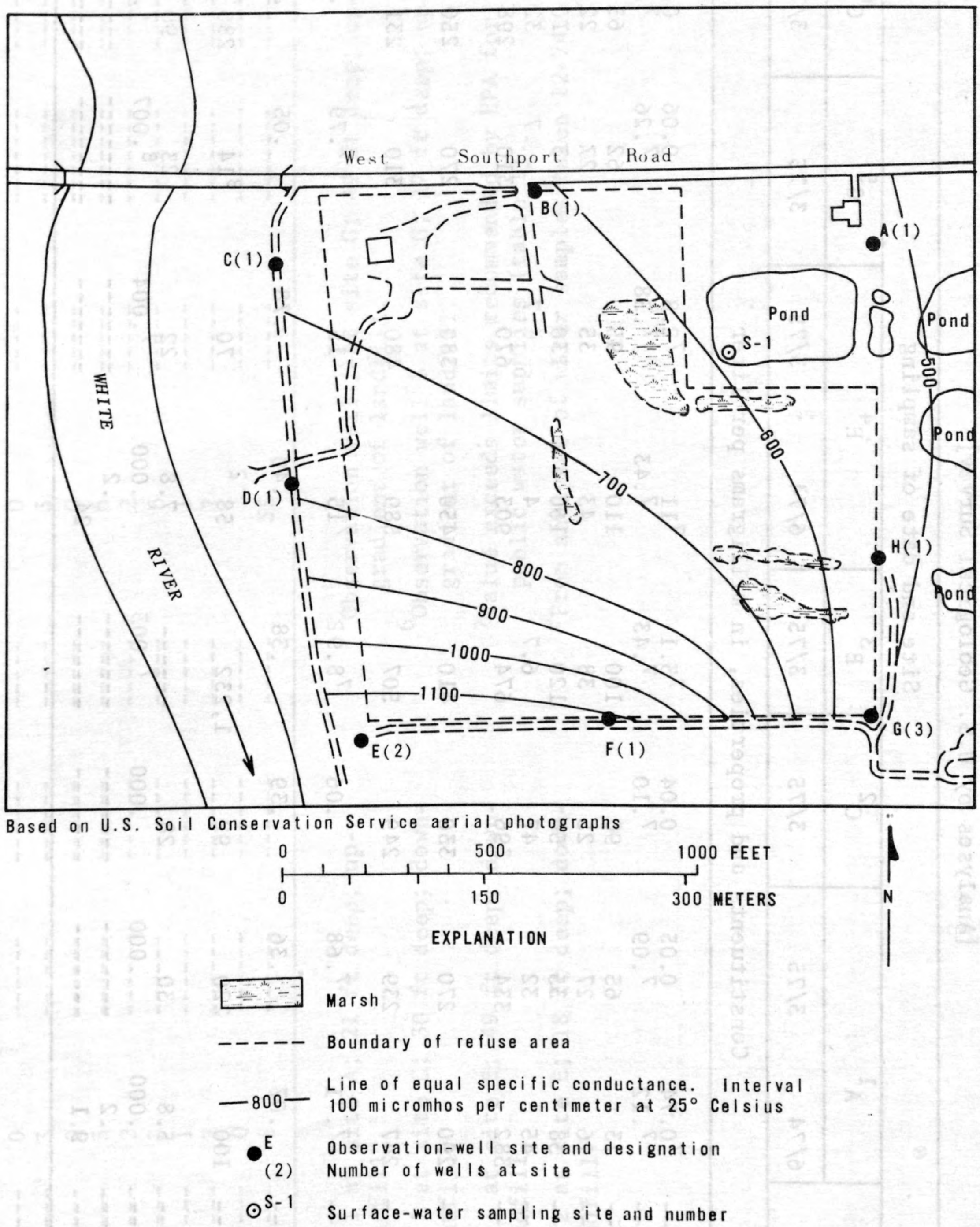


Figure 48. — Specific conductance of water in the shallow aquifer below landfill area at 4300 West Southport Road, March 1975.

Table 8.--Analyses of water from selected sites on or near landfill at 4300 West Southport Road

[Analyses by U.S. Geological Survey]

Constituents and properties	Site and date of sampling							
	A[1]		C[2]	E[3]	E[4]		G[5]	G[6]
	6/74	3/75	3/75	3/75	6/74	3/75	3/75	3/75
	Constituents and properties, in milligrams per liter							
Iron (Fe)----------	[7]0.74	0.05	0.04	[7]3.1	[7]11	[7]2.8	0.06	0.10
Manganese (Mn)------	[7].12	[7].09	[7].10	[7].43	[7].43	[7].38	[7].26	[7].28
Calcium (Ca)--------	73	65	90	100	110	95	62	65
Magnesium (Mg)------	26	27	25	38	43	35	27	22
Chloride (Cl)-------	38	35	50	120	160	130	3	10
Sulfate (SO_4)------	45	32	47	6.7	4	6.7	.7	32
Dissolved solids----	382	334	396	674	903	670	310	298
Hardness, Ca, Mg (total)----------	290	270	330	410	450	380	270	250
Alkalinity (as $CaCO_3$)--------	247	239	249	507	589	480	310	231
Ammonia (as nitrogen)---------	[7].71	[7].68	.06	[7]8.9	[7]15	[7]15	[7].79	.16
Phosphorus (P) (total)----------	.07	.36	.39	.38	.40	.78	.05	.61
COD (chemical oxygen demand)----	100	220	92	1,232	58	70	[8]14	280
TOC (total organic carbon)----------	5.8	30	28	------	7.8	22	23	90
Phenols-------------	.000	.000	.000	[7].003	.000	[7].004	[8].007	[7].002
Fluoride (F)--------	.2	-------	-------	-------	.2	-------	--------	-------
Silica (SiO_2)-------	9.1	-------	-------	-------	24	-------	--------	-------

Constituents, in micrograms per liter

Arsenic (As)---------	0	------	------	-----	1	-----	-------	------
Beryllium (Be)-------	0	------	------	-----	0	-----	-------	------
Cadmium (Cd)---------	3	------	------	-----	3	-----	-------	------
Chromium (Cr)--------	0	------	------	-----	0	-----	-------	------
Cobalt (Co)----------	3	------	------	-----	6	-----	-------	------
Copper (Cu)----------	2	------	------	-----	2	-----	-------	------
Lead (Pb)------------	3	------	------	-----	6	-----	-------	------
Silver (Ag)----------	1	------	------	-----	1	-----	-------	------
Zinc (Zn)------------	7	------	------	-----	7	-----	-------	------
Mercury (Hg)---------	0	------	------	-----	.5	-----	-------	------
Nickel (Ni)----------	5	------	------	-----	35	-----	-------	------

[1] Observation well 1 at site A; 21 ft deep; up-gradient of landfill.

[2] Observation well 1 at site C; 30 ft deep; down-gradient of landfill.

[3] Observation well 1 at site E; 49 ft deep; down-gradient of landfill.

[4] Observation well 2 at site E; 18 ft deep; down-gradient of landfill.

[5] Observation well 1 at site G; 49 ft deep; up-gradient of landfill.

[6] Observation well 3 at site G; 17 ft deep; up-gradient of landfill.

[7] Value exceeds limits recommended by EPA for public water supplies (table 1).

[8] From analyses of water samples taken 12-74.

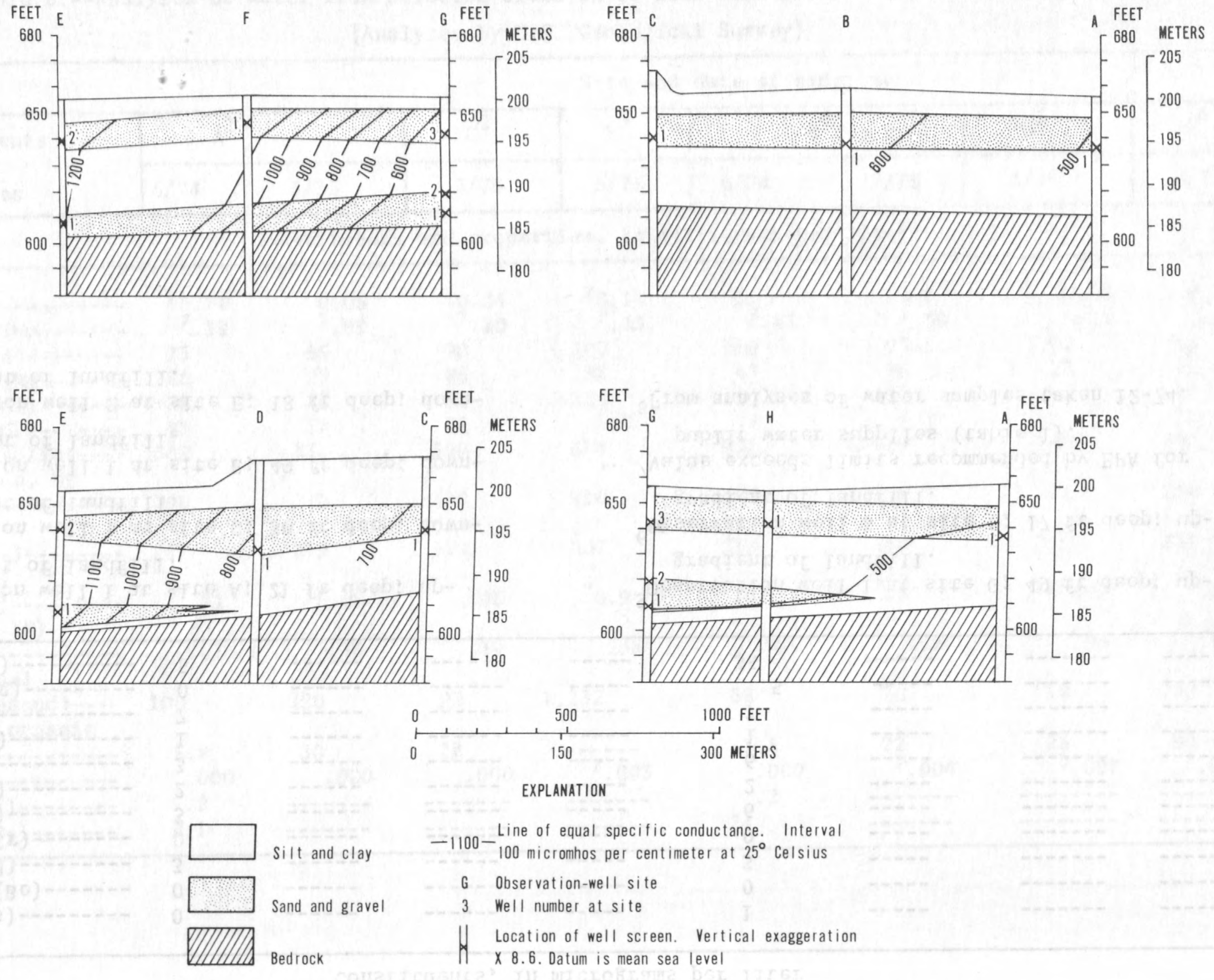


Figure 49.-- Sections showing distribution of specific conductance in landfill area at 4300 West Southport Road, March 1975.

the ground water below the south and west parts of the landfill should not adversely affect the nearby ground-water supply because the contaminated ground water is being discharged into the White River where it is greatly diluted.

SUMMARY AND CONCLUSIONS

This brief study has provided a preliminary evaluation of the effect of landfilling on quality of water in the unconsolidated aquifers at each of the seven landfills in the Indianapolis area.

In five of the landfill areas (U.S. Highway 52 and Senour Road, 2561 Kentucky Avenue, 800 West Raymond Street, Banta Road and Tibbs Avenue, and 4300 West Southport Road), movement of ground water is from the deep aquifers into the uppermost aquifer, which precludes leachate contamination in the lower aquifers. In two of the landfill areas (West 96th Street and Zionsville Road and 2700 South Emerson Avenue), movement of ground water is from the shallow aquifers to the deeper aquifers so that leachate is transported to the deeper aquifers. In all the landfills, the predominant direction of ground-water movement is lateral. Placing refuse in the landfills has occasionally altered the local, but not the regional, flow patterns. However, local ground-water pumping has altered regional flow patterns beneath landfills at 2561 Kentucky Avenue and 800 West Raymond Street.

Landfill at U.S. Highway 52 and Senour Road

The ground-water flow pattern beneath this landfill is upward and toward the southeast. Thus, leachate is only in water of the shallow aquifer beneath and at the southeast corner of the refuse. Hydrologic data indicate that the leachate plume beneath the southeast corner is moving slowly toward Buck Creek. Therefore, several observation wells will be constructed between Site E and Buck Creek in order to pinpoint the outer limit of the plume and observe its rate of movement. Also, both Grassy Creek and Buck Creek, through the reach adjacent to the landfill, will be sampled during low-flow periods to determine if ground water being discharged to the streams contains measureable leachate.

Landfill at West 96th Street and Zionsville Road

The flow pattern beneath this landfill is downward and outward from the fill area because of ground-water mounding. In addition, leachate has altered the water quality at shallow depths along the landfill boundary. Because of the need to know the regional direction of ground-water flow near the landfill and the effect of leachate on ground-water quality downgradient from the landfill, additional wells will be constructed.

A report by Bleuer (1970) and data collected in this study indicate that the landfill is in an area having the best hydrologic and geologic conditions for solid-waste disposal in the Indianapolis area. Continuation of the study at West 96th Street and Zionsville Road not only will provide data for determining the degree of recovery of the ground-water quality as it moves from the landfill but also will provide data needed to support standards used in selecting landfill sites.

Landfill at 2561 Kentucky Avenue

The shallow and the deep aquifers beneath this landfill are separated by clay. Direction of flow in the shallow aquifer is southeast toward the White River, whereas flow in the deep aquifer is northwest because of local ground-water pumping. Thus, highly mineralized ground water is moving toward an industrial water supply. The highest mineralization is in the deep aquifer and is assumed to be largely due to leakage from sludge lagoons east of the landfill. Verification of this assumption would require additional water-level and chemical data from the shallow and deep aquifers at points east, north, and south of the landfill.

Landfill at 800 West Raymond Street

Water beneath this landfill is moving northward as a result of industrial well pumping. Leachate from the refuse has altered the water quality in the unconsolidated aquifer in the immediate area of the landfill, and this water is moving in the direction of the industrial wells. To trace the movement of the leachate plume would require installation of wells between the landfill and the industrial wells. Because of the proximity of the industrial wells to the landfill, water-level and water-quality data should be collected frequently.

Landfill at 2700 South Emerson Avenue

Flow in the shallow aquifer is to Lick Creek; flow in the deep aquifer is toward the White River. The unconsolidated aquifers beneath the fill are contaminated, but the areal extent of contamination outside the landfill area is not known. An inventory of domestic and industrial wells in the area may provide a data source for determining the extent of the contamination and the direction in which the contaminated water is moving.

Landfills at Banta Road and Tibbs Avenue and 4300 West Southport Road

Water in the unconsolidated aquifers underlying these two landfills is contaminated. Because the ground-water flow at both landfills is to the west, the contaminated water is being discharged toward White River. The period of data collection at these two landfills has been very brief; therefore, sampling will be continued on a semiannual basis to obtain additional data on leachate concentration in the ground water. The data can be used to estimate the amount and the concentration of leachate being discharged into White River.

Water-level measurements and water-quality sampling of wells continued on a semiannual basis would show when leachate is no longer contaminating water supplies in the area.

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Tables 9-15

Table 9.--Logs of test holes on or near landfill at U.S. Highway 52 and Senour Road

[ID no. (site-identification number): latitude, first 6 digits; longitude, next 7 digits]

Material	Thick-ness (ft)	Depth (ft)
Site A ID no. 3943590855836	Altitude:	835 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Cover/subsoil	12	12
Clay, gravel and sand stringers	43	55
Gravel	6	61
Clay, gravel and sand stringers	103	164
Sand, coarse	6	170
Clay	4	174
Devonian System:		
Middle Devonian Series:		
Limestone	6	180
Site B ID no. 3944100855839	Altitude:	818 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Cover/clay, brown	21	21
Gravel	11	32
Clay	46	78
Site C ID no. 3944150855838	Altitude:	812 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Cover/clay, brown	14	14
Gravel	17	31
Clay, gravel and sand stringers	101	132
Gravel	17	149
Clay, gravelly	14	163
Devonian System:		
Middle Devonian Series:		
Limestone	2	165

Table 9.--Logs of test holes on or near landfill at U.S. Highway 52 and Senour Road--Continued

Material	Thick-ness (ft)	Depth (ft)
Site D ID no. 3944060855816	Altitude:	799 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Cover soil	3	3
Clay, sandy	9	12
Gravel, clay stringers	22	34
Clay, sandy and gravelly	24	58
Gravel	10	68
Clay	69	137
Gravel	3	140
Clay, gray	3.5	143.5
Devonian System:		
Middle Devonian Series:		
Limestone	143.5	
Site E ID no. 3943590855815	Altitude:	798 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Cover soil	4	4
Clay, sandy	5	9
Gravel and sand	13	22
Clay	3	25
Gravel and sand	24	49
Clay	13	62
Gravel	5	67
Clay	74.5	141.5
Devonian System:		
Middle Devonian Series:		
Limestone	141.5	
Site F ID no. 3943590855826	Altitude:	809 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Refuse	15	15
Gravel, clay stringers	19	34
Clay	7	41
Gravel, clay stringers	30	71
Clay	16	87

Table 9.--Logs of test holes on or near landfill at U.S. Highway 52 and Senour Road--Continued

Material	Thickness (ft)	Depth (ft)
Site G ID no. 3944160855834 Altitude: 814 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Till, clayey	22	22
Gravel	4	26
Clay, tan	6	32
Gravel	3	35
Clay, sandy	42	77
Site H ID no. 3944150855824 Altitude: 829 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Refuse	35	35
Clay, sandy	12	47
Gravel and sand	20	67
Clay	32	99
Site I ID no. 3944020855818 Altitude: 814 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Refuse	50	50
Clay, sandy and gravelly	11	61
Clay	17	78
Gravel	5	83
Clay	2	85
Site J ID no. 3944210855834 Altitude: 810 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, silty, brown	14	14
Sand and gravel	5	19
Clay, sandy and gravelly	4	23
Sand and gravel	3	26
Clay, sandy and gravelly	18	44
Sand and gravel	4	48
Clay, sandy and gravelly	5	53
Sand and gravel	57	110

Table 9.--Logs of test holes on or near landfill at U.S. Highway 52 and Senour Road--Continued

Material	Thick-ness (ft)	Depth (ft)
Site K ID no. 3944170855815	Altitude:	810 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, brown	11	11
Clay, some sand	7	18
Sand and gravel, some trace of clay	12	30
Sand and gravel strips	10	40
Clay, gray	5	60
Site L ID no. 3943540855815	Altitude:	797 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, brown	8	8
Sand and gravel	28	36
Clay, sand and gravel	44	80

Table 10.--Logs of test holes on or near landfill at West 96th Street and Zionsville Road

[ID no. (site-identification number): latitude, first 6 digits; longitude, next 7 digits]

Material	Thick-ness (ft)	Depth (ft)
Site A ID no. 3955240861434	Altitude:	887 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, heavy	19	19
Sand and gravelly clay	7	26
Clay with sand and gravel	22	48
Clay	13	61
Clay, gravelly	2	63
Clay, gravelly stringers	29	92
Gravel with some clay	4	96
Clay, sand and gravel stringers	40	136
Clay	22	158
Devonian System:		
Lower Devonian Series:		
Clay with shale chips	8	166
Shale		166
Site B ID no. 3955240861430	Altitude:	885 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, heavy	9	9
Clay, gravelly	16	25
Gravel	4	29
Clay, gravelly	30	59
Sand, coarse, containing gravel	3	62
Clay, gray, containing gravel	8	70
Sand, coarse, containing clay	3	73
Clay, gravelly	78	151
Clay, hard	14	165
Clay containing sand	3	168
Devonian System:		
Lower Devonian Series:		
Shale	4	172

Table 10.--Logs of test holes on or near landfill at West 96th Street and Zionsville Road--Continued

Material	Thickness (ft)	Depth (ft)
Site C ID no. 3955200861429	Altitude:	888 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Refuse	40	40
Clay, hard	15	55
Clay	33	88
Clay containing sand and gravel	20	108
Clay containing gravel	52	160
Clay, sandy	5	165
Devonian System:		
Lower Devonian Series:		
Shale	165	
Site D ID no. 3955110861428	Altitude:	883 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Clay	21	21
Gravel and sand	4	25
Clay	23	48
Clay containing gravel	50	98
Clay	23	121
Clay containing gravel	30	151
Clay containing gravel and clay chips	7	158
Devonian System:		
Lower Devonian Series:		
Shale	2	160
Site E ID no. 3955170861439	Altitude:	884 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Clay	19	19
Clay with some gravel	10	29
Clay	66	95
Clay with some gravel	4	99
Clay, hard	6	105
Clay containing some gravel	4	109
Clay	30	139
Clay, sandy	5	144
Clay	9	153

Table 10.--Logs of test holes on or near landfill at West 96th Street and Zionsville Road--Continued

Material	Thick-ness (ft)	Depth (ft)
Site E--Continued		
Devonian System:		
Lower Devonian Series:		
Shale	3	156
Site F ID no. 3955200861438	Altitude:	890 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Refuse	40	40
Clay, soft	15	55
Clay, gravelly	5	60
Clay, soft with stringers of hard clay	52	112
Clay, sandy	22	134
Clay	19	153
Clay, gravelly	9	164
Clay	2	166
Devonian System:		
Lower Devonian Series:		
Shale		166

Table 11.--Logs of test holes on or near landfill at 2561 Kentucky Avenue

[ID no. (site-identification number): latitude, first 6 digits; longitude, next 7 digits]

Material	Thickness (ft)	Depth (ft)
Site A ID no. 3943160861219 Altitude: 680 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay	16	16
Sand, coarse	13	29
Sand, fine	11	40
Gravel	6	46
Clay, with sand	21	67
Sand and gravel, coarse	12	79
Sand, medium to fine	12	91
Sand, medium to coarse	11	102
Devonian System:		
Lower Devonian Series:		
Limestone		102
Site B ID no. 3943170861151 Altitude: 675 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay and silty sand	9	9
Gravel with some sand	7	16
Sand and gravel, coarse	11	27
Sand and gravel with some clay	9	36
Clay with some sand and gravel	17	53
Sand, coarse, with some clay	5	58
Clay with some sand and gravel	6	64
Sand and gravel	28	92
Clay with some sand and gravel	5	97
Site C ID no. 3943130861151 Altitude: 671 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay	8	8
Sand with some clay	2	10
Sand and gravel	19	29
Clay with some sand and gravel	10	39

Table 11.--Logs of test holes on or near landfill at 2561 Kentucky Avenue--Continued

Material	Thick-ness (ft)	Depth (ft)
Site D ID no. 3943100861150 Altitude: 675 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Top soil and clay	11	11
Sand and gravel	15	26
Clay with sand and gravel	23	49
Clay, sand and gravel stringers	15	64
Sand and gravel	9	73
Sand and gravel, clay stringers	10	83
Gravel and sand	18	101
Devonian System:		
Lower Devonian Series:		
Boulders	1	102
Shale		102
Site E ID no. 3943130861204 Altitude: 695 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, brown	8	8
Sand with some clay	4	12
Sand and gravel	14	26
Clay with sand	40	66
Sand, medium, with some clay	19	85
Gravel	10	95
Clay	5	100
Devonian System:		
Lower Devonian Series:		
Shale		100
Site F ID no. 3943110861213 Altitude: 680 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, brown	14	14
Gravel and sand	3	17
Clay with silt and sand	10	27
Sand, coarse	7	34
Clay, sandy	18	52
Sand with some clay	18	70
Sand and gravel with clay stringers	17	87
Sand and gravel	6	93
Clay	26	119

Table 11.--Logs of test holes on or near landfill at 2561 Kentucky Avenue--Continued

Material	Thick-ness (ft)	Depth (ft)
Site F--Continued		
Devonian System:		
Lower Devonian Series:		
Limestone		119
Site G ID no. 3943170861205 Altitude: 690 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay cover	0	0
Refuse	22	22
Clay, gravel and sand	17	39
Site H ID no. 3943170861054 Altitude: 687 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay cover	4	4
Refuse	14	18
Clay	1	19

Table 12.--Logs of test holes on or near landfill at 800 West Raymond Street

[ID no. (site-identification number): latitude, first 6 digits; longitude, next 7 digits]

Material	Thick-ness (ft)	Depth (ft)
Site A ID no. 3944290861015	Altitude: 691 ft	
Quaternary System:		
Holocene and Pleistocene Series:		
Top soil and clay	15	15
Gravel and coarse sand	6	21
Sand and gravel, very coarse	18	39
Sand and gravel, sorted coarse	16	55
Sand and gravel, coarse	25	80
Clay	2	82
Devonian System:		
Lower Devonian Series:		
Limestone		82
Site B ID no. 3944240861029	Altitude: 683 ft	
Quaternary System:		
Holocene and Pleistocene Series:		
Fill, soil, and sand	9	9
Sand and gravel	25	34
Sand, gravel, and pebbles	4	38
Clay	8	46
Sand and gravel, clay stringers	9	55
Sand and gravel	23	78
Clay with sand and gravel	9	87
Devonian System:		
Lower Devonian Series:		
Limestone		87
Site C ID no. 3944180861039	Altitude: 674 ft	
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, silt, sand and gravel	19	19
Sand	11	30
Sand and gravel	6	36
Sand	5	41
Sand and gravel	40	81
Clay	1.5	82.5

Table 12.--Logs of test holes on or near landfill at 800 West Raymond Street--Continued

Material	Thick-ness (ft)	Depth (ft)
Site C--Continued		
Devonian System		
Lower Devonian Series:		
Limestone		82.5
Site D ID no. 3944140861018 Altitude: 694 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, brown	7	7
Gravel	2	9
Clay, brown	12	21
Gravel and sand, fine	14	35
Sand and gravel	24	59
Sand and gravel with some clay stringers	32	91
Devonian System:		
Lower Devonian Series:		
Shale		91
Site E ID no. 3944110861026 Altitude: 679 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Soil with sand and gravel	9	9
Sand and gravel	7	16
Clay with sand and gravel	5	21
Sand and gravel	9	30
Clay	1	31
Sand and gravel, coarse	6	37
Clay with some sand and gravel	18	55
Sand and gravel with some clay	24	79
Sand and gravel	2	81
Sand, gravel and clay	4	85
Devonian System:		
Lower Devonian Series:		
Limestone	4	89

Table 12.--Logs of test holes on or near landfill at 800 West Raymond Street--Continued

Material	Thick-ness (ft)	Depth (ft)
Site F ID no. 3944230861021	Altitude:	690 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Top soil, clay with some sand and gravel	11	11
Sand, gravel and pebbles	8	19
Sand and gravel	25	44
Clay layer	2	46
Gravel, sorted	13	59
Sand and gravel	26	85
Sand and gravel with some clay	6	91
Devonian System:		
Lower Devonian Series:		
Limestone		91
Site G ID no. 3944230861021	Altitude:	690 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Cover		1.5
Refuse	50.5	52
Clay, gray	10	62
Sand and gravel	5	67
Site H ID no. 3944190861031	Altitude:	683 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Refuse	47	47
Clay mixture	8	55
Sand and gravel mixture	7	62

Table 13.--Logs of test holes on or near landfill at 2700 South Emerson Avenue

[ID no. (site-identification number): latitude, first 6 digits; longitude, next 7 digits]

Material	Thick-ness (ft)	Depth (ft)
Site A ID no. 3943450860500	Altitude: 808 ft	
Quaternary System:		
Holocene and Pleistocene Series:		
Clay and silt	1.5	1.5
Cinders and asphalt	1	2.5
Subsoil with sand and gravel	9.5	12
Sand, gravel and pebbles	5	17
Clay with some sand and gravel	21	38
Clay, sandy and gravelly	16	54
Sand and gravel layer	2	56
Clay, sandy and gravelly	43	99
Clay with sand and gravel stringers	20	119
Sand and gravel with some clay	9	128
Clay with some sand and gravel	20	148
Clay	16	164
Devonian System		
Middle Devonian Series:		
Shale	1	165
Site B ID no. 3943580860508	Altitude: 808 ft	
Quaternary System:		
Holocene and Pleistocene Series:		
Soil, brown	14	14
Clay	7	21
Gravel stringers	3	24
Clay with gravel stringers	4	28
Clay, hard, gray	24	52
Clay with gravel	4	56
Clay, hard	56	112
Clay, sand stringers	15	127
Clay	24	151
Clay with sand and gravel	19	170
Clay	3	173
Devonian System:		
Middle Devonian Series:		
Limestone		173

Table 13.--Logs of test holes on or near landfill at 2700 South Emerson Avenue--Continued

Material	Thick-ness (ft)	Depth (ft)
Site C ID no. 3943540860617	Altitude:	796 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Soil	16	16
Clay with gravel	4	20
Gravel with some clay stringers	10	30
Clay with sand and gravel	25	55
Clay, sandy	1	56
Clay with sand	8	64
Clay, gravelly	1	65
Clay, sand and gravel stringers	36	101
Sand and gravel with some clay	7	108
Clay, sand and gravel	56	164
Clay and sand	75	171.5
Devonian System:		
Middle Devonian Series:		
Limestone		171.5
Site D ID no. 3943460860521	Altitude:	791 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Soil with sand and gravel	14	14
Clay	6	20
Sand and gravel	12	32
Clay, heavy	8	40
Clay	17	57
Clay, sand and gravel stringers	46	103
Sand, sorted layer	2	105
Clay, sandy	15	120
Site E ID no. 3943390860515	Altitude:	813 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, brown to tan	20	20
Sand and gravel	4	24
Clay, sandy and gravelly	8	32
Sand and gravel	8	40
Clay, sand and gravel stringers	64	104
Sand and gravel	4	108

Table 13.--Logs of test holes on or near landfill at 2700 South Emerson Avenue--Continued

Material	Thick-ness (ft)	Depth (ft)
Site E--Continued		
Quaternary System--Continued:		
Holocene and Pleistocene Series--Continued:		
Clay, sand and gravel stringers	16	124
Clay	26	150
Clay, sand and gravel stringers	23	173
Devonian System:		
Middle Devonian Series:		
Limestone		173
Site F ID no. 3943380860504 Altitude: 810 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Cover and refuse	12	12
Clay	13	25
Clay, sandy and gravelly	8	33
Sand and gravel	8	41
Clay	42	83
Sand and gravel, some clay	4	87
Clay, sandy and gravelly	7	94
Clay	56	150
Site G ID no. 3943400860456 Altitude: 814 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, brown	22	22
Clay, sandy and gravelly	7	29
Sand and gravel	5	34
Clay, traces of sand and gravel	81	115
Sand and gravel, traces of clay	19	134
Clay	4	138
Site H ID no. 3943430860509 Altitude: 832 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Cover dirt	4	4
Refuse	42	46
Clay	10	56

Table 14.--Logs of test holes on or near landfill at Banta Road and Tibbs Avenue

[ID no. (site-identification number): latitude, first 6 digits; longitude, next 7 digits]

Material	Thick-ness (ft)	Depth (ft)
Site A ID no. 3940150861257 Altitude: 670 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay fill, brown	14	14
Clay, brown, some gravel	12	26
Gravel, sandy, medium; some clay	13	39
Gravel, medium to heavy; some clay	19	58
Clay, dark gray	8	66
Sand, coarse, to heavy gravel	19	103
Mississippian System:		
Lower Mississippian Series:		
Shale, black	5	108
Site B ID no. 3940140861314 Altitude: 670 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Refuse	15	15
Clay	3	18
Site C ID no. 3940120861334 Altitude: 670 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Refuse	29	29
Gravel, sandy, with clay	31	60
Clay	15	75
Mississippian System:		
Lower Mississippian Series:		
Bedrock		75
Site D ID no. 3940120861349 Altitude: 660 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, dark brown	12	12
Gravel, sandy, medium to coarse	4	16
Clay, gray	24	40

Table 14.--Logs of test holes on or near landfill at Banta Road and Tibbs Avenue--Continued

Material	Thickness (ft)	Depth (ft)
Site D--Continued		
Quaternary System--Continued:		
Holocene and Pleistocene Series--Continued:		
Sand and gravel	2	42
Clay	4	46
Mississippian System:		
Lower Mississippian Series:		
Limestone		46
Site E ID no. 3940230861329 Altitude: 672 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Refuse	24	24
Clay	34	58
Mississippian System:		
Lower Mississippian Series:		
Bedrock		58
Site F ID no. 3940230861329 Altitude: 672 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Soil, dark brown	5	5
Sand and medium gravel	5	10
Gravel, coarse	5	15
Clay, gray		15
Site G ID no. 3940160861339 Altitude: 675 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Refuse	26	26
Clay	4	30
Site H ID no. 3940140861405 Altitude: 662 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, silty, brown	14	14
Gravel	2	16

Table 14.--Logs of test holes on or near landfill at Banta Road and Tibbs Avenue--Continued

Material	Thick-ness (ft)	Depth (ft)
Site H--Continued		
Quaternary System--Continued:		
Holocene and Pleistocene Series--Continued:		
Clay, gravelly	10	26
Clay, gray	12	38
Clay, soft, greenish	5	43
Mississippian System:		
Lower Mississippian Series:		
Dolomite		43

Table 15.--Logs of test holes on or near landfill at 4300 West Southport Road

[ID no. (site-identification number): latitude, first 6 digits; longitude, next 7 digits]

Material	Thick-ness (ft)	Depth (ft)
Site A ID no. 3939460861348	Altitude:	659 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Soil, dark brown	9	9
Gravel, sandy	12	21
Clay with sandy stripe	7	28
Clay, soft, gray	17	45
Clay, firm, gray	4.5	49.5
Mississippián System:		
Lower Mississippian Series:		
Bedrock		49.5
Site B ID no. 3939470861405	Altitude:	661 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, gravelly	9	9
Gravel, coarse	16	25
Site C ID no. 3939460861404	Altitude:	669 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, heavy	18	18
Sand and gravel	12	30
Clay, brown	6	36
Clay, gray	8	44
Mississippian System:		
Lower Mississippian Series:		
Shale, soft	10	54
Shale, hard	5	59
Site D ID no. 3939390861402	Altitude:	668 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, gravelly	12	12
Clay, silty	3	15
Clay, sandy	2	17

Table 15.--Logs of test holes on or near landfill at 4300 West Southport Road--Continued

Material	Thickness (ft)	Depth (ft)
Site D--Continued		
Quaternary System--Continued:		
Holocene and Pleistocene Series--Continued:		
Sand and gravel	19	36
Clay	3	39
Site E ID no. 3939340861402 Altitude: 656 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Clay, sandy and gravelly	10	10
Gravel, muddy	3	13
Sand and gravel, clean	6	19
Clay, gray, with sandy strips	28	47
Gravel and sand, some clay	6	53
Mississippian System:		
Lower Mississippian Series:		
Shale, weathered, and bedrock	2	55
Site F ID no. 3939340861356 Altitude: 658 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Soil, dark brown	5	5
Sand and medium gravel	5	10
Gravel, coarse	5	15
Clay, gray		15
Site G ID no. 3939340861347 Altitude: 659 ft		
Quaternary System:		
Holocene and Pleistocene Series:		
Soil, brown	5	5
Clay, sandy and gravelly	4	9
Sand and gravel	9	18
Clay, gray	20	38
Clay, sandy and gravelly	9	47
Gravel, coarse	4	51
Clay, gray	4	55
Mississippian System:		
Lower Mississippian Series:		
Shale		55

Table 15.--Logs of test holes on or near landfill at 4300 West Southport Road--Continued

Material	Thick-ness (ft)	Depth (ft)
Site H ID no. 3939400861347	Altitude:	659 ft
Quaternary System:		
Holocene and Pleistocene Series:		
Soil, brown, silty	4	4
Sand, silty	3	7
Gravel and sand	11	18
Clay, gray	1	19

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U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849