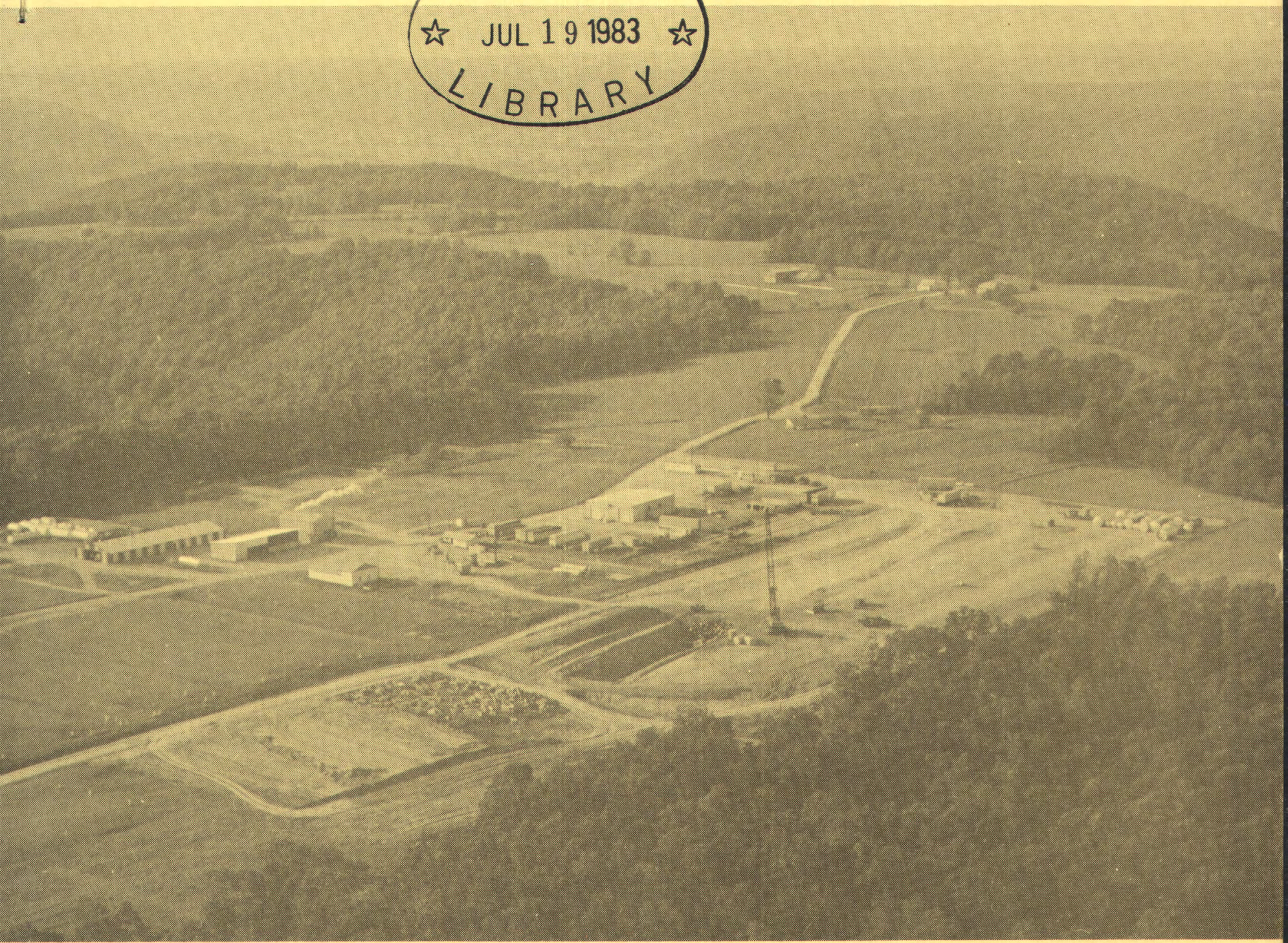
HYDROGEOLOGIC INVESTIGATION OF THE MAXEY FLATS RADIOACTIVE WASTE BURIAL SITE, FLEMING COUNTY, KENTUCKY



U.S. GEOLOGICAL SURVEY OPEN-FILE REPORT 83-133

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

HYDROGEOLOGIC INVESTIGATION OF THE MAXEY FLATS RADIOACTIVE WASTE BURIAL SITE, FLEMING COUNTY, KENTUCKY

By Harold H. Zehner

Open-File Report 83-133

Louisville, Kentucky

1983

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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CONVERSION FACTORS AND ABBREVIATIONS

"Inch-pound" units of measure used in this report may be converted to International System (metric) units by using the following factors:

Multiply	*By*	*To obtain*
inch (in.)	2.540	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
pound (lb)	0.4536	kilogram (kg)
Curie (Ci)	3.7×10^{10}	becquerel (Bq)
picocurie (pCi)	3.7×10^{-2}	becquerel (Bq)
micromho per centimeter at 25° Celsius (umhos/cm at 25°C)	1.000	microsiemen per centimeter at 25° Celsius (uS/cm at 25°C)
degree Fahrenheit (°F)	°C = 5/9 (°F-32)	degree Celsius (°C)

ALTITUDE DATUM

The term "National Geodetic Vertical Datum of 1929" (abbreviation, NGVD of 1929) replaces the formerly used term "mean sea level" to describe the datum for altitude measurements. The NGVD of 1929 is derived from a general adjustment of the first-order leveling networks of both the United States and Canada. The NGVD of 1929 is reference to as sea level in this report.

HYDROGEOLOGY OF THE MAXEY FLATS RADIOACTIVE WASTE BURIAL SITE, FLEMING COUNTY, KENTUCKY

By Harold H. Zehner

ABSTRACT

Part of a hilltop named Maxey Flats was used as a commercial radioactive waste burial site from 1963 to 1977. The hill is located in northeastern Kentucky, about 9 miles from the city of Morehead. The climate of the area is humid, with normal annual precipitation 44.30 inches for the period 1941 through 1970.

Most of the 47 burial trenches on the site are completed in weathered shale. They are covered with clay and crushed shale, but water infiltrates the covers and accumulates in the waste. The contaminated trench water is later removed and evaporated. Assuming water in trenches would not overflow onto the ground surface, flow through fractured rocks would be the principal means of contaminated-water transport if trench water were to move from the burial site. The bases of most trenches consist of a 1.5-foot-thick sandstone bed, at a depth of about 25 feet below ground level. Radionuclides have moved laterally through fractures in the bed as much as 270 feet from the nearest burial trench.

Rocks underlying the burial site are of Mississippian, Devonian, and Silurian age, about 80 percent of which are shale. The bedrock has poor water-transmitting capability, and virtually all flow is through fractures. The spacing between most fractures is several feet, although it ranges from a few inches to more than 100 feet. Most fractures terminate, or are offset, at bedding planes. The ground-water system is therefore very nonuniform, and more permeable in the horizontal direction.

At least eight hydrologic units underlie the burial site. These strata probably contain at least two water tables: one about 25 feet, and the other about 300 feet, below ground level. Other saturated-unsaturated sequences may be located between these two water tables. The complex ground-water system in bedrock is analyzed by assuming that flow is through uniform fracture openings. Fracture-spacing data and a conceptual flow model are used to estimate the maximum potential discharge from bedrock in the drainage basin below the site. The estimated discharge is about 0.1 inch per year, which is about 5 percent of the mean annual base flow. The remaining 95 percent is ground-water discharge from colluvium and alluvium that largely cover hillsides and valley bottoms. Maximum potential discharge from bedrock underlying the burial site is estimated as 0.5 percent of mean annual base flow.

Chloride concentration is several thousand milligrams per liter in lower rocks, which indicates that the most active part of the ground-water system in bedrock is in the less saline, upper part of the hill. Several waste isotopes were identified in water from the weathered shale on the hilltop. Tritium was the only waste isotope that indicated deeper flow of trench water. Overland runoff and ground water in colluvium and alluvium considerably dilute water that is discharged from bedrock. The dilution factor for water that is discharged from bedrock underlying the trench area is about 2,000, based on mean-monthly streamflow.

Tritium was the only waste radionuclide detected in water from alluvium, and may have been due to shallow infiltration of precipitation that had first fallen through vapor effluent from the trench-water evaporator. Most waste radionuclides in streams are probably due to transport of contaminated soil from the surface of the burial site during runoff events.

Assuming infiltration through trench caps continues to exceed flow from trenches to surrounding rocks, overflow of trench water would result if trench-water pumping were to cease. Covering the burial area with poorly permeable material will reduce infiltration into trenches, but will also cause increased runoff and accelerated erosion of the adjacent hillsides. Erosion rates are unknown in the Maxey Flats area, but knowledge of such rates is necessary for understanding the long-term stability of the burial site.

Additional monitoring of the Maxey Flats site could include construction of sediment stations, additional stream-gaging stations, and shallow wells. Data from the stations could be used for computing dissolved and particulate radionuclide loads in the valleys adjacent to the burial site. Sediment stations could also be used to monitor erosion in the area. Shallow wells completed in colluvium and alluvium could be used to monitor discharge of radionuclides from bedrock.

INTRODUCTION

Purpose, Scope, and Description of Study

The purpose of this report is to describe the hydrogeology of the Maxey Flats radioactive waste burial site (hereafter referred to as the Maxey Flats site). The information gained from the study may be used for evaluation of proposed radioactive waste burial sites in hydrologic and geologic settings similar to Maxey Flats. Maxey Flats is one of five areas which were investigated in order to describe hydrologic conditions at radioactive waste burial sites located in different terrains and climates. The studies were undertaken at the request of the United States Congress.

The scope of the study involved investigation of local surface-water and ground-water systems in the Maxey Flats area, with particular emphasis on the burial site. Numerous observations of road cuts, outcrops, and walls of burial trenches were made for determining the relationship of fractures to ground-water flow. The ground-water system was studied principally by measurement of fracture spacing in the Maxey Flats area, and by use of data obtained on the burial site from 30 wells and 47 burial trenches. The well data were used to estimate positions of saturated zones and water-transmitting characteristics of the rocks, and to examine the relationship of ground-water flow and water quality.

The period of study for this report was from 1975 through 1980. Some information, particularly that relating to water use in the area, was obtained from a study conducted in 1974 and 1975 (Zehner, 1980).

Ground-water studies generally involve quantitative description of the hydrologic system, including volumes, velocities, and directions of flow. Papadopulos and Winograd (1974), describe inherent difficulties in studying poorly permeable fractured systems, and state that, regardless of cost, evaluation of such systems may not be possible. To an extent, this was found to be true for the Maxey Flats system. Extensive data relating to ground-water flow were collected, but much of it yielded only limited useful information. This is primarily due to the difficulty of obtaining meaningful hydrologic information from poorly permeable strata which have different hydraulic properties, and in which most flow is through fractures. The report therefore consists mostly of a simplified description of the complex flow system.

Location and Site History

Maxey Flats is located 9 mi northwest of the city of Morehead, in northeastern Kentucky (fig. 1). The area is shown on the south-central part of the Plummers Landing 7.5-minute topographic quadrangle map. The Maxey Flats site is irregular in shape, but is about 5,000 ft long by about 3,000 ft wide (fig. 2). The part of the site underlain by trenches is about 1800 ft long by about 1200 ft wide.

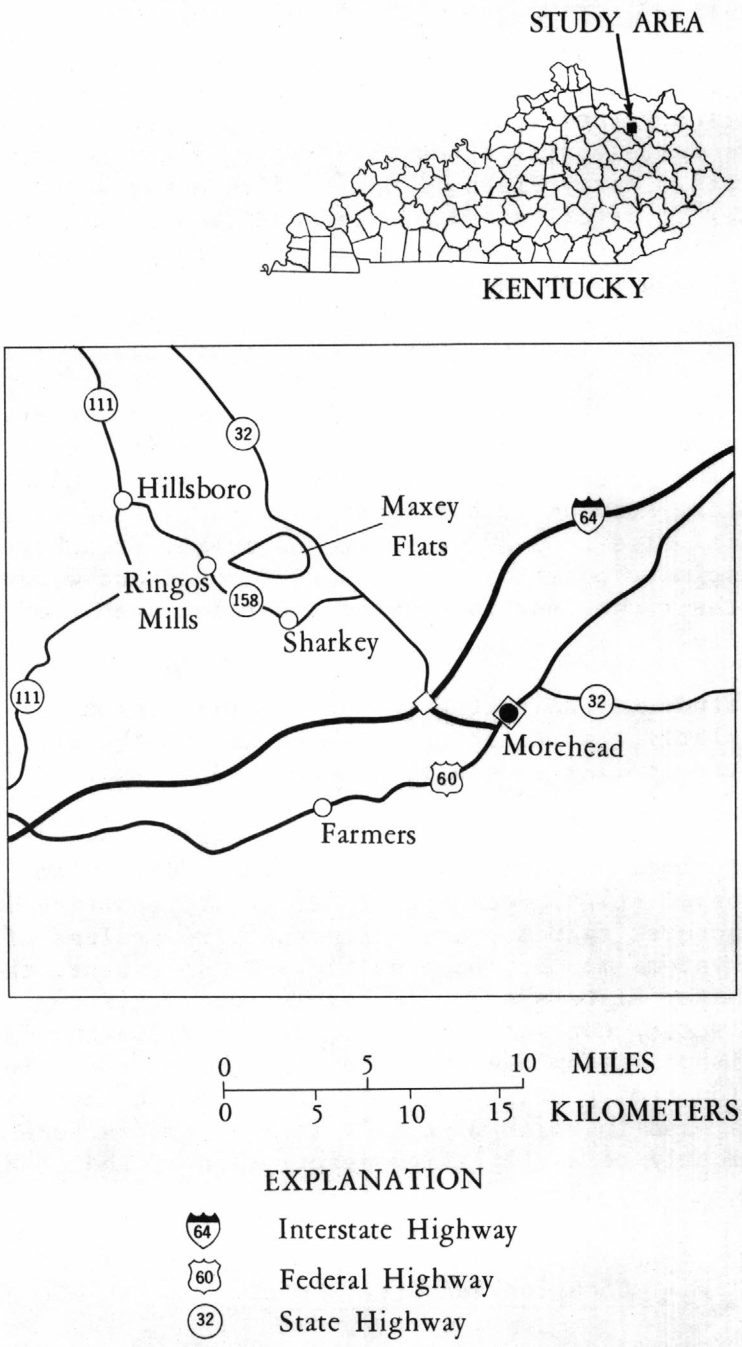
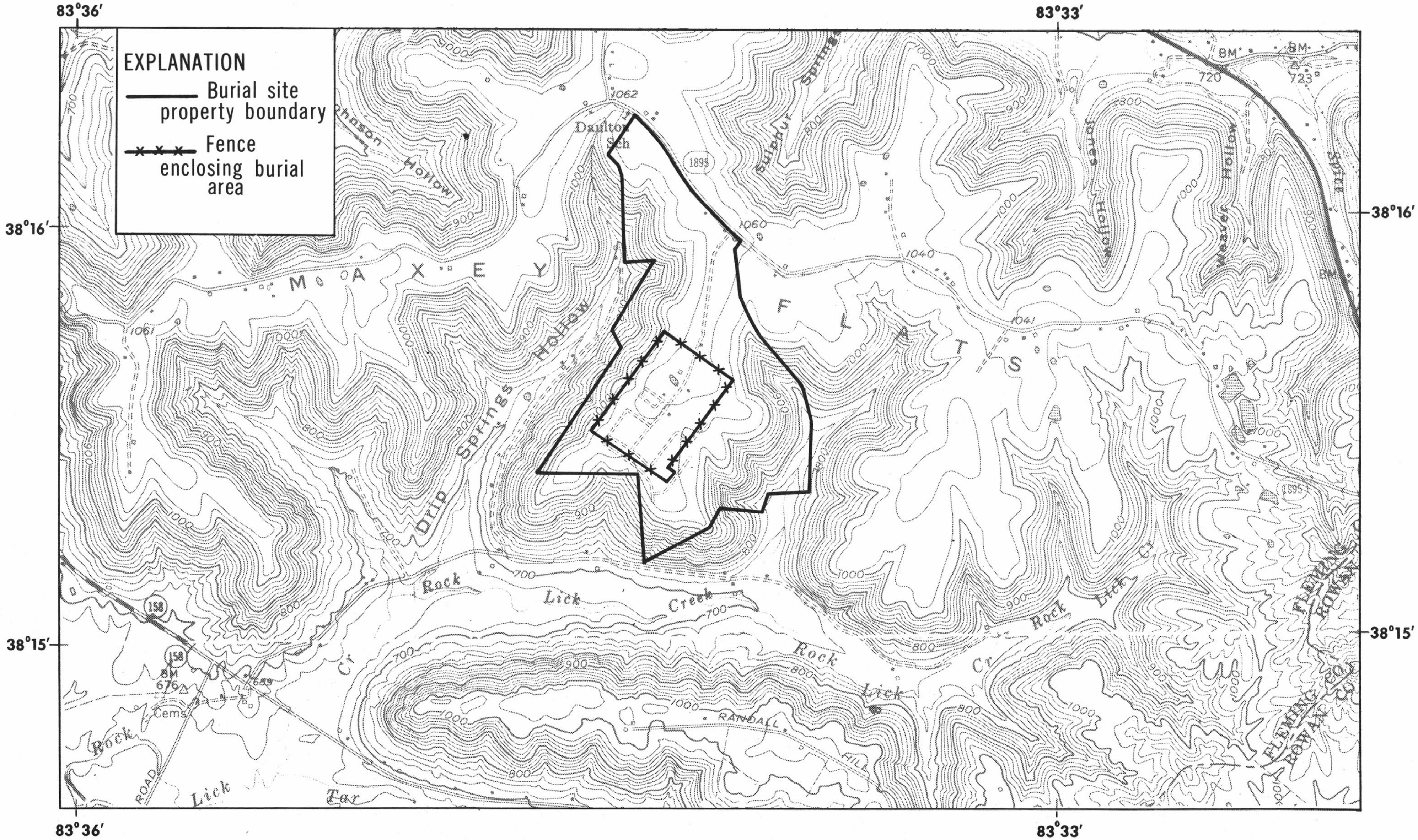


Figure 1.--Location of Maxey Flats and study area.



Base from U.S. Geological Survey Plummers Landing 1:24000, 1951, revisions as of 1979 and Farmers 1:24000, 1970.

1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

CONTOUR INTERVAL 20 FEET

National Geodetic Vertical Datum of 1929

Figure 2.-- Location of the Maxey Flats site.

The Maxey Flats site was operated by Nuclear Engineering Company (now named U.S. Ecology Company) as a commercial radioactive waste burial facility from May 1963 until operation ceased in December 1977. Since then, only waste that is generated on site from routine monitoring and maintenance activities is buried. The site is presently being maintained and decommissioned by a commercial firm, under contract with the Kentucky Department for Natural Resources and Environmental Protection. This department also holds title to the land. Radiation monitoring is done by the Kentucky Department for Human Resources.

Approximately 4.8 million cubic feet of waste, containing over 2.4 million curies of byproduct material, 431 kilograms of special nuclear material, and 533 thousand pounds of source material were buried during the period of commercial operation (D. Clark, Kentucky Department for Human Resources, written commun., April 1980). Briefly defined: byproduct material is material made radioactive by exposure to radiation; special nuclear material is plutonium, uranium-233, and enriched uranium-235; and source material is uranium and thorium, not including special nuclear material. By convention, the unit for quantity of special nuclear material is gram, whereas that of source material is pound.

Most waste is in solid form and is buried in 47 rectangular trenches, most of which are about 25 ft deep. The trenches are separated by about 5 to 10 ft of shale containing several thin (less than 3 ft) sandstone beds. When filled, they are covered with approximately 3 to 10 ft of compacted clay and crushed shale. A program was initiated in 1972 to remove and evaporate water that had accumulated in the trenches. Dewatering continues as rainfall infiltrates the trench area.

Previous Studies

Clark (1973) outlined the history of the Maxey Flats site, and described the quantities of radioactive material buried there. The Kentucky Department for Human Resources (1974) reported concentrations of radioactivity around the Maxey Flats site. Problems regarding shallow land burial of radioactive wastes were identified by the Comptroller General of the United States (1976). Meyer (1976) discussed transuranium nuclides in the environment at Maxey Flats. Hydrologic data collected from 1963 to 1977 were reviewed by Dames and Moore consulting firm (March 1977). Montgomery and others (1977) and Blanchard and others (1978) described radionuclides in evaporator effluent, and in ground and surface water near the site. Water-quality samples were analyzed by personnel from Brookhaven National Laboratory as part of the present hydrologic study, and results were reported by Weiss and Colombo (1980). Cleveland and Rees (1981) described complexed plutonium species in trench water at Maxey Flats.

The following reports deal with the geology and hydrology at, or near, the Maxey Flats site:

(a) Hall and Palmquist (1960) described the lithology and general water-yielding characteristics of wells in a three-county area, including Fleming County.

(b) Walker (1962) described the lithology and injected-water acceptance in eight holes drilled on the Maxey Flats site.

(c) H. Hopkins (U.S. Geological Survey, written commun., 1962) briefly described results of streamflow measurements and a hydrologic reconnaissance of wells and springs in the area.

(d) McDowell and others (1971), and McDowell (1975) mapped the geology of the area.

(e) Papadopulos and Winograd (1974) reported current knowledge and future data needs to evaluate potential modes and rates of nuclide migration that could possibly occur in the ground-water system.

(f) Emcon Associates (1975) described lithologic and hydrologic characteristics of 14 wells on the Maxey Flats site.

(g) Zehner (1980) described the general hydrology of the Maxey Flats area.

(h) Pollock and Zehner (1981) described a two-dimensional model of the ground-water system.

Acknowledgments

Thanks are given to the Kentucky Department for Human Resources for supplying administrative assistance and radionuclide data. Staff from Brookhaven National Laboratory performed principal-ion, organic, and nuclide analyses on trench and well water with funds appropriated by the U.S. Nuclear Regulatory Commission. Some radiochemical analyses were performed by the U.S. Environmental Protection Agency. Health physics work was done by the Dames and Moore consulting firm, which also generously provided the base map of the trench area.

Nuclear Engineering Company provided administrative assistance, some rainfall data, and storage facilities for equipment. The Kentucky Department for Finance and Administration allowed drilling to proceed in the trench area, and financed health physics work performed during drilling operations. The U.S. Geological Survey borehole geophysics group logged many wells on the burial site.

TOPOGRAPHY AND CLIMATE

The Knobs Region of Kentucky is the remnant of an eroded plateau, characterized by the presence of many knoblike erosional remnants of Silurian, Devonian, and Mississippian rocks (McFarlan, 1943). Maxey Flats is the top of one "knob" in this plateau. The burial site occupies a part of this knob, and is at a height of 300 to 400 ft above the valley bottoms. Valleys extend around part of the site, with an unnamed valley to the east, Rock Lick Creek to the south, and Drip Springs Hollow to the west (fig. 2). Figure 3 is an aerial photograph of the burial site and the adjacent valleys. Topographic gradients of the hillsides are steep (30 to 40 percent), and outcrops of sandstone on much of the upper one-third of the hillsides form near-vertical erosional scarps.

Normal annual precipitation at a U.S. Weather Bureau station in Farmers, Kentucky, located 8 mi south of the Maxey Flats site (fig. 1), was 44.30 in. for the period 1941 through 1970 (U.S. Department of Commerce, 1973). Collection of daily rainfall data began at the Maxey Flats site in 1972 (Nuclear Engineering Company, 1975). A continuous recording rain gage was installed at the burial site on October 1, 1975 for the present study. Daily rainfall from the continuous-recording gage represents midnight-to-midnight periods. Precipitation data from Farmers were used for short periods (less than 10 days) when data were lost due to gage failure. Monthly precipitation at Maxey Flats and normal monthly precipitation at Farmers, Kentucky, are given in table 1.

Annual rainfall at Farmers and Maxey Flats is shown in figure 4. Rainfall at both sites was greater than normal four of the six years (1974 through 1979) during which rainfall data were collected at Maxey Flats. Figure 5 is a plot of daily rainfall at Maxey Flats. Reference to the plot is made later in the report, regarding the relationship of precipitation and water levels in trenches and wells.

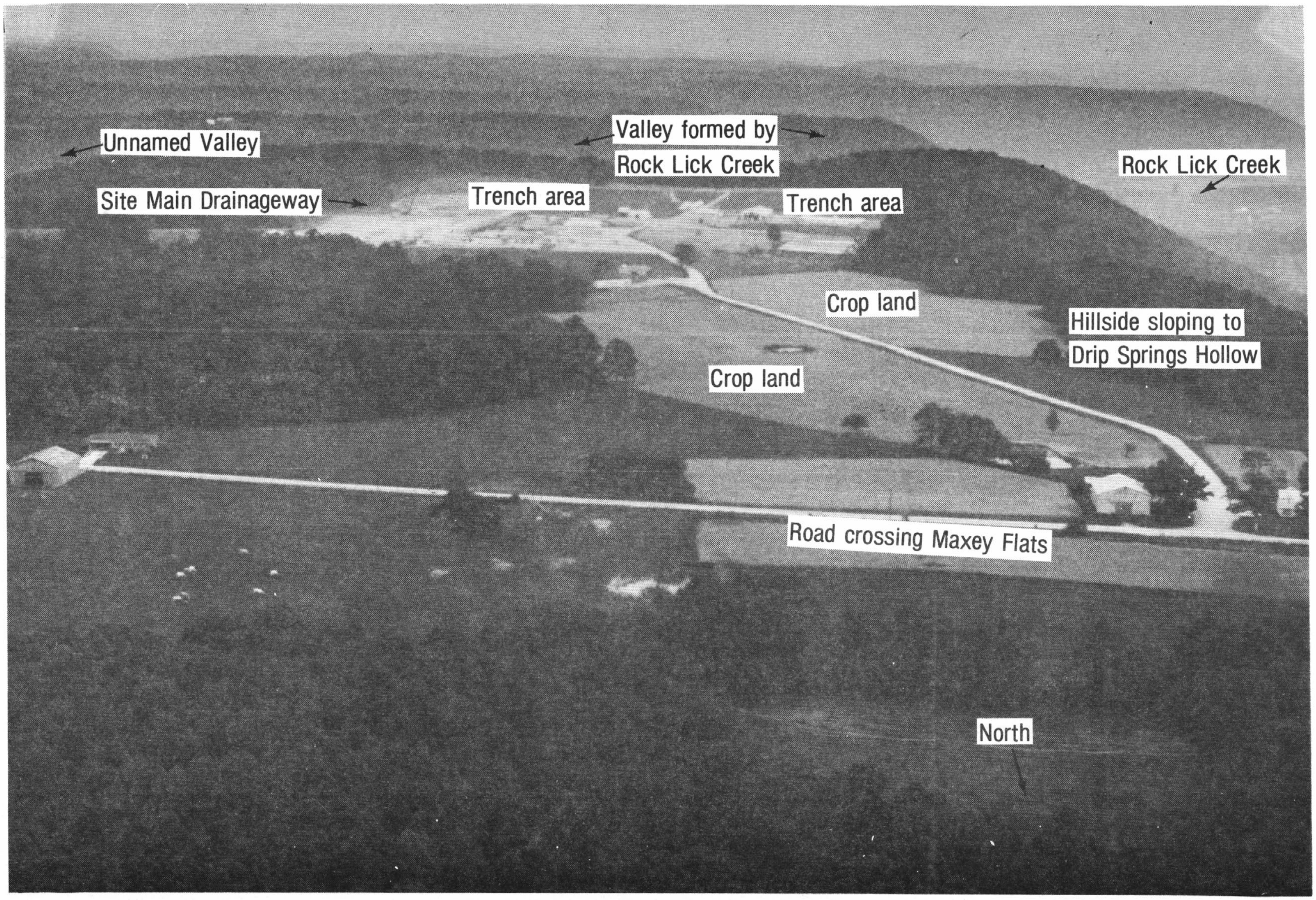


Figure 3.-- Maxey Flats site. Photograph courtesy of EG&G, Inc., Las Vegas, Nevada.

TABLE 1.--Monthly rainfall at Maxey Flats, and normal monthly rainfall at Farmers, Kentucky

[Data from Maxey Flats through September 1975 from Nuclear Engineering Co., 1975, except where indicated. Values in inches.]

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
1973	1.73	1.96	3.03	4.86	5.30	3.30	4.64	1.20	2.92	3.08	5.65	2.42	40.09
1974	6.56	1.61	5.92	4.66	[1]5.82	[1]6.09	2.56	9.36	4.26	1.17	2.35	4.41	54.77
1975	3.51	5.27	8.12	5.10	3.12	3.30	4.80	3.89	6.79	[1]5.05	2.34	3.36	54.65
1976	[1]2.93	[1]3.18	3.77	0.96	3.37	4.78	4.56	2.56	4.16	3.57	0.26	1.66	35.76
1977	1.06	0.87	3.35	4.41	2.59	3.59	3.64	6.34	1.16	3.28	3.23	2.33	35.85
1978	6.87	1.01	4.15	2.24	5.83	2.99	9.81	5.25	2.27	3.13	3.13	9.81	56.49
1979	4.87	3.63	2.25	2.85	4.07	5.17	10.81	4.39	7.00	3.30	3.14	3.75	55.23
Mean	3.93	2.50	4.37	3.58	4.30	4.17	5.83	4.71	4.08	3.23	2.87	3.96	47.55
Normal[2]	3.61	3.45	4.50	3.84	4.20	3.93	4.84	3.95	3.21	2.18	3.35	3.24	44.30

[1]Part of data from U.S. Weather Bureau station at Farmers, Ky.
[2]Normal for period 1941 through 1970 at Farmers, Ky. (U.S. Department of Commerce, 1973).

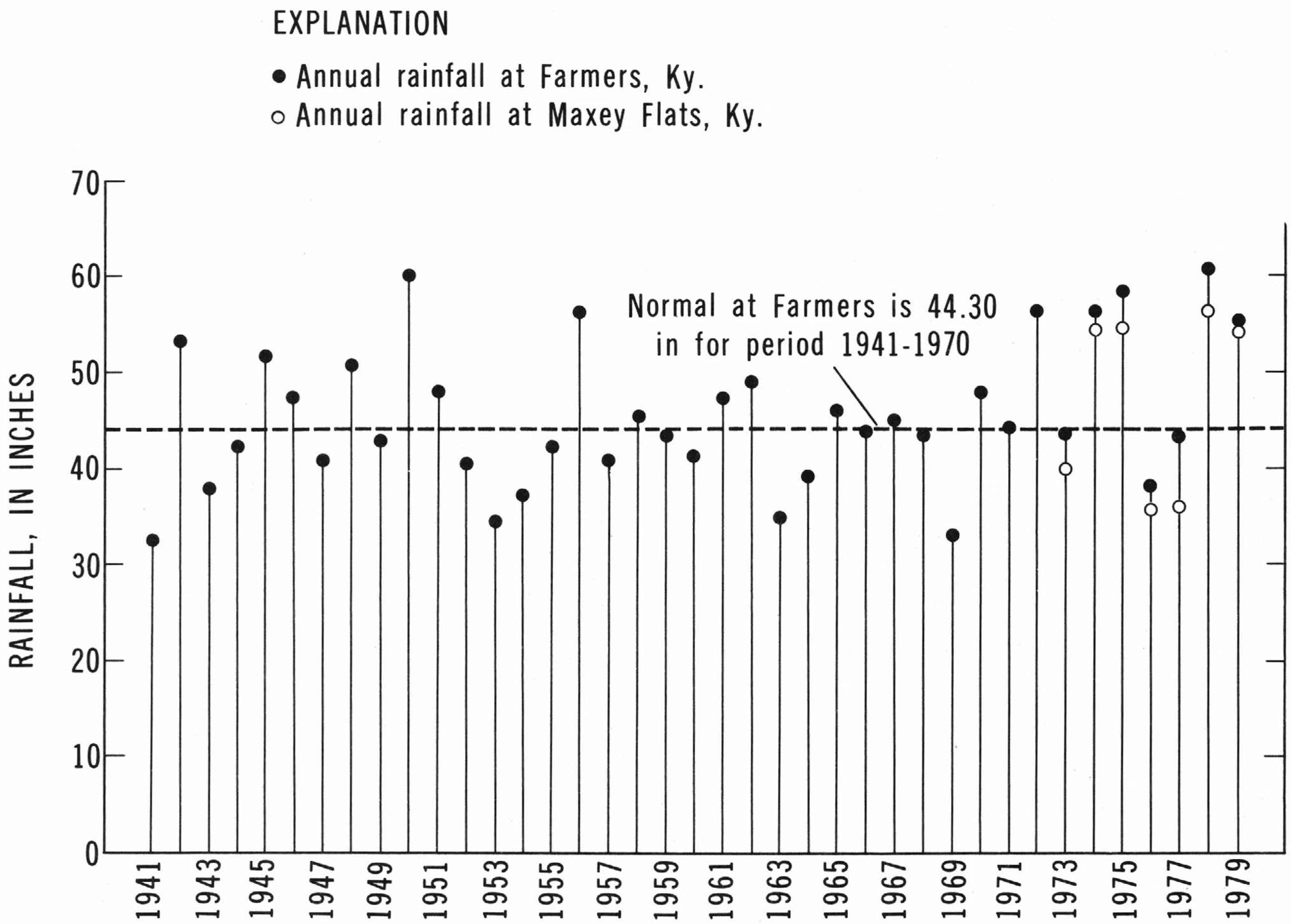


Figure 4.-- Annual rainfall at Farmers (1941 through 1979) and Maxey Flats (1973 through 1979). Farmers data from U.S. Department of Commerce (1977, and unpublished data, 1975 through 1979).

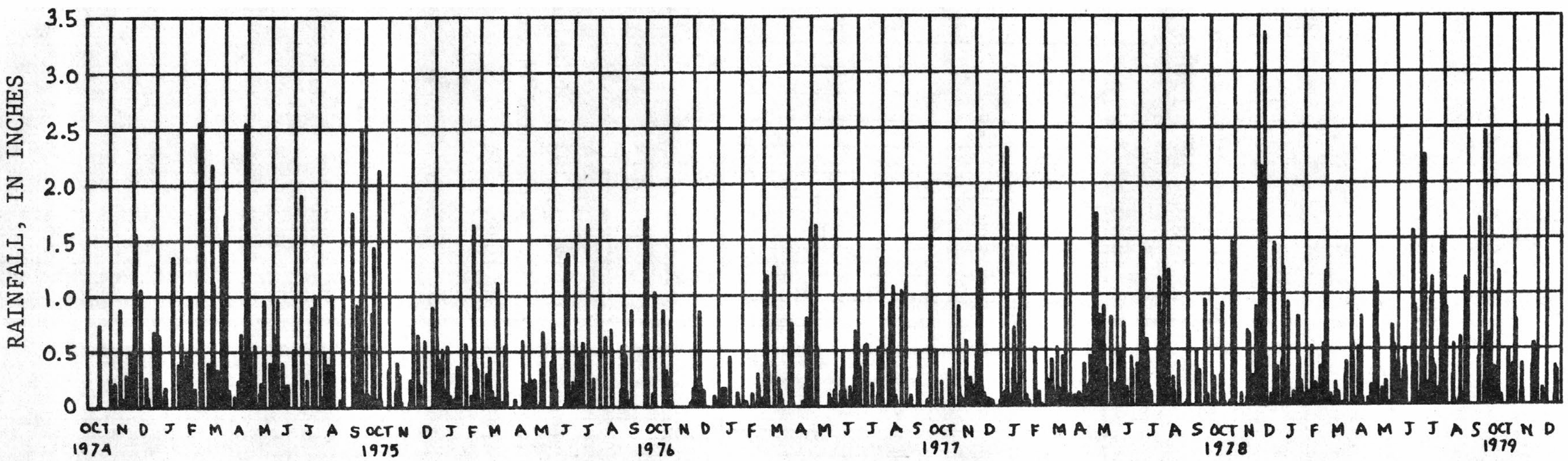


Figure 5.-- Daily rainfall at Maxey Flats.

STRATIGRAPHY AND HYDROLOGIC UNITS

Bedrock

The rock strata and geologic systems directly underlying the Maxey Flats site are, in descending order (a) the lower part of the Nancy Member (shale) and the Farmers Member (sandstone) of the Borden Formation, the Henley Bed (shale) of the Farmers Member of the Borden Formation, and the Sunbury Shale -- all Mississippian, (b) the Bedford Shale -- Mississippian and Devonian, (c) the Ohio Shale -- Devonian, and (d) the upper part of the Crab Orchard Formation -- Silurian. The Ohio Shale and upper part of the Crab Orchard Formation are exposed in the valleys around Maxey Flats. A diagrammatic, geologic section of the Maxey Flats site, to the level of Rock Lick Creek, is shown in figure 6. Lithologic descriptions are shown in table 2. All radioactive wastes are buried in the Nancy Member.

Sandstone beds become more numerous, and shale interbeds become thinner, progressing downward through the Borden Formation, from the lower part of the Nancy Member to the lower part of the Farmers Member. The contact of the Nancy and Farmers Members is defined as that horizon at which shale beds between sandstone beds become less than 3 ft thick (McDowell and others, 1971). The shale-sandstone sequence near the contact of these members is more fractured than the lower, predominantly sandstone, part of the Farmers Member. Also, the upper, weathered part of the Nancy Member contains two sandstone beds (referred to in this report as the upper and lower sandstone marker beds), which are more fractured than the deeper sandstones. The more-fractured zones form different hydrologic units.

Hydrologic contacts are considered to correspond to stratigraphic contacts below the Farmers Member, based on data collected during this study. Four hydrologic units are defined above the base of the Farmers Member, and they may have different boundaries than the stratigraphic units. They are: (1) the regolith (weathered rock, which is mostly shale at Maxey Flats), which contains the upper and lower sandstone marker beds, (2) the unweathered, mostly shale, part of the Nancy Member, (3) the shale-sandstone sequence at the base of the Nancy and top of the Farmers Members, and (4) the lower, predominantly sandstone part of the Farmers Member.

The hydrologic contact between the shale-sandstone sequence and the underlying, predominantly sandstone, unit is somewhat arbitrary, but is defined here as the horizon below which shale beds between sandstone beds become less than 2 ft thick, with most beds less than 1 ft thick. Locally, the hydrologic contact at the top of the shale-sandstone sequence coincides with the contact of the Nancy and Farmers Members. On the Maxey Flats site, the shale-sandstone sequence and the predominantly sandstone unit each average about 20 ft thick. The unweathered part of the Nancy Member, between the base of the lower sandstone marker bed and top of the shale-sandstone sequence, averages about 15 ft thick.

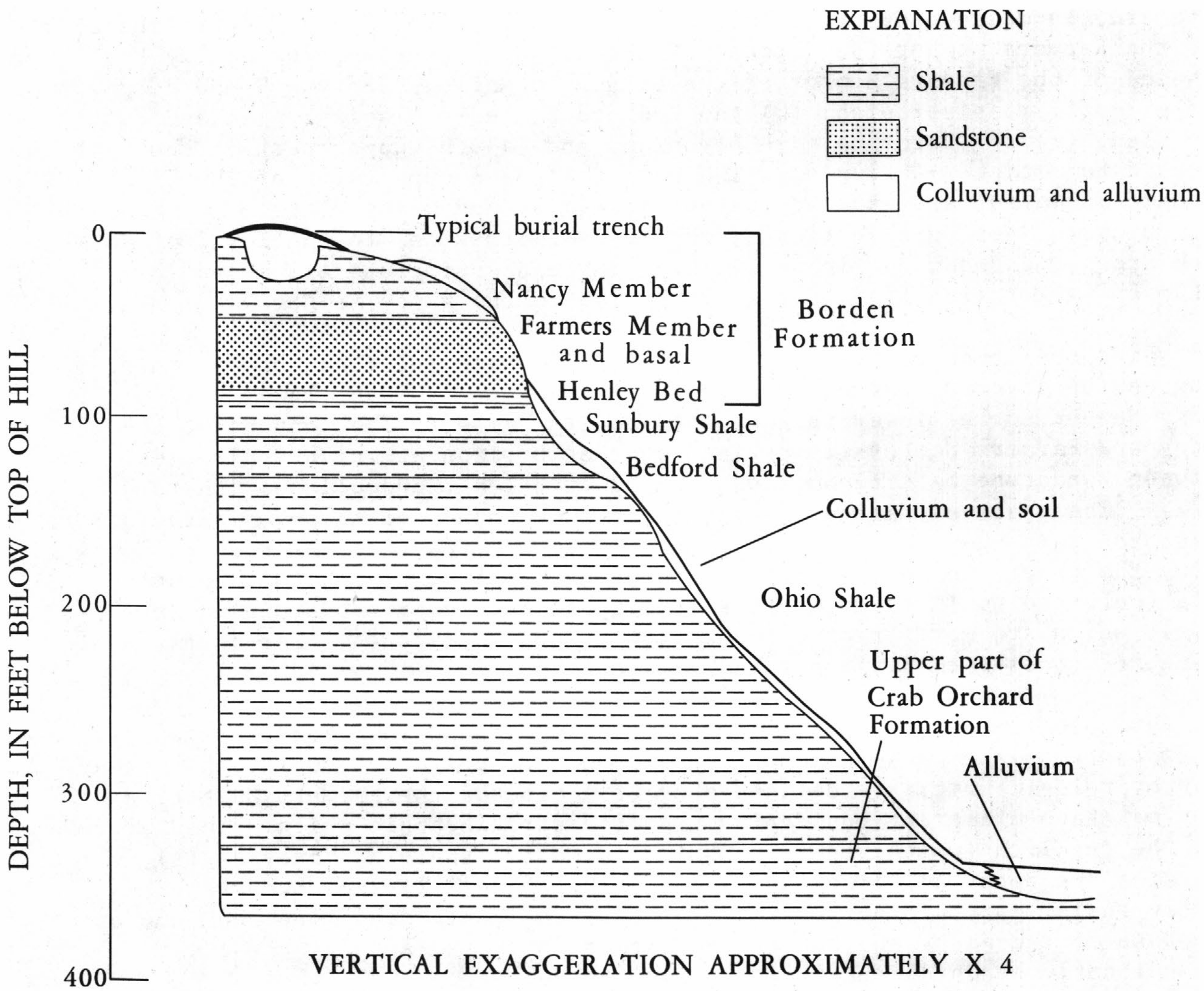


Figure 6.--Diagrammatic geologic section of the Maxey Flats site.

TABLE 2.--Lithologic description of the section from the Borden Formation through the upper part of the Crab Orchard Formation at the Maxey Flats site

[Modified from McDowell, 1971]

System	Formation, member, and bed	Description	Average thickness (ft)
Mississippian	Nancy Member of the Borden Formation	Shale, siltstone, and sandstone: Shale, bluish to greenish gray, weathers olive-gray to grayish-orange: slightly to very silty, poorly fissile; ironstone concretions common. Siltstone, shaley, in minor amounts, occurs mostly near top of unit. Sandstone, yellowish-brown, very fine grained, evenly bedded, similar to sandstone of underlying unit; occurs near base in two or three lensing beds as much as several feet thick and locally in thin beds and stringers.	45
	Farmers Member of the Borden Formation	Sandstone and minor shale: Sandstone light brownish gray to yellowish brown, very fine grained, well sorted, well indurated, medium to thick bedded, tabular, quartzose; beds as much as 4 ft thick, thickest near base. Shale, greenish-gray, clayey, silty, similar to shale of overlying unit; occurs as partings and interbeds less than 3 ft thick; thickest and most abundant in upper part.	35
	Basal Henley Bed of the Farmers Member	Shale, greenish-gray, clayey; commonly contains a few sandstone beds or lenses 1 to 2 ft thick in upper part, and one or more ferruginous siltstone beds near middle.	6
	Sunbury Shale	Shale, dark-gray to black, highly carbonaceous, highly fissile, sparsely pyritic.	18

TABLE 2.--Lithologic description of the section from the Borden Formation through the upper part of the Crab Orchard Formation at the Maxey Flats site--Continued

System	Formation, member, and bed	Description	Average Thickness (ft)
Missis-sippian	Bedford Shale	Shale, dominantly greenish-gray to light-olive-gray silty shale; weathers reddish to yellowish-brown; contains pyritic nodules and numerous very thin siltstone lenses. Locally a thin bed or lens of very fine grained sandstone occurs several feet above base; basal few feet commonly composed of interbedded dark-gray and olive-gray shale with thin siltstone ribs. Fissility poor.	25
Devonian	Ohio Shale	Shale, dark-gray to black, highly carbonacous, weathers medium gray to light brown; highly fissile; sparsely pyritic, pyrite concretions as much as 2 in. diameter. Fresh exposures characteristically conspicuously jointed. Greenish-gray clay shale in beds as much as 10 ft thick occur locally, especially 50 to 60 ft below top of unit. Lower part of unit, to as much as 20 ft above base, commonly characterized by interbedded greenish clay shale and black shale.	185
Silurian	Upper part of Crab Orchard Formation	Clay shale, mostly greenish-gray to gray, with thin zones of brownish-red to brownish-yellow; bedding indistinct; mostly poorly fissile; very plastic when wet. Few beds of dolomitic siltstone as much as 8 in. thick near top; thin rubbly weathering dolomite beds locally near base. Only top of the formation exposed at the Maxey Flats site.	

Regional dip of the rocks in the Maxey Flats area, as determined from structural contours drawn on the base of the Sunbury Shale by McDowell and others (1971), is about S. 65° E. at about 25 ft/mi. The contact between the Henley Bed of the Farmers Member and Sunbury Shale was picked from geophysical logs of eight wells at the Maxey Flats site to determine the local dip, which is S. 65° E. at about 40 ft/mi.

The upper part of the Crab Orchard Formation exhibits little fracturing. The formation is assumed to be the lower hydrologic boundary of the flow system because of its sparsity of fractures and location in valley bottoms. The rocks that are of primary interest in this report are therefore in the section from the Nancy Member of the Borden Formation to the upper part of the Crab Orchard Formation. Regolith covers the tops of the hills, colluvium covers part of the hillsides, and alluvium covers most of the valley bottoms. Descriptions of the near-surface materials follow.

Regolith

Weathering of the Nancy Member forms the regolith in the Maxey Flats area. McDowell and others (1971) mapped two beds in the regolith, which they called sandstone beds. They are very fine grained silty sandstones in some areas, but are siltstones in others. They are called sandstone beds in this report, so as to conform to the terminology used when they were mapped. One bed (upper sandstone marker bed) is at about the middle, and the other (lower sandstone marker bed) is at the base, of the regolith. The upper bed ranges in thickness from less than 1 in. to about 2 ft, with average of about 1 ft. The lower bed ranges in thickness from less than 1 in. to about 3 ft, with average of about 1.5 ft. They are absent locally, particularly where erosion has removed the upper bed, but are present over most of the Maxey Flats site.

The upper part of the Nancy Member on the burial site weathers to form a yellow-brown regolith, which extends at least to the depth of the upper sandstone marker bed. In places, the shale between the upper and lower sandstone beds is only partly weathered, exhibiting a mottled yellow-brown and gray color. In other places, the shale is weathered yellow-brown from ground surface down to a few inches below the lower sandstone marker bed. In local areas where the sandstone marker beds are very thin or absent, weathering extends several feet below the depths at which the beds would usually occur. The regolith ranges in thickness from a few inches to about 25 ft on the Maxey Flats site.

Colluvium and Alluvium

The slopes at Maxey Flats are mostly covered with colluvium. Fragments are mostly from the Farmers Member, and range from pebble to boulder size. Sand and silt-size particles occupy voids between the larger fragments. Bedrock is exposed in places, particularly on the upper part of the hillsides where the erosion-resistant Farmers Member forms steep scarps. Finer grained, thicker (at least 6 ft) colluvium is present along the crests of hills between small valleys eroding the side slopes of Maxey Flats. More bedrock and coarser grained colluvium is present within the small valleys on the slopes.

The valley bottoms are covered with alluvium. Most fragments are from the Farmers Member, and range from pebble to boulder size. The alluvial deposits grade laterally into the colluvium on hillsides, and extend to the heads of the valleys. They are probably at least as deep as the hand-dug wells in the area, most of which are about 10 ft deep.

DESCRIPTION OF FRACTURES AND THEIR RELATIONSHIP TO GROUND-WATER FLOW

All rocks in the Maxey Flats area contain major fractures. "Major fractures," or simply "fractures," referred to in this report are breaks in the rock caused by regional stress. In outcrops and walls of burial trenches, the fractures are: present in sets; vertical or near-vertical (dip ranges from 80° to 90°); continuous in length from about a foot to several tens of feet; generally widely spaced (most several feet, but ranging from several inches to more than 100 ft); and exhibit brown, iron-oxide stained alteration bands which are several inches wide, and due to movement of ground water. A typical fracture is shown in the wall of burial trench 43 (fig. 7).

A multitude of minor fractures are also present, which form roughly cubic-shaped blocks ranging in size from 1 in. to about 6 in. They are most prominent in the regolith and on outcrop surfaces, and probably form by near-surface weathering and stress relief. The meshwork of minor fractures probably does not extend more than a few feet to tens of feet in depth.

Most fractures at depths greater than about 30 ft have extremely small (less than about 0.01 ft) spaces in fracture planes, but openings of about 0.1 ft are present in the shallow upper and lower sandstone marker beds. The shallow openings are largely filled with weathered shale, which is evidently carried down by water from the overlying regolith.

The amount of fracturing is different for different strata, and ground-water discharge is greater from the more-fractured rocks. Seeps were observed at fractures in road cuts and trench walls, in every formation from the Borden to the upper part of the Crab Orchard. The seeps are most common in the more-fractured sandstone marker beds, and in the shale-sandstone sequence at the base of the Nancy and top of the Farmers Members. The greater discharge from the thin (less than about 3 ft) sandstone beds is an indication of greater hydraulic conductivity of these units, as compared to the thicker, less-fractured, sandstones and shales. Seepage from the thicker beds also occurs, but it is less obvious because the discharge rate only slightly exceeds the evaporation rate during much of the year.

Fracture continuity is less vertically than laterally. Some fractures are continuous through many rock beds, but most terminate, or are offset, at beds with different lithologies. Discharge from thin sandstone beds is commonly observed where fractures terminate at underlying, less-fractured, shale beds. The unfractured part of the shale allows very little flow, so the water is perched in the sandstone fractures. The water therefore moves laterally until a fracture in the underlying shale is encountered. Because the positions and directions of the fractures in the sandstone and shale beds do not coincide, the water enters the shale fracture at a point, rather than along a plane. Such conditions cause significant anisotropy, with preferential movement in the horizontal direction.

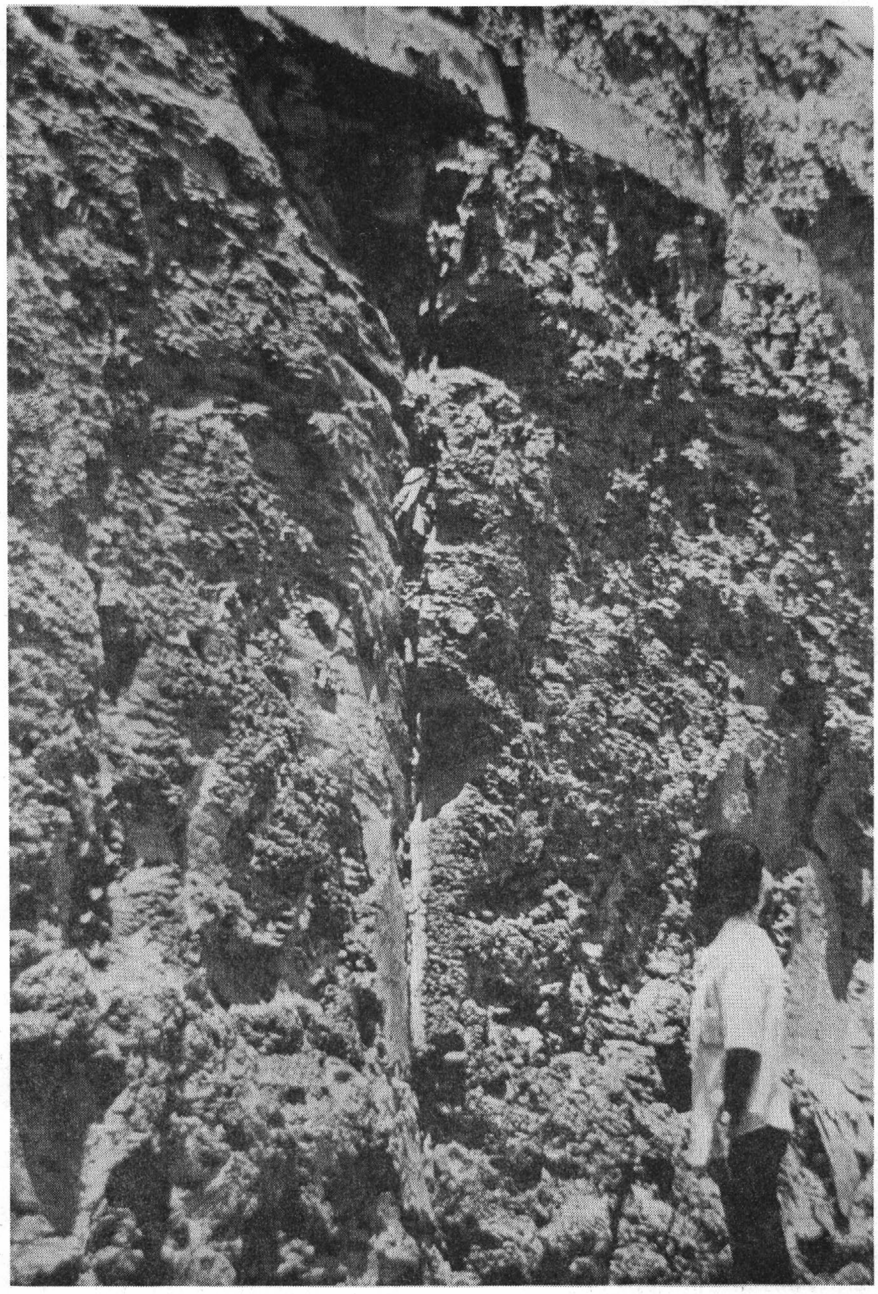


Figure 7.-- Fracture in burial trench 43. Strata near the top of the trench is the lower sandstone marker bed.

The paths traced by particles of water in fractured media thus form very tortuous, zig-zag patterns in both the vertical and horizontal directions. Location and direction of such pathways are difficult to define. The larger the fracture spacing and more numerous the fracture offsets, the longer and larger are the changes in direction of flow, thus increasing the difficulty of defining specific pathways.

Fracture Intensity

A study of fractures in the area was conducted as part of the hydrologic investigation at Maxey Flats, and most of the following discussion is derived from the report (Werner, 1980) resulting from that study. The survey included all area shown on the Plummers Landing, Cranston, Farmers, Morehead, and Salt Lick 7.5-minute topographic quadrangle maps. Fractures were measured in 38 exposures and outcrops, most of which were along recent (less than 15 years old) road cuts. One outcrop, and many excavated blocks, of the sandstone marker beds were measured on the Maxey Flats site. Fewer than four hydrologic units were usually exposed at any one place.

The origin of the regional stress that produced fractures in the Maxey Flats area is not known, but it may be related to (a) the Cincinnati Arch, located about 40 mi to the west, (b) the Waverly Arch, located about 20 mi to the east, or (c) the Kentucky River fault system, located about 30 mi to the southwest, which is the nearest known fault system to the Maxey Flats site.

Tectonic fractures commonly occur in sets, with individual fractures nearly parallel to one another. If only one set is present, and S is the mean distance between fractures, then 1/S is the frequency, or number of fractures per mean distance (Wheeler and Dixon, 1980). Vialon and others (1976) describe fracture density (equivalent to fracture intensity here) as: $I = \Sigma 1/S_{(j)}$, $j = 1, 2...m$, where I is fracture intensity of a fracture system composed of m sets of fractures, and S is mean spacing between individual fractures in a set. Fracture intensity is therefore the sum of the single-set intensities (frequencies) for all sets measured in the rocks.

The unit for intensity is 1/Length, which is equivalent to fracture area (one side) per unit volume of rock. Intensity can be used to estimate the amount of flow through the rocks, if velocity of flow in the fractures is known, and cross-sectional area of flow can be estimated by the height and width of the fracture. Such estimates are presented later in this report.

Orientation and spacing of only tectonic fractures were intentionally measured to obtain intensity, but some fractures resulting from blasting in roadcuts, slumping, or weathering may have been included unintentionally. Where possible, the latter types were recognized and disregarded - those due to blasting showed a radial fracture pattern, and those due to slumping and weathering exhibited an irregular, broken appearance. Because many fractures are discontinous vertically and sometimes have different orientations in different beds, combining measurements for several beds would yield erroneously high intensity values. Measurements were therefore reported only for single beds.

Fracture orientations were plotted on rose diagrams, as a first step in computing intensity. Locations of measuring sites and predominant orientations are shown in figure 8. Orientation of fracture sets (and fracture intensities shown on figure 9) do not show as 100 percent of all fractures measured because some fractures do not occur in predominent sets. Major trends are approximately north-south, N. 45° E., N. 55° E., and N. 70°-to-75° E.

The number of sets for each rock strata, at each exposure or outcrop, were determined by visual inspection of the rose diagram. Fracture intensity was computed using the equation above, except that the trimean, as described by Tukey (1977), was used instead of the mean where there were more than three measurements. The trimean weights values in the center part of the data, and is defined as: $S_T = (Q_1 + 2S_M + Q_3)/4$, where S_T is the trimean, S_M is the median, and Q_1 and Q_3 are the first and third quartiles. The median, and first and third quartiles, were determined by the equations: $M = (n+1)(0.50)$, $Q_1 = (n+1)(0.25)$, and $Q_3 = (n+1)(0.75)$, where n is the number of measurements. Extrapolaton between numbers were made where necessary.

Figure 9 shows orientations and intensities for each set of fractures at several exposures of the unweathered part of the Nancy Member and the shale-sandstone sequence at the base of the Nancy and top of the Farmers Members. Fracture intensities for all locations measured are shown in table 3.

A fracture intensity of 0.71/ft was initially computed from measurements at eight sites for the upper and lower sandstone marker beds. This may be too small a value because a northeast-trending set could not be measured at three exposures due to inaccessibility. The actual intensity may be closer to the trimean of the values where both sets were measured, which is 0.96/ft, and is assumed to be the correct fracture intensity for these beds. Although measurements were made in each bed, one value for intensity is given for both sandstone marker beds, and is the mean of the two.

The thin (3 to 8 in.) sandstone beds in the shale-sandstone sequence at the base of the Nancy and top of the Farmers Members have a much greater fracture intensity than other strata, with trimean of 2.37/ft. Thinner sandstone beds are probably less competent than thicker ones, so tend to fracture more easily. This is particularly evident where the sandstone beds are separated by shales at least several inches thick. Under stress, the shale tends to deform without breaking, whereas the sandstone beds tend to break. Where shale beds between sandstone beds are thin (less than about 3 in.), as in the lower part of the Farmers Member, the thin sandstones are less fractured. This is probably because they are less mechanically isolated, and act as one thick bed.

The Bedford Shale has the lowest fracture intensity, with trimean of 0.06/ft. The Henley Bed and Bedford Shale appear to be very similar at exposures and outcrops. They probably have similar intensities, but fractures in the Henley Bed were not measured. The mean intensity of 0.15/ft for the upper part of the Crab Orchard Formation is approximate because only two unweathered exposures were found.

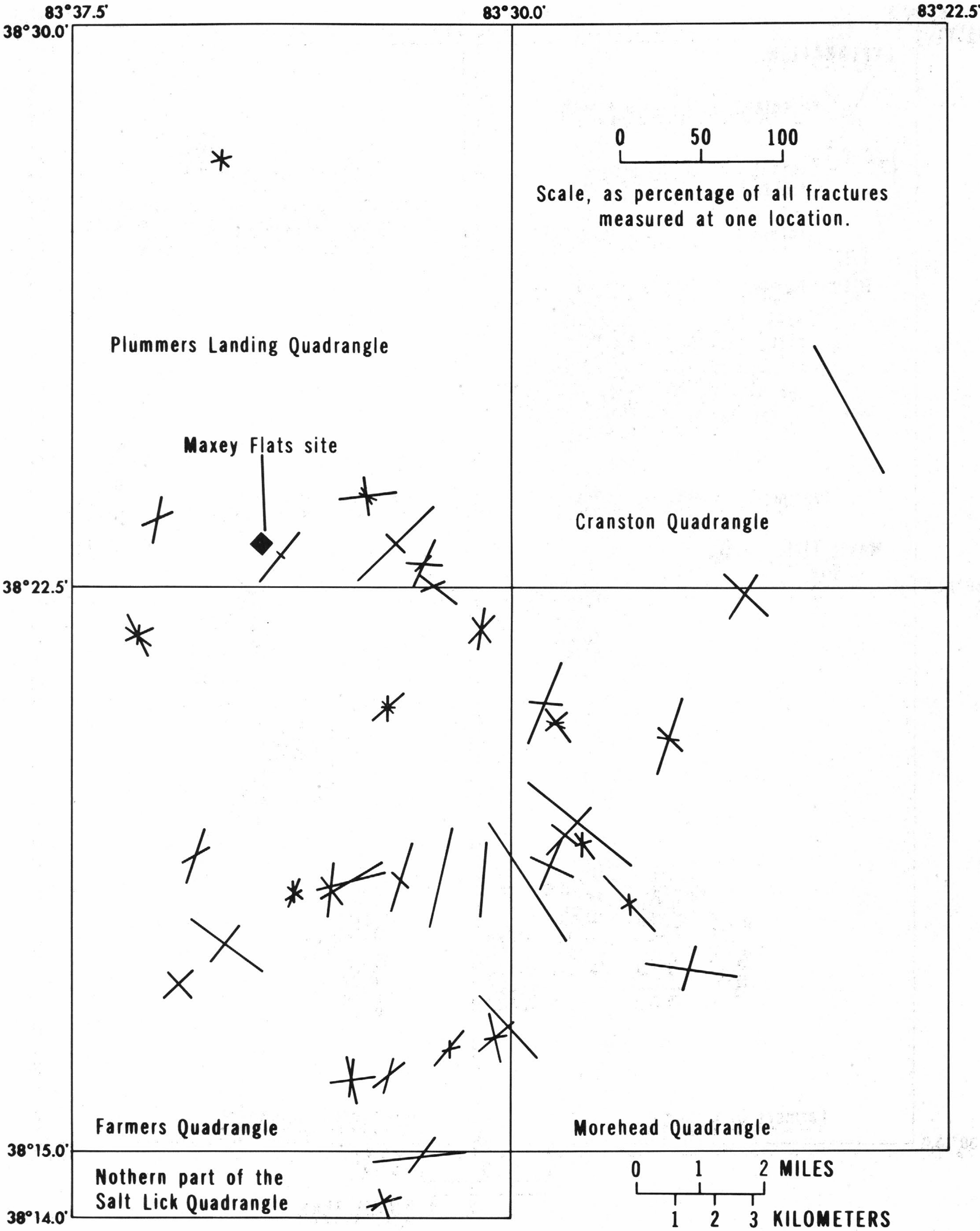


Figure 8.-- Predominant orientations of fracture sets in the Morehead area. Percentage scale represents, for each location, the ratio (multiplied by 100) of the number of fractures measured in one orientation to total number of fractures measured in all orientations.

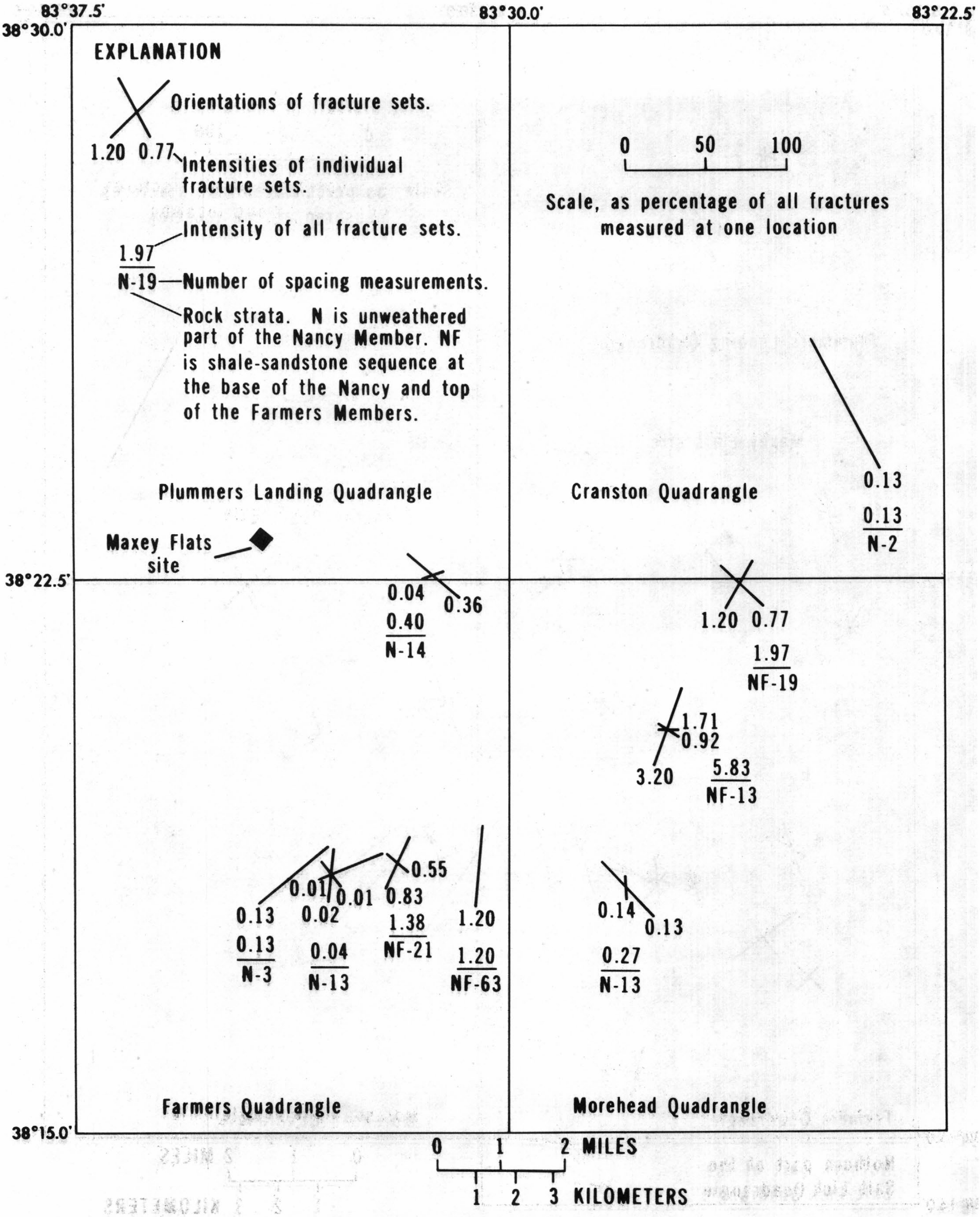


Figure 9.-- Fracture intensities in the Nancy and Farmers Members of the Borden Formation in the Morehead area. Percentage scale represents, for each location, the ratio (multiplied by 100) of the number of fractures measured in one orientation to total number of fractures measured in all orientations.

TABLE 3.--Fracture intensities in the Morehead area, Kentucky[1]

[Values are per foot]

	NF	SSM	O	S	LF	UCO	N	B
	1.20 (63-F)	0.13 (4-F)	0.20 (14-F)	0.09 (6-F)	0.05 (1-P)	0.10 (5-F)	0.01 (2-F)	0.03 (1-F)
	1.38 (21-F)	.34 (3-F)	.29 (17-F)	.11 (11-M)	.06 (16-M)	.20 (8-F)	.04 (13-F)	.03 (2-M)
	1.97 (19-M)	.54 (*)	.39 (3-P)	.20 (6-P)	.07 (7-S)		.12 (**)	.08 (3-F)
	5.83 (13-M)	.57 (7-F)	.40 (8-F)	.24 (16-M)	.10 (11-M)		.13 (3-F)	.14 (5-F)
		.81 (23-M)	.67 (11-F)	.25 (7-S)	.11 (8-P)		.13 (2-C)	
		.97 (7-F)	.79 (44-F)	.31 (20-F)	.14 (8-M)		.27 (13-M)	
		.11 (10-F)	1.40 (20-P)	.31 (8-S)	.19 (4-F)		.40 (14-P)	
		.36 (14-P)	1.79 (7-P)	.36 (17-M)	.32 (15-P)			
			2.06 (53-F)	.38 (4-P)	.37 (7-F)			
				.39 (3-F)	.40 (13-F)			
				.41 (9-F)	.43 (14-F)			
				.42 (7-F)				
				.58 (12-P)				
				.70 (23-F)				
				1.46 (14-P)				
Overall trimean intensity	2.37	0.96***	0.85	0.35	0.18	****	0.14	0.06
Range	1.20-5.83	0.13-1.36	0.20-2.06	0.09-1.46	0.05-0.43	0.10-0.20	0.01-0.40	0.03-0.14

[1]In order of greatest to least overall trimean intensity. Parentheses contain number of spacing measurements and initial of 7.5 minute quadrangle map where measurements made: P - Plummers Landing, C - Cranston, F - Farmers, M - Morehead, and S - Salt Lick. NF - lower part of Nancy Member and upper part of Farmers Member of Borden Formation, SSM - upper and lower sandstone marker beds of Nancy Member, O - Ohio Shale, S - Sunbury Shale, LF - lower part of Farmers Member of Borden Formation, UCO - upper part of Crab Orchard Formation, N - unweathered part of Nancy Member, and B - Bedford Shale.

*Measurements of loose blocks on burial site not accurately counted, but were about 200.

**Twenty-seven fractures measured at walls of trench 43 on burial site.

***Trimean computed only from measurements where all sets observed - see explanation in text.

****Insufficient measurements to compute trimean. Mean is 0.15.

The fracture intensity data shown in table 3 indicate relative hydraulic conductivities of the different rock strata because most flow is through fractures. The relationships are approximate, however, because fracture intensity varies areally in the same stratum, as well as in different strata at the same location. Some fractures produced by local stresses, such as those resulting from erosion, may account for the areal variation in fracture intensity.

SURFACE WATER

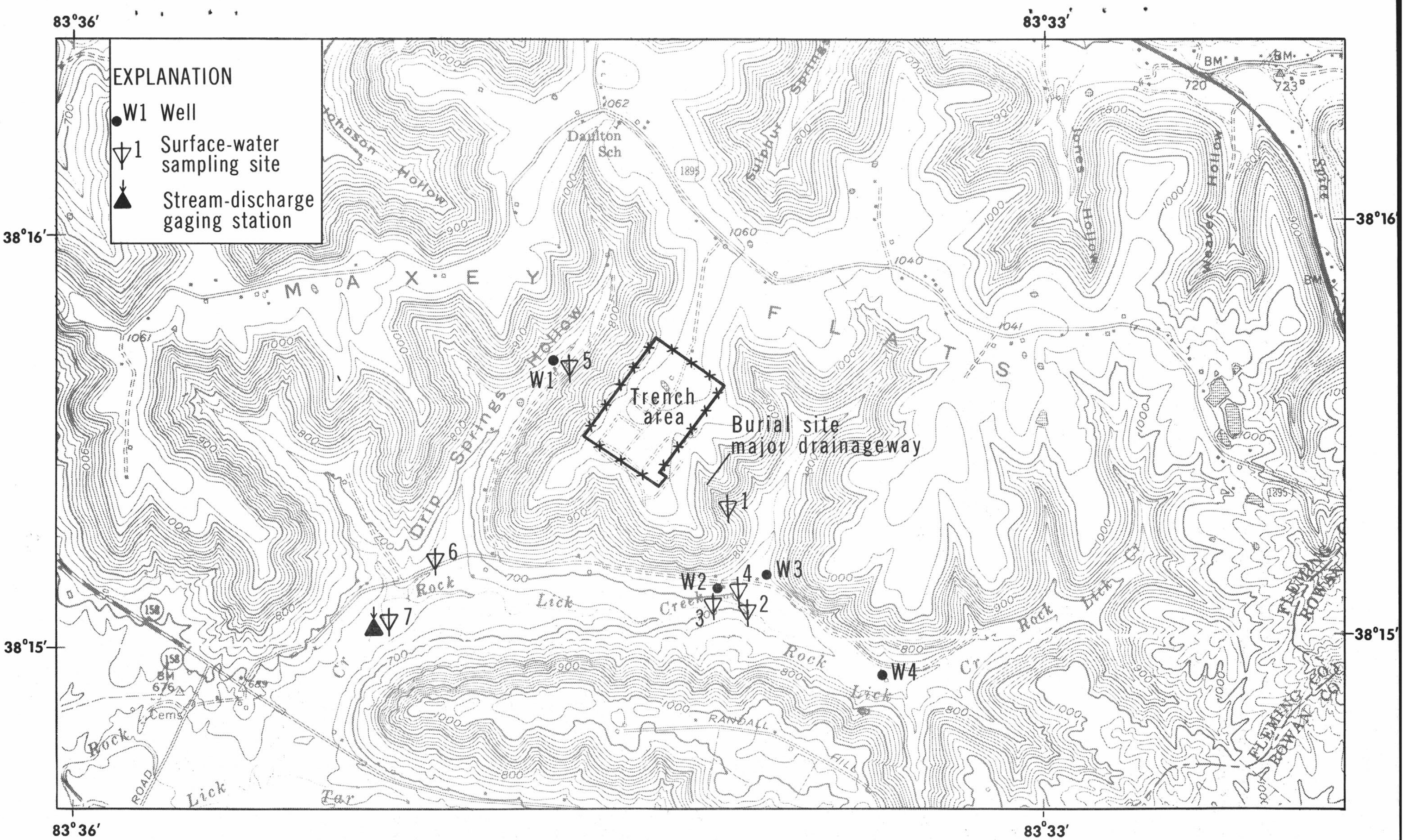
Stream discharge

Surface-water drainage from the Maxey Flats site is by Drip Springs Hollow to the west, Rock Lick Creek to the south, and the unnamed stream (hereafter referred to as unnamed stream, or the stream in unnamed valley) to the east. Surface flow occasionally ceases in all of these streams. Pools are always present in low areas within the stream channels, however, indicating subsurface-to-surface flow. Sixty-five percent of the runoff from the burial area flows down the small valley shown as "burial site major drainageway" in figure 10, as determined from a large-scale topographic map of the burial site.

Streamflow data have been collected at the U.S. Geological Survey gaging station on Rock Lick Creek near Sharkey since August 1973. It is located 0.8 mi southwest of the Maxey Flats site (fig. 10), and drainage area above the station is 4.01 mi^2. Sharkey is not shown on figure 10, but is located 2 mi southeast of the gaging station. Most streamflow records for the Sharkey, Kentucky, station are described as good for the water years (October through September) 1976 through 1978, but only fair or poor for all other years. Fair or poor records result primarily from loss of gage height data by siltation around the manometer orifice, periods of backwater from Fox Creek, and occasional ice effects.

Records from the Sharkey gaging station showed that streamflow sometimes exceeded rainfall, on a monthly basis. This may occur for several reasons, such as: streamflow may be predominantly ground-water discharge (base flow) in some months; delayed release of water temporarily stored as ice or snow; differences in rainfall over the drainage basin, particularly during summer thunderstorm activity; and errors introduced when estimating flow during periods of no gage-height record.

Records indicated that stream discharge exceeded rainfall six times in 1979, which was more frequent than in any other year. Four of the months were consecutive, and not a typical period for thunderstorm activity (November through February). Also, the runoff to rainfall ratio was greater than 1.5 four of the months, and this value had only been exceeded twice during all other months of record. The unusual values probably do not precisely represent actual flow, so 1979 streamflow data are not used in the report.



Base from U.S. Geological Survey Plummers Landing 1:24000, 1951, revisions as of 1979 and Farmers 1:24000, 1970.

1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

CONTOUR INTERVAL 20 FEET

National Geodetic Vertical Datum of 1929

Figure 10.-- Maxey Flats area showing locations of the stream-gaging station near Sharkey, wells outside the burial site, and surface-water sampling points.

Monthly discharge data are given in table 4, and a summary is shown in table 5. Mean daily discharge is several cubic feet per second. However, short-term, large discharges account for much of the annual flow. The flow duration curve (fig. 11) shows that 50 percent of the time mean daily flow equals or exceeds 1 ft^3/s, and 10 percent of the time mean daily flow equals or exceeds 15 ft^3/s.

Base Flow and Underflow

Base flow is that part of streamflow derived from ground-water discharge to the stream. It originates from both bank storage very near the stream and regional ground water farther from the stream. Most base flow in Rock Lick Creek is from the colluvium and alluvium. Only a small part is from the less-permeable bedrock, as will be shown later in the report.

An estimate of base flow can be obtained graphically by using hydrograph separation techniques (Rorabaugh, 1964). The method of analysis used here is the same as that described by Cable and others (1971). It involves construction of a base-flow hydrograph by use of a constant recession slope, and estimation of the height of the base-flow curve during floods. The term "flood" used here refers to streamflow that has an overland runoff component, and does not necessarily mean widespread inundation by water.

The ground-water gradient is from the stream toward the aquifer during floods (reversed from that present during base flow), and some water during these periods becomes bank storage. With the method used in this report, base flow is not made equal to zero during gradient reversal, and some bank storage may be included in the analysis. Because regional ground-water flow is of primary interest, inclusion of bank storage in the computations is minimized by positioning the base flow peak about 4 to 5 days after the flood peak.

The slope of the base flow recession for Rock Lick Creek near Sharkey could not be determined precisely because: flooding is frequent, so recessions often do not develop; and the slope changes with season, probably because of evapotranspiration (as described by Daniel, 1976 for Indian Creek near Troy, Alabama); and probably because saturated area at the upper parts of the valleys increases during wet periods.

TABLE 4.--Monthly discharge for Rock Lick Creek near Sharkey, Kentucky

[Values in cubic feet per second - days]

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
1974	10.60	212.70	39.68	414.09	87.90	517.1	432.5	215.34	249.98	23.52	228.37	191.96
1975	13.77	91.31	447.7	386.4	592.84	891.4	451.1	186.42	11.96	23.52	5.94	157.31
1976	381.93	73.85	266.0	339.3	253.71	249.5	38.07	18.69	37.15	15.44	2.67	3.53
[1]1977	18.05	8.25	19.82	1.34	44.31	251.13	241.87	183.80	27.36	75.88	87.63	6.15
1978	51.62	91.80	410.2	765.22	31.24	645.35	37.49	552.22	14.17	368.35	192.29	19.19

[1]Stage-discharge relation affected by ice from December 20, 1976, to February 10, 1977.

TABLE 5.--Summary of discharge data for Rock Lick Creek near Sharkey, Kentucky

Water year	Maximum daily (ft^3/s)	Mean daily (ft^3/s)	Minimum daily (ft^3/s)	Total (ft^3/s-d)
1974	130	7.19	0.00	2,623.74
1975	193	8.93	.00	3,259.67
1976	142	4.59	.00	1,679.84
1977	76	2.65	.01	965.59
1978	183	8.71	.14	3,179.14

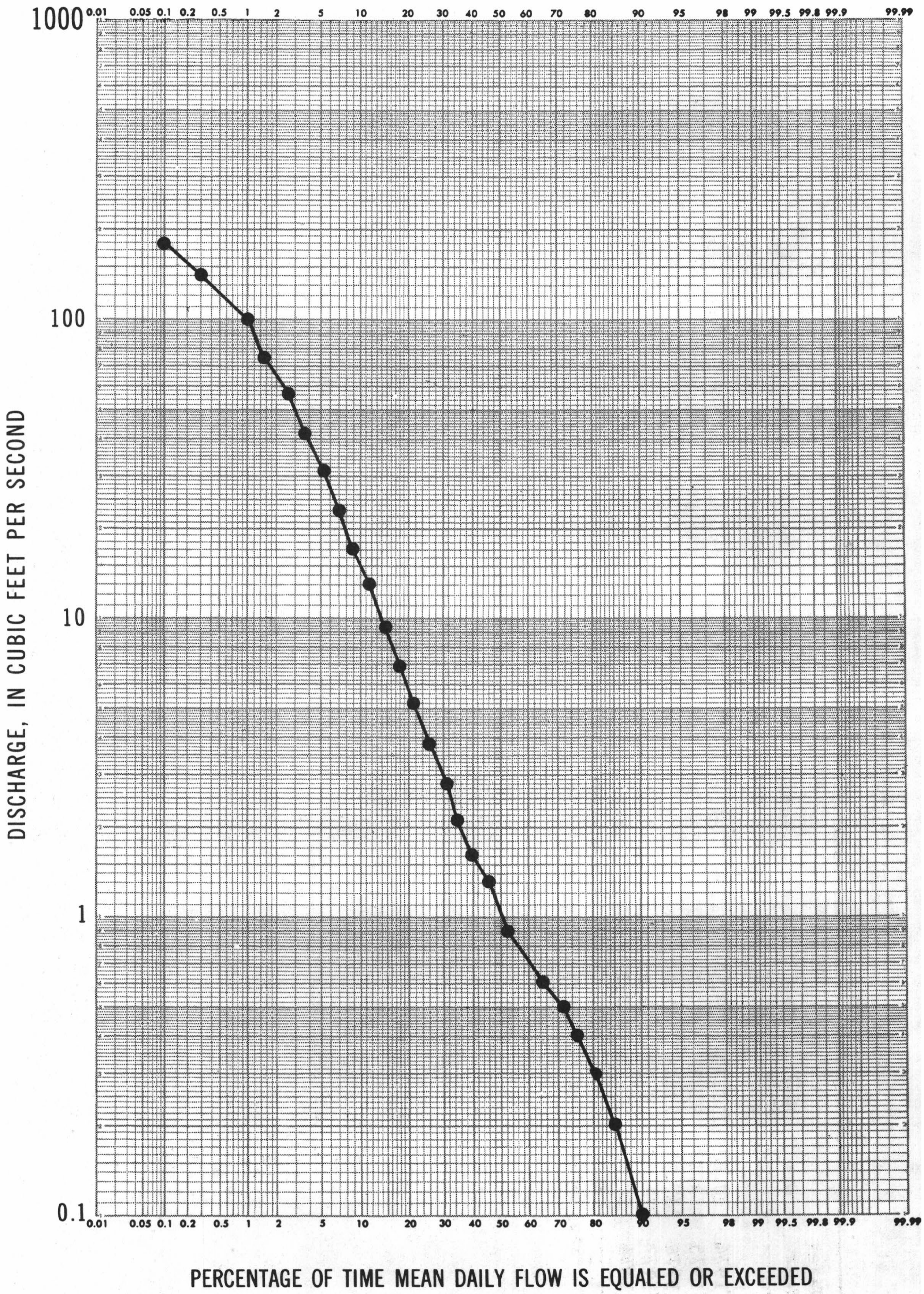


Figure 11.– Daily flow-duration curve for Rock Lick Creek near Sharkey. Data for water years 1974 through 1978.

Recessions that occurred during late October and early November 1975 (fig. 12), and during April, May, and June 1976 (fig. 13) were the best available on record for determining the slope of the recession at Sharkey. The consistent slope that best fitted these recessions was 70 days per log cycle, which was used for all data analysis. The magnitude of the base flow curve had to be approximated during periods of frequent flooding. The peaks could have been extended higher than shown for some events; for example, below the series of floods in January 1976. However, some of the flow was due to overland runoff, and too large an extension may have represented a flow that, in reality, exceeded the transmitting capability of the aquifer. Also, the mid-February recession indicated a rapid return to the slope of 70 days per log cycle at lower discharge.

Maximum base flow was limited to 2 ft^3/s for all data analysis. This limit was based on: an approximation of the hydraulic conductivity of the alluvium, obtained from ground-water level and stream-discharge data at one location in Drip Springs Hollow; and estimates of hydraulic gradient and saturated thickness in the alluvium during maximum base flow. Discussion of computing the limit follows.

The hydraulic conductivity of the alluvium at well W1 (location shown on figure 10) is estimated from streamflow and water-level data by using Darcy's law: $K = Q/(IA)$, where K is hydraulic conductivity, Q is flow rate, I is hydraulic gradient, and A is cross-sectional area perpendicular to flow. It is assumed that: the water table in the stream bank near well W1 is at the same level as the water surface in the stream (negligable seepage face on the bank); head change in the vertical direction is negligible within the saturated alluvium; the well bottom is at the base of the aquifer; and the depth of the well water represents the saturated thickness for most of the near-stream part of the aquifer at this location.

Discharge in the stream adjacent to the well was estimated during a period of base flow on July 30, 1975. Water velocity was about 2 ft/s, mean width was about 0.5 ft, and mean depth was about 0.1 ft. Approximate discharge was therefore (2 ft/s)(0.5 ft)(0.1 ft) = 0.1 ft^3/s. This was, as expected, less than the 0.37 ft^3/s mean discharge for that day at the Sharkey gaging station. Considering that about one-half the flow in the stream was from the side on which the well was located, $Q = 0.05\ ft^3/s$. The water level in the well was 0.9 ft above the water level in the stream 50 ft from the well: therefore $I = (0.9\ ft)/(50\ ft) = 0.02$. The alluvium extends about 3,000 ft upstream from the well, and water depth in the well was 4 ft, so $A = (3{,}000\ ft)(4\ ft) = 12{,}000\ ft^2$. Then $K = Q/(IA) = 2 \times 10^{-4}$ ft/s, which is about 20 ft/d.

An estimate of maximum base flow for the drainage basin above the Sharkey gaging station may then be computed from Darcy's law, using the K computed for the area near well W1, and solving for Q. Two unknowns, however, are the saturated thickness and hydraulic gradient in the alluvium along Rock Lick Creek. An approximation of saturated thickness during base flow was made from water levels in wells W2, W3, and W4 (locations shown in figure 10). Wells W2 and W3 are both 10 ft deep, and W4 is 12 ft deep.

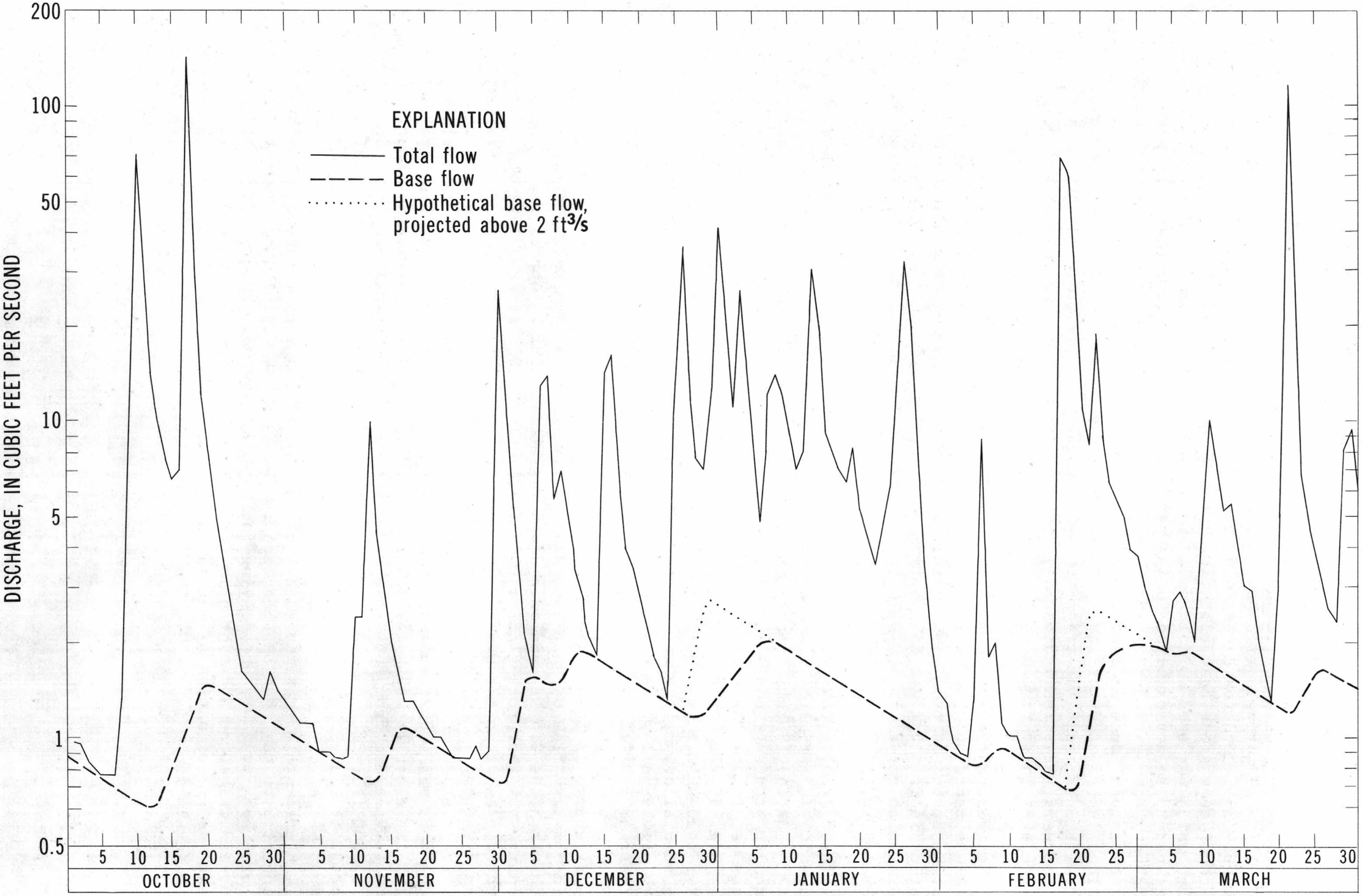


Figure 12.-- Stream-discharge hydrograph and base-flow component for Rock Lick Creek near Sharkey: October 1975 through March 1976.

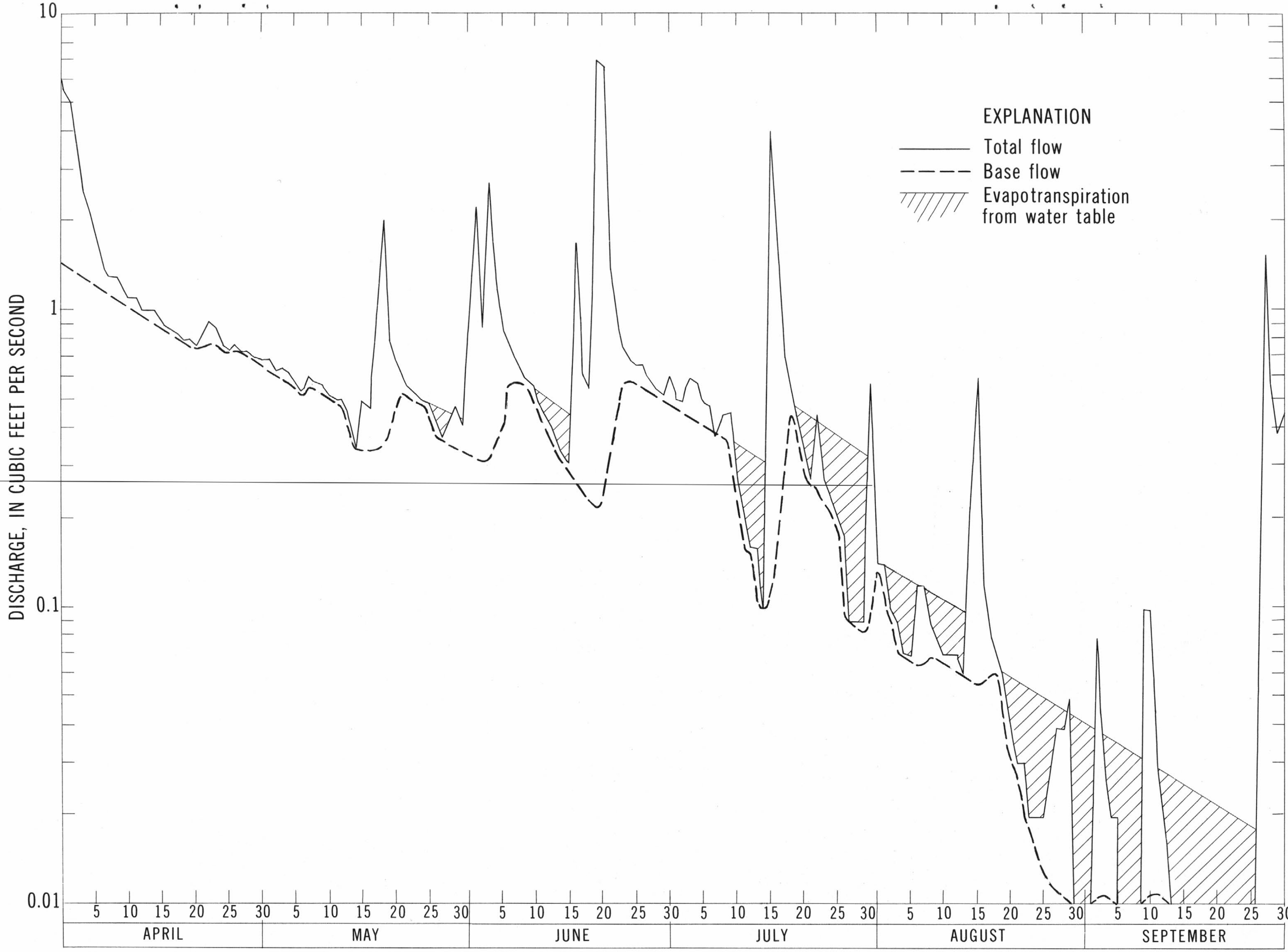


Figure 13.-- Stream-discharge hydrograph with base-flow and evapotranspiration components for Rock Lick Creek near Sharkey: April through September 1976.

Depths of water in the wells were measured on July 29, 1974, and were: W2 - 3.5 ft, W3 - 5 ft, and W4 - 3 ft. Mean streamflow at the Sharkey gaging station that day was 0.35 ft^3/s. Assumptions were that the wells were dug to the base of the alluvium, and that the mean depth of water in the wells represented the saturated thickness of the alluvium near the streams at low flow. The increase in saturated thickness near the stream, from low to maximum base flow, was estimated as about 1 ft. This was based on one water-level measurement. Depth of water in well W3 was 1 ft greater during a flow of 6.4 ft^3/s than it was during a flow of 0.35 ft^3/s.

Most increase in flow would therefore occur by change in hydraulic gradient because the change in saturated thickness near the stream is small. As an approximation for computing maximum sustained base flow, hydraulic gradient given previously for computing K at well W1 is doubled. Rorabaugh (1960) showed that gradients increase many fold during the periods shortly after recharge events. In this case, the volume of discharge would likely be small during that short period, so the doubling is assumed to be conservative. Length of the alluvial deposits above the Sharkey gaging station is 26,900 ft. Both sides of the stream contribute flow, so the streamlength is multiplied by 2.0, giving a contributing length of 54,000 ft. Saturated thickness is 5 ft, so A is 2.7×10^4 ft^2. Approximate maximum base flow is therefore $Q = KIA = (2 \times 10^{-4}$ ft/s$)(0.04)(2.7 \times 10^4$ $ft^2) = 2$ ft^3/s.

Table 6 shows annual base flow for water years 1974 through 1978, as derived from the stream hydrographs. Monthly values are given in appendix 1. The upper part of the Crab Orchard Formation underlies the alluvium along Rock Lick Creek. Flow through these rocks is probably extremely small, and is assumed to be zero. If underflow through the alluvium and evapotranspiration losses are small, the values for base flow closely approximate the ground-water flow through the rocks and sediments in the Rock Lick Creek drainage basin above the Sharkey gaging station.

TABLE 6.--Annual base flow for Rock Lick Creek near Sharkey, Kentucky

Water year	Base flow (ft^3/s-d)	Base flow/total discharge (percent)
1974	280	11
1975	330	10
1976	300	18
1977	97	10
1978	200	6.3
Mean	240	11

Underflow is the downstream flow of water that does not enter the stream, but instead flows through the materials underlying the stream. Darcy's law is applied, using the same K as derived for the alluvium at well W1 (2×10^{-4} ft/s), to compute underflow. Width of the alluvium at the gaging station is about 500 ft. Using a saturated thickness of 5 ft (from well W3), A is 2,500 ft^2. The maximum I along the stream is equal to the gradient of the stream channel, which is 0.015 ft/ft. Maximum underflow is therefore estimated as Q = KIA = 0.008 ft^3/s. The mean annual base flow is 240 ft^3/s-d, which is equivalent to a mean daily flow of 0.66 ft^3/s. Underflow is therefore only about one percent of base flow, and is considered to be negligible.

Evaporation losses from the stream are small because the stream channel has small area. Total losses could be assumed equal to annual rainfall (about 4 ft), to illustrate an extreme condition. Average stream width during base flow is about 2 ft. Evaporation losses along the stream for such a case would be (21,900 ft)(2 ft)(4 ft) = 2×10^5 ft^3, which is equivalent to 2 ft^3/s-d. This is less than one percent of the 240 ft^3/s-d mean annual base flow, and is considered negligible.

Evapotranspiration losses from the water table are illustrated on figure 13, and total 2 ft^3/s-d for the 1976 water year. This is less than 1 percent of the 300 ft^3/s-d base flow for that year. Percentages were similar for other years. Consequently, evapotranspiration losses from the water table are small compared to annual base flow, and are somewhat offset by neglecting base flow greater than 2 ft^3/s.

The values given for K and base flow are estimates because of the grossly simplified assumptions. The values most likely to effect the estimates are (a) I at well W1 - the stream does not fully penetrate the aquifer, so heads may change with depth (upward flow through the alluvium to the stream may occur), (b) estimated K of the alluvium at well W1 may not be representative of other areas in the basin, (c) near-stream saturated thickness at low flow in other areas of the basin may be different than those based on water-level measurements in wells W2, W3, and W4, (d) saturated thickness at maximum base flow was estimated from only one water-level measurement, which may not be representative for other areas along the stream, and (e) I used for computing maximum base flow could be in error because it was crudely estimated by doubling that obtained at well W1.

Of the quantities estimated, those relating to (d) and (e) are the most unreliable. They were used only to obtain maximum estimated values for base flow and underflow. Use of the values does not result in significant error for annual base flow, as is explained below.

With a recession slope of 70 days per log cycle and time lag of 4 days after peak flow for release of bank storage, base flow could only have exceeded the estimated maximum (2 ft^3/s) for 24 days in the 1976 water year (fig. 12). This would have resulted in about 15 ft^3/s increase in flow, which is about 5 percent possible error in the 300 ft^3/s-d computed for that year.

Possible error in other water years is similar. Maximum base flow is not significantly less than 2 ft^3/s because the recession in April 1976 (fig. 13) indicates it is greater than 1 ft^3/s. Underflow is probably less than the estimated maximum. Most flow is likely to be across, rather than along, the valley, so the 500-ft width used in computing area of underflow is too large.

The base flow computed is assumed to approximate ground-water flow through the rocks and sediments above the Sharkey gaging station because (a) estimates used as maximum values for base flow and underflow did not result in significant error in computing base flow, and (b) the following constitute small percentages of base flow: underflow; evaporation from the stream; and evapotranspiration from the water table.

Principal-ion Chemistry

All water samples described in this report, unless otherwise specified, were filtered through 0.45-micrometer membrane filters, and the portion for cation analysis was acidified in the field to pH less than 2.0. Most samples (other than trench water) collected after May 1979 were titrated in the field for alkalinity, as bicarbonate. Values for total dissolved solids were obtained by evaporation at 180°C.

Stream-water samples were collected from seven sites for analysis of principal ions. Site locations are shown on figure 10. Results of analyses are given in table 7. Samples were taken during periods of base flow, except those collected on October 25, 1979.

Site 1 is a pool located in the burial site major drainageway. Water collects in the pool from seeps in the colluvium. The colluvium contains greater quantities of shale fragments than the alluvium, and these fragments contain pyrite. Most alluvium is composed of less soluble silica-rich sandstone and siltstone. The greater concentrations of calcium, magnesium, and sulfate, and the lower pH and bicarbonate at site 1, as compared to sites farther downstream, are probably due to leaching of the pyrite and other minerals in the shale fragments. Humic acid from the adjacent forest soil may also cause the lower pH.

Site 5 is located in the upper part of Drip Springs Hollow. Greater concentrations of calcium, magnesium, and sulfate at this location, as compared to sites 6 and 7, may also be due to flow from the colluvium. Much of the water in downstream alluvial deposits may originate from infiltration of precipitation and runoff into more permeable and less soluble sediments. Stream water in lower parts of the valleys is therefore less mineralized than that in headwater areas where the amount of colluvium per unit drainage area is greater. Water quality is similar for samples obtained from downstream areas, such as: the stream in the unnamed valley east of the burial site (site 4), Rock Lick Creek above and below the unnamed valley (sites 2 and 3), the lower part of Drip Springs Hollow (site 6), and Rock Lick Creek at the Sharkey gaging station (site 7).

TABLE 7.--Principal-ion analyses of water from streams located near the Maxey Flats burial site

[NA means not analyzed. Analyses by U.S. Geological Survey laboratory.]

Site[1]	Date sampled	Discharge[2] (ft^3/s)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Bicarbonate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	Silica (mg/L)	Dissolved solids (mg/L)	pH
1	6/04/79	0.51	34	24	3.8	17	0	5.2	200	NA	NA	19	362	4.7
1	8/17/79	.85	37	22	5.2	18	2	4.4	230	NA	NA	26	376	4.8
1	10/25/79	3.0	28	18	3.9	14	4.9	4.1	170	0.01	0.23	19	273	5.9
2	6/07/79	.32	9.9	5.4	3.1	5.3	6.0	5.1	49	0	.47	12	119	6.1
2	8/18/79	.85	8.4	4.1	3.3	5.4	5.0	2.5	48	NA	NA	12	118	5.9
2	10/25/79	3.0	11	6.5	2.6	5.5	9.8	3.5	55	.02	1.2	11	104	6.4
3	6/07/79	.32	9.9	5.3	3.2	5.5	2.4	NA	54	0	.45	13	112	5.4
3	8/17/79	.85	8.9	4.2	3.4	5.6	5.0	2.8	44	NA	NA	14	128	5.4
3	10/25/79	3.0	11	5.9	2.7	5.2	7.3	3.6	53	.10	.31	11	100	6.3
4	6/07/79	.32	9.6	4.7	3.1	6.0	1.0	4.2	53	0	.19	16	110	5.4
4	8/17/79	.85	8.5	3.8	2.9	6.9	4.0	3.0	48	NA	NA	16	124	5.4
4	10/25/79	3.0	9.5	4.5	2.5	4.3	3.7	3.3	53	.01	.50	13	91	5.7
5	6/04/79	.51	17	13	4.0	7.3	7.3	3.0	100	NA	NA	17	196	5.4
5	10/25/79	3.0	17	11	3.9	6.7	8.5	4.7	90	.10	.37	15	168	6.5
6	6/07/79	.32	16	9.3	4.1	6.0	17	3.0	72	0	.42	16	162	6.3
6	8/17/79	.85	14	7.2	4.2	5.2	10	2.7	63	NA	NA	17	148	6.4
6	10/25/79	3.0	14	8.2	3.8	5.5	5	3.8	71	.01	.60	15	125	6.5
7	6/07/79	.32	13	6.6	3.5	5.8	15	3.2	58	0	.04	13	117	6.2
7	8/17/79	.85	12	5.5	3.8	5.2	15	3.3	48	NA	NA	13	136	6.7
7	10/25/79	3.0	12	6.3	3.4	5.2	11	4.2	52	.01	.38	13	120	6.7

[1]Site location shown on figure 10.
[2]Mean daily discharge at Sharkey, Kentucky, gaging station on date sample collected.

Streamflow was only about 1 ft^3/s greater than maximum estimated base flow when samples were collected on October 25, 1979 (table 7). By comparison with most other samples, most principal ions in samples collected on this date show only slight dilution of base flow.

Bicarbonate concentrations shown in table 7 are small, due to the low pH. The dissolved carbon-dioxide species are predominantly in the form H_2CO_3 at the pH values shown, and the H_2CO_3 is not accounted for in the titrations for alkalinity.

Radiochemistry

Radiochemical samples were collected from streams in the burial-site area only once for this study. Ten samples were analyzed for tritium, gross alpha, and gross beta. Tritium ranged from 8,600 picocuries per liter (pCi/L) in Fox Creek below Rock Lick Creek to 38,000 pCi/L in the unnamed stream. Gross alpha was less than 1 pCi/L at all locations. Gross beta was greater than the minimum detectable limit of 4 pCi/L at only two locations, and was: 130 pCi/L in the burial site major drainageway, and 170 pCi/L in the unnamed stream. Complete descriptions of the analyses are given by Weiss and Colombo (1980).

The Kentucky Department for Human Resources has collected radiochemical samples in the Maxey Flats area about monthly since 1963. Radioactivity in streams and sediments around the burial site increased between 1970 and 1974 (Kentucky Department for Human Resources, 1974). More recently, Montgomery and others (1977) described radionuclides in stream-water samples collected in October and November 1974, and March 1975. A brief discussion of the 1977 report follows.

Tritium concentrations ranged from less than 200 pCi/L in Fox Creek to 179,000 pCi/L in a small valley about 200 ft west of the trench-water evaporator on the burial site. Tritium levels in the burial site major drainageway were as high as 45,000 pCi/L. Other dissolved waste radionuclides found in the major drainageway (and their maximum concentrations, in pCi/L) were: cobalt-60 (5), strontium-90 (80), niobium-95 (0.9), zirconium-95 (<0.6), ruthenium-106 (<0.4), and cesium-137 (0.2) (Montgomery and others, 1977). With the exception of the tritium samples from Fox Creek, these samples were collected on the burial-site property.

Sampling points and maximum concentrations of dissolved radionuclides found outside the burial-site property were: unnamed valley near Rock Lick Creek (13,000 pCi/L tritium and 6 pCi/L strontium-90), Drip Springs Hollow near Rock Lick Creek (4,700 pCi/L tritium and 0.9 pCi/L strontium-90), and Rock Lick Creek below unnamed valley (4,700 pCi/L tritium and 5.8 pCi/L strontium-90). Strontium-90 levels were 2 pCi/L in Crane Creek, which is 1.5 mi north of, and isolated from, the burial-site drainage. Cobalt-60 was not detectable in Crane Creek. Ambient tritium levels are influenced by the trench-water evaporator (Montgomery and others, 1977).

Radionuclides in streambed sediments were found at greater distances from the burial site than those found dissolved in water. Analyses showed that cobalt-60, strontium-90, cesium-137, plutonium-238, and plutonium-239 have moved from the burial site in sufficient quantities to be detected in the streambed sediment in Rock Lick Creek as far as 2.2 mi below its confluence with the unnamed stream. Concentrations of dissolved radionuclides and those found in streambed sediments generally decreased from the burial site major drainageway, to the unnamed stream, to Rock Lick Creek (Montgomery and others, 1977).

The major source of tritium found in the streams may be from the trench-water evaporator. Primary sources of other radionuclides are from surface runoff carrying contaminated soil from the burial site, or flow from trenches through the rocks, or a combination of the two. Radiochemical data from streams, and from wells outside the trench area, are of little value in determining the pathways of the waste radionuclides, but the presence of short-lived isotopes such as Niobium-95 (35-day half life) in the streams indicate some or all are from surface flow. The concentrations of principal ions in base flow (table 7) are about one order of magnitude less than those in water from bedrock, as will be shown later in the report. This indicates that the amount of flow from bedrock is much smaller than that from near-surface sources in the colluvium and alluvium, and that most radionuclides may originate from runoff carrying contaminated soil from the burial site.

WATER USE AND WATER QUALITY IN WELLS AND SPRINGS LOCATED OUTSIDE THE BURIAL SITE

Most of the information described in this section was obtained from a well and spring reconnaissance conducted in 1974 and 1975, when 52 drilled wells, 65 dug wells, and 27 springs were inventoried in the Maxey Flats area. A complete description of the study is given in an earlier report (Zehner, 1980). Only a summary is presented here, and recent water-quality data are included.

Most bedrock wells yield only enough water for limited domestic use (less than about 500 gal/d). Use of water from wells completed in bedrock is also limited because of a moderately high dissolved solids content, as indicated by a median specific conductance of 1,150 micromhos per centimeter (umho/cm) for samples from 40 wells. Hand-dug wells completed in regolith and alluvium are more common than wells completed in bedrock. The dug wells also supply quantities only suitable for limited domestic use. The shallow ground water has lower dissolved solids than water from bedrock, however, as indicated by a median specific conductance of 300 umhos/cm for samples from 62 wells.

Many drilled and dug wells occasionally go dry, and are then used as cisterns. There are exceptions. Adequate supplies for domestic use have been obtained on Maxey Flats from at least two dug wells completed in regolith, and one drilled well completed in the Nancy and Farmers Members. Many wells completed in valley alluvium provide adequate supplies for domestic use throughout the year.

Wells W1, W2, W3, and W4 (fig. 10) are completed in the alluvium, and are less than 15 ft deep. Analyses of water from three of the wells show small concentrations of most ions (table 8). They are considerably less than in wells completed in bedrock, as will be shown later in the report. Analyses from well W2 had large cation-anion imbalances (>12 percent difference), so are not presented. The lower dissolved solids in the alluvial wells is probably due to less travel time of the ground water, and the lower solubility of the silica-rich sediments, compared to deeper water in shale bedrock.

Most concentrations shown in table 8 are similar to those found in streams near the wells (table 7) on the same sampling date. Well W1 is near site 5, well W3 is near site 4, and well W4 is near site 2 (fig. 10). Noticeable differences, however, are: pH, which is generally greater in stream water; and bicarbonate and sulfate, which in some samples are greater in stream water and in some samples are greater in ground water. The latter differences are probably related to differences in solution of carbon dioxide. The general similarity in quality of water from alluvium and stream water indicates hydraulic connection between the two.

TABLE 8.--Principal-ion analyses of water from shallow wells located near the Maxey Flats burial site

[Date is month/year sample collected. NA means not analyzed. Analyses by U.S. Geological Survey laboratory.]

Well	Date	Calcium (mg/l)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Bicarbonate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	Silica (mg/L)	Dissolved solids (mg/L)	pH
W1	4/75	13	8.6	3.7	6.0	7.0	2.3	77	0	0.34	12	141	5.3
W1	6/79	14	11	3.9	7.4	0	4.2	87	NA	NA	15	191	4.4
W1	10/79	14	11	4.3	7.2	2.4	6.4	84	0.01	.35	14	149	5.0
W3	3/75	10	2.9	4.0	6.9	22	4.5	23	0	2.6	7.3	NA	6.0
W3	10/79	6.4	1.8	3.4	4.8	9.8	4.3	22	.01	0	11	175	5.4
W4	6/79	13	5.3	5.3	4.3	2.4	3.3	55	NA	NA	24	131	4.5
W4	10/79	11	4.3	6.3	4.2	2.4	2.9	48	.01	2.0	23	107	4.8

Radiochemical quality of water from wells located outside the burial site are described by the Kentucky Department for Human Resources (1974), and by Montgomery and others (1977). Tritium was the only radionuclide detected in well water at concentrations which reflect contribution from burial site operations, when samples were collected in October 1974, and April and August 1975 (Montgomery and others, 1977). Concentrations in wells W1, W3, and W4 ranged from less than 200 to 2,000 pCi/L, with both lowest and highest values (for different dates) from well W4. Most of the tritium may originate from the trench-water evaporator operated on the burial site.

Springs, ponds, and streams are also used for water supply. Most springs are located at the bases of hillsides. The water has low specific conductantce relative to that of water from bedrock, with median of 280 umhos/cm for samples from 25 springs. This indicates that most of the water is of near-surface origin; probably from the colluvium on the hillsides.

WELLS ON THE MAXEY FLATS SITE

History and Well Numbers

Three groups of wells were drilled on the burial site, each at different times. The first group of eight wells was constructed in 1962, before burial operations began. Descriptions of the wells are given by Walker (1962). They are numbered 1 through 8. A second group of 14 wells was drilled in 1973, and are described by Emcon Associates (1975). These wells are numbered 1E through 14E, and are referred to as E wells. Well 7E collapsed during drilling, and no longer exists. The third group was drilled for the present study, and was installed in two clusters. The first (A) cluster of four wells was drilled about 1,000 ft northeast of the trench area in July and August 1976. These are called UA wells, and are numbered UA1 through UA4. The second (B) cluster of 5 wells was drilled in the trench area in October and November 1977. These are called UB wells, and are numbered UB1, UB1-A, UB2, UB3, and UB4.

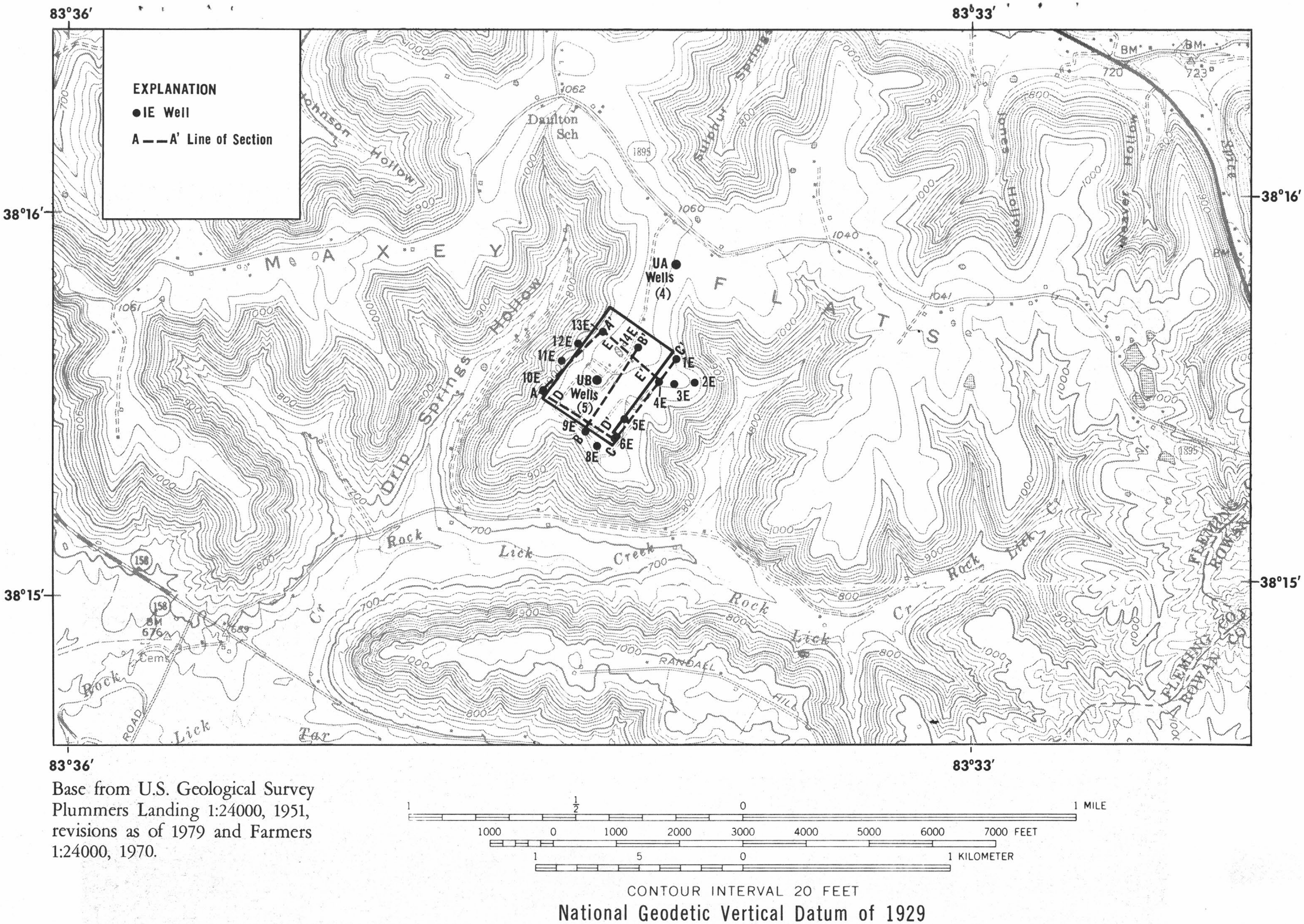
Well locations are shown on figure 14, except for wells 1 through 8. UA and UB well-cluster locations are each shown as one point on the diagram. Positions of individual UA wells are analagous to corners of a square, with distance of 30 ft between wells. UB-well spacing ranges from 15 to 30 ft. Figure 15 is a photograph of the burial area, showing relative positions of wells and trenches.

Altitudes of wells 1 through 8 are given in appendix 2, and those of UA, UB, and E wells are given in appendix 3. Altitudes of all wells are referenced to the 1,060-ft altitude shown on figure 14, at the intersection of the road crossing Maxey Flats and the road leading to the Maxey Flats site. Accuracy of the individual well datum is ±0.03 ft.

Wells 1 through 8 were drilled into the shale-sandstone sequence at the base of the Nancy and top of the Farmers Members. Steel pipes were set from slightly above ground level to the bottom of the drillholes. The wells were not cemented, so both surface and ground water can seep into them. Sediment has filled the lower 10 ft of most pipes since completion (see well depths in appendix 2).

Diagrams for proposed E well construction are given in appendices 4 and 5, and were drafted before the wells were completed (J. McCollough, Emcon Associates, oral commun., 1975). Depths shown may be different from those measured during the present study because of change in drilling plans when the wells were being constructed. Geophysical logs indicate cement depth in well 4E is 20 ft, instead of the 10 ft shown.

Construction diagrams of UA and UB wells are given in appendices 6 and 7. UB1 was cored from 5 ft below ground level to a depth of 27 ft. UA4 and UB2 were cored from near ground level to the bottoms of the wells. Details regarding drilling and coring operations at UA and UB wells are given in the following section.



Base from U.S. Geological Survey Plummers Landing 1:24000, 1951, revisions as of 1979 and Farmers 1:24000, 1970.

Figure 14.-- Maxey Flats area showing wells on the burial site.

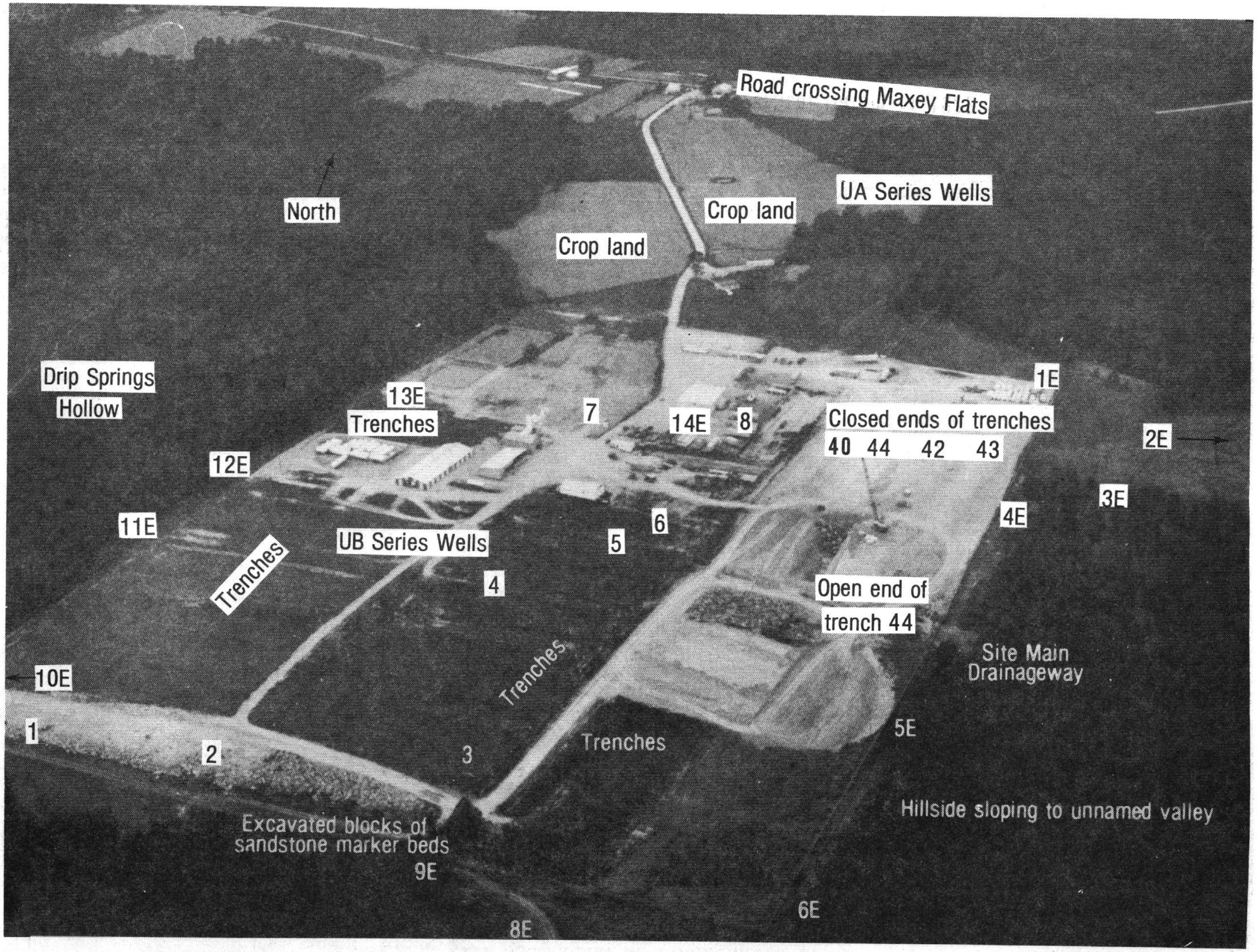


Figure 15.-- Maxey Flats site and well and trench locations. Numbers 40, 42, 43 and 44 represent trenches. All other numbers represent wells. Photograph courtesy of EG&G, Inc., Las Vegas, Nevada.

Construction of UA and UB Wells

Drilling, coring, and well-construction methods are particularly important when investigating poorly permeable fractured rocks. Several methods, and their application at Maxey Flats, are discussed in this section. It should be realized at the outset that a well which does not encounter a fracture may accumulate such a small volume of water that it is not measureable by standard techniques for long periods of time (months to years) even though the interstices in the rocks open to the well are saturated.

"Useable" or "stable" head data, as used here, means those that are representative of heads in the aquifer, rather than those due to recovery fro drilling and sampling. "Non-native" water is that which is not representativ of water in the aquifer. Collection of stable head data may be obtained within a reasonable time (a few months) after well completion, by adding or removing water. If non-native water is added to a well, however, months to years of withdrawals may be necessary to obtain a water-quality sample representative of that in the aquifer. Useable head data are lost during thi time.

Provided the rock is competent so that the drillhole remains open, air-rotary drilling has several advantages, compared to other methods such as cable-tool, mud-rotary, or air-rotary with water-spray injection. The principal advantage is that non-native water is not introduced, so that: (a) a water-yielding zone (usually part of a fracture at Maxey Flats) can possibly be detected during drilling, enabling completion of the well in such a zone, and (b) water-quality data can be collected during, or reasonably soo after, drilling. Other advantages are: usually, rapid drilling time; no necessity for mud pits; and no necessity for hauling drilling fluids.

The major disadvantages of coring or drilling with only air injection are: (a) cores become hot and dessicated, (b) fractures may be plastered closed at the borehole wall by damp drill cuttings (although this situation i usually temporary), (c) commonly, a "ring" of cuttings forms between the drilling tools and borehole, so that frequent jarring of the tools is necessary to prevent them from being stuck in the hole, (d) a very large volume of air is needed to remove cuttings, and (e) such drilling causes tool to wear rapidly from heat and abrasion. The latter three disadvantages may require more time and equipment than other drilling methods, which increase drilling costs.

Completion of wells in water-yielding zones was optimized by drilling or coring through one hydrologic unit, then letting the equipment sit idle while the hole was measured for water accumulation. Usually, the one to four hours of idle time normally used were not sufficient for measureable amounts of water to enter the drillhole, but water levels could be measured in some drillholes after leaving then undisturbed overnight. When significant amount of water entered a well from a zone in which another well had not been completed, the well was completed in that zone.

Non-native water had to be injected into some UA wells during drilling, and some was poured into well UA1 to obtain a stable head when recovery from drilling was found to be extremely slow. This water was obtained from the Morehead city supply, rather than from the Maxey Flats site.

Control of the cuttings was not necessary when drilling the UA wells because no waste radionuclides were encountered. Most were blown out of the wells as chips, but some were pulverized to a fine powder. This caused considerable airborne dust, often engulfing the drilling site. This situation was prevented when drilling the UB wells because some cuttings contained waste radionuclides. The UB wells were drilled with air injection only, but water spray had to be injected during coring operations in well UB2.

Three extra items of equipment were used to eliminate dust when drilling the UB wells. One was a blowout preventer, which was attached to the surface casing and prevented drilling dust from escaping upward along the drillpipe. The cuttings-discharge line was attached to the side of the blowout preventer. The second device was a water spray installed in the discharge line, which changed the dust to a thin mud. The spray was operated only when drilling, so that the drilling air prevented non-native water from entering the boreholes. The discharge line extended to the top of the third device, which was a covered tank used to contain the water and cuttings. Water from the tank was returned to the water spray.

The water tank was emptied frequently to prevent thickening mud from clogging the water spray. The water was not released until radionuclide concentrations were determined, which required about two days. It was therefore stored in seventy-five 55-gal drums. If radionuclide concentrations were at or below background levels, permission to release the water into the burial site drainage system was given by the Kentucky Department for Human Resources. Seven barrels contained water and cuttings with radionuclide concentrations above background. These were processed through the evaporator on the burial site, and solid materials were emplaced in a burial trench.

Most, possibly all, water containing radionuclide concentrations above background came from one, or both, of the sandstone marker beds. Completion of a well in these beds was not initially intended in the drilling program, so none were drilled at the UA well site. Because of the radionuclide data, and the conclusion that the bases of most trenches around the UB wells consisted of the lower sandstone marker bed, well UB1-A was completed in both sandstone marker beds.

Ideally, a well should be progressively cased and cemented through many intervals as the well is drilled deeper, so that water quality in lower zones is not altered by that entering the well from above. Drilling costs, and the difficulty of controlling the large volume of cuttings that would be produced in the large diameter, upper part of such holes, prevented this type of well construction at Maxey Flats. Only single casing and cement seal were used.

An important aspect of well construction is the cementing of zones other than those from which data are to be collected. Even slight seepage along the surfaces of cement bonds, or through the cement itself, may cause non-representative heads and substantially alter water quality in a sensitive, complex system.

Cementing procedure consisted of injecting the cement inside the casing, dropping a drillable plug on the cement, and using a pressurized water drive against the plug to move the cement down the casing, then up the casing-borehole annulus, filling the annulus from the bottom to ground level. A polystyrene-styrene base polymer cement was used in well UA3 as an experiment, with the intention of possibly using it in other wells. Polymer cement is very resistant to corrosion by water, and the density and viscosity can be adjusted so that part of it will flow into the rock, producing a very good cement-borehole bond. Because the cement had rapid settng time (less than about 25 minutes at 90°F), it was impractical to use in other wells, particularly deeper ones that required large batches of cement.

Portland cement was used in all other UA wells. Sodium chloride and calcium chloride were added to provide expansion and accelerate setting time. The UB wells were cemented with similar additives, but the cement base was 50 percent portland and 50 percent pozzolan (high-silica), to provide resistance to sulfates in the ground water. Hydraulic conductivity was determined in the laboratory for one cement sample from well UB4, and was 5.7×10^{-6} ft/d. A water composition similar to that in the Farmers Member was used in the test for hydraulic conductivity.

Water from upper strata accumulated in the bottoms of some wells, prior to completion. Pumping was undertaken in these wells, so that water depth was limited to a maximum of a few feet prior to casing and cementing, and the water was removed immediately after the wells were completed. The pumping produced small heads in the wells, which promoted flow from the lower strata into the wells. This reduced, or eliminated, the flow of accumulated shallow-strata water into the lower strata.

BURIAL SITE OPERATION AND RADIOACTIVE WASTE

Trench Design and Waste Burial

Information from many sources was used for describing trench construction and burial operations, and much of it was obtained by observations conducted during this study. Much is "common knowledge" obtained from personnel employed at the burial site. Specific documentation for most of the information is available at the Kentucky Department for Human Resources. The only documentation cited here is that given for trenches 21L and 22, which was furnished by D. Clark (Kentucky Department for Human Resources, written commun., April 1980).

Most trenches are about 300 ft long, 50 ft wide, and about 20 to 25 ft deep. Waste was dumped into the open trenches, and the top (and waste front in parts of many trenches) of the waste was covered with regolith as the trench was progressively filled. These are called "common trenches" in this report. A cap composed of clay and crushed shale, required to be at least 3 ft thick, covers the tops of all trenches. The caps are graded to increase the runoff to rainfall ratio, and grass is grown on them to reduce erosion and increase evapotranspiration of infiltrating water. Most trenches contain one or two steel riser pipes, which are slotted in the lower several feet. Locations of trenches and riser pipes are shown on plate 1. Only one of about 18 pipes is shown for trench 33L. The bottoms of the trenches are sloped a minimum of 1 percent so that infiltrating water will flow to the pipes for removal.

"S" trenches, such as 5S, were used for burial of "special" types or amounts of wastes which have longer biological or physical half-lives than those in other trenches. Examples are strontium-90 and plutonium. These were constructed and filled in a manner similar to most trenches, and are referred to as common trenches in this report.

Several trenches were either constructed differently, or contained different physical forms of waste than the common trenches. Solidified liquid wastes, or liquid holding tanks, were buried in "L" trenches, such as 4L. Most "L" trenches are much smaller than common trenches (plate 1), and probably have very little void space in the waste. Trench 21L (which formerly contained liquids) contains several contaminated empty tanks. Trenches 22 and 34 each contain a series of individual cells in which large volume, high specific-activity wastes were buried. Trench 33L consists of several adjacent slit trenches, ranging in width from 2 to 8 ft. Each is about 250 ft long, with depth of about 10 ft. The slit trenches were lined with plastic, onto which liquid slurries of various compositions were pumped. The slurry solidified in place, and the slit trenches were covered with one cap of regolith. Trench 41 was not used for waste burial. It was temporarily left open after excavation, and used to hold water that was pumped from other trenches in an attempt to use natural evaporation to dispose of the trench water. The empty trench was later filled with regolith and capped.

"Hot wells" are vertical steel casings used for burial of small-volume wastes with high specific activity. The upper several feet of the casings were filled with cement after burial completion. Hot wells 1 through 8 are located adjacent to one another, and are capped with one large slab of concrete. They are about 10 to 15 ft deep, and 1 to 2 ft in diameter. Several other hot wells are located against the walls of common trenches, and extend from ground surface to the bottom of the trenches. Figure 16 shows a typical trench at Maxey Flats. It is about 10 to 15 ft deeper than most, however, and exposes the unweathered part of the Nancy Member.

Accurate dimensions of the trenches are not available, partly due to slumping of the weathered shale part of the walls, and partly due to sketchy records, particularly during the early years of operation. Approximate trench dimensions and closure dates are given in table 9. The volume of waste and amount of radioactivity shown in table 9 were obtained from a waste inventory of the burial site (Kentucky Department for Human Resources, December 1977). Radioactivity is that referred to as "total radioactivity," and waste volume is that referred to as "solid waste, by total" in the inventory. Radioactivity of liquid waste is included in table 9, but volume of liquid is not.

Two primary sources for error in waste volume and radioactivity are cited by Gat and others (1976) in an earlier inventory. These were inaccuracies in radiation shipment records and incomplete correction of erroneous computer entries in the inventory data. Although the data shown in table 9 are updated and more accurate than those in the 1976 inventory, the sources for error are still present, and the data should be considered as approximate (D. Clark, Kentucky Department for Human Resources, oral commun., April 1980). An obvious error is shown for trench 5S, in which the volume of the waste exceeds the volume of the trench. Values from inventory data were rounded as follows: volume of waste to two significant figures; and radioactivity to three significant figures.

Waste Form and Concentration of Radioactivity

Most waste is in solid form and is contained in steel drums, although plywood and cardboard boxes were also used. Some container-enclosed liquids and solidified liquid wastes were buried during the early years of operation. Most containers were intended for short-term holding of the waste during shipment. The earth in which the waste is buried is intended to be the long-term container. The waste is in various physical forms, including paper, glassware, clothing, shielding material, animal carcasses, laboratory reagents, and trench-water leachates resulting from contact of infiltrating rainfall with wastes. Little is known about the original, non-isotopic, chemical composition of the waste.

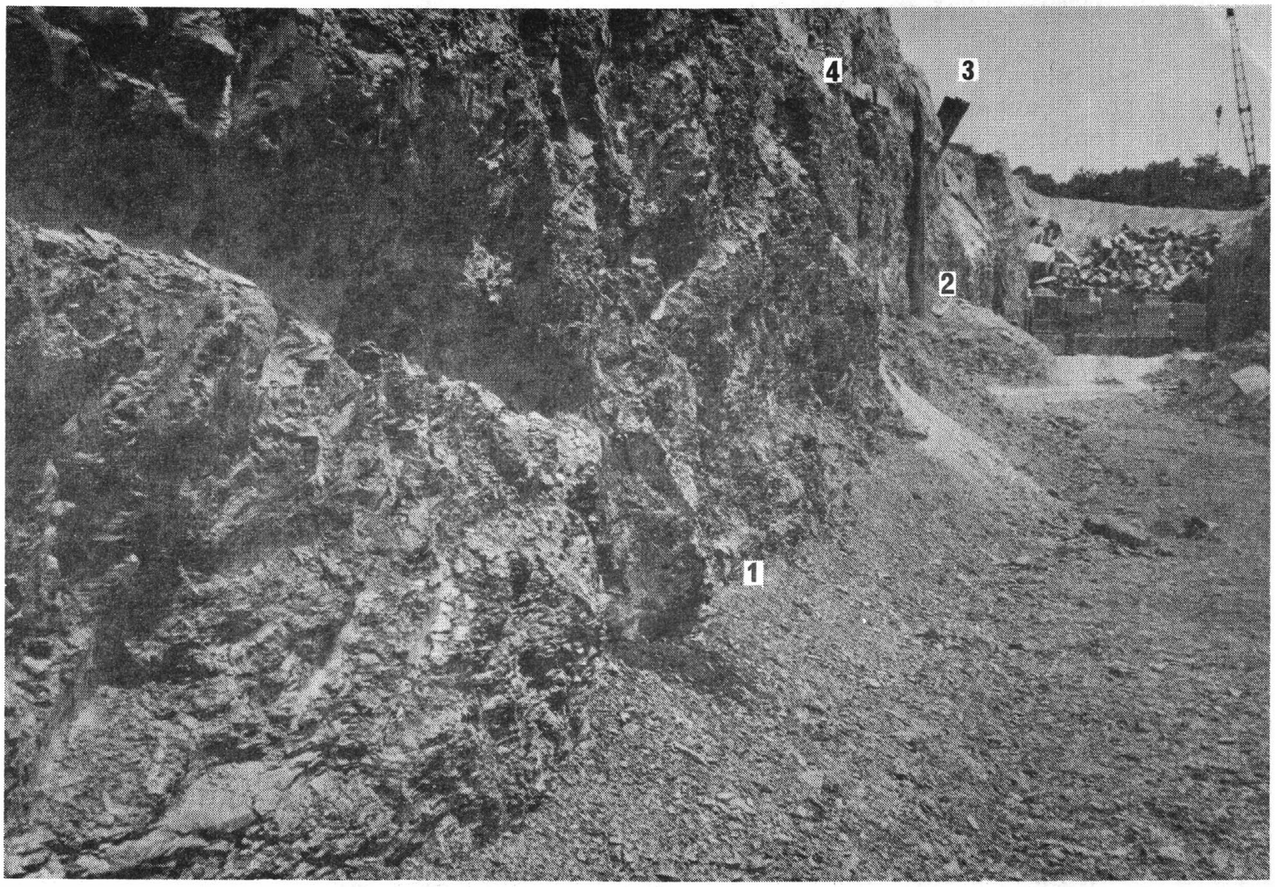


Figure 16.-- Burial trench 43. Dark area at lower center (1) is a seep from a fracture in the Nancy Member of the Borden Formation. Vertical pipe at upper right (2) is a riser pipe for trench-water removal. Slanted pipe behind riser pipe (3) is a "hot well" in the adjacent trench. Lower sandstone marker bed (4) is visible near top of riser pipe.

TABLE 9.--Trench dimensions, closure dates, and characteristics of waste

[Data from Kentucky Department for Human Resources, December 1977. Dash means value unknown or unavailable.]

Trench number	Trench dimensions[1] (ft)	Trench volume (ft^3)	Solid-waste volume (ft^3)	Radioactivity at time of burial (curies)	Date closed (month/year)
1	150-10-15	22,000	7	306	5/63
1S	75-25-15	28,000	580	2,300	9/63
2	180-25-15	68,000	-	-	7/63
3	250-15-15	56,000	500	5,900	9/63
4L	30-15-15	6,800	0	1	10/63
5S	30-15-14	[2]6,300	[2]7,800	6,480	4/64
6L	25-15-14	5,200	1,000	<1	11/63
7	225-15-15	50,000	23,000	16,200	4/64
8L	20-15-13	3,900	0	<1	1/64
9L	20-15-12	3,600	-	-	3/64
10	300-30-15	140,000	78,000	426,000	12/64
11S	300-30-12	100,000	45,000	16,100	9/65
12L	15-10-08	1,200	84	2	7/64
13L	15-10-08	1,200	56	<1	9/64
14L	15-09-05	700	-	-	6/66
15	300-50-12	180,000	73,000	44,900	9/65
16L	15-10-08	1,200	3	<1	4/65
17L	30-15-10	4,500	0	5	12/65
18	300-40-09	100,000	75,000	49,100	2/66
19S	300-40-10	120,000	69,000	66,800	12/66
20	300-40-12	140,000	77,000	103,000	11/66
21L	300-42-15	190,000	25,000	2,540	-
22	300-20-12	72,000	3,000	20,600	1/72
23	300-60-10	180,000	60,000	20,400	6/67
24	300-50-10	150,000	62,000	8,420	10/67
25	300-30-11	99,000	49,000	18,100	1/68
26	300-50-10	150,000	66,000	11,000	5/68
27	350-70-18	440,000	160,000	35,200	2/69
28	350-70-18	440,000	160,000	34,700	9/69
29	350-70-18	440,000	240,000	871,000	6/70
30	460-75-22	760,000	240,000	30,600	2/71

TABLE 9.--Trench dimensions, closure dates, and characteristics of waste--Continued

Trench number	Trench dimensions[1] (ft)	Trench volume (ft^3)	Solid-waste volume (ft^3)	Radioactivity at time of burial (curies)	Date closed (month/year)
31	460-75-22	760,000	190,000	672,000	10/71
35	300-70-20	420,000	67,000	13,900	10/72
36	200-20-18	72,000	14,000	5,670	11/72
37	200-20-18	72,000	15,000	1,370	12/72
38	200-20-17	68,000	19,000	222	12/72
39	200-50-16	160,000	27,000	36	7/73
32	350-70-22	540,000	120,000	27,000	5/72
33L	-	-	0	809	1/72
34	500-30-10	150,000	900	79,100	8/72
40	686-70-30	1,400,000	440,000	-	5/74
41	-	-	-	-	1/73
42	650-70-30	1,400,000	370,000	-	6/75
43	614-50-30	920,000	390,000	-	12/75
44	681-55-30	1,100,000	500,000	-	9/76
45	-	-	55,000	-	11/77

[1]In order of length, width, and depth.
[2]Data must be in error because volume of waste exceeds volume of trench. See discussion in text regarding possible sources of error.

Table 10 shows, for most common trenches, initial (at time of burial) concentration of radioactivity by volume in the waste and in each trench as a whole. The latter concentration includes volume of void space in the trench, fill material placed between the waste, and trench cap material that has moved down into the waste. Also shown is the ratio of waste volume to trench volume, or fraction of trench volume occupied by solid waste. Subtracting this value from 1.0 gives an approximation of the maximum porosity in the emplaced waste.

Some porosity may have been formed in the trench when partially filled containers were breached because the volume of waste is determined by the outside dimensions of the container. Porosity was reduced in some trenches by frequent emplacement of fill material at the front of the waste pile, in order to reduce radiation exposure during burial operations, and to prevent rainfall from encountering the waste. Overall porosity has probably decreased since the time of burial, however, because of compaction of the waste by heavy equipment during burial and trench capping, weight of the waste, and decomposition of waste and waste containers. Subsidence holes commonly form on the trench caps, indicating a decrease in porosity. Filling the holes and regrading the caps is one of the routine maintenance operations at the burial site.

TABLE 10.--Concentration of radioactivity in waste

[Values calculated from data in table 9. Dash means value unknown.]

Trench	Ratio of radioactivity[1] to waste volume (curies/ft^3)	Ratio of radioactivity[1] to trench volume (curies/ft^3)	Ratio of waste volume to trench volume (dimensionless)
1	44	0.014	<0.010
1S	4.0	.082	.020
3	12	.11	.008
7	.70	.32	.46
10	5.4	3.0	.56
11S	.36	.16	.45
15	.61	.25	.41
18	.7	.5	.8
19S	.97	.56	.58
20	1.3	.74	.55
22	6.9	.29	.041
23	.34	.11	.33
24	.14	.056	.41
25	.37	.18	.49
26	.17	.073	.44
27	.22	.080	.36
28	.22	.079	.36
29	3.6	1.9	.55
30	.13	.040	.32
31	3.5	.88	.25
32	.22	.050	.22
35	.21	.033	.16
36	.40	.079	.19
37	.09	.019	.21
38	.01	.0030	.28
39	<.01	<.0010	.17
40	-	-	.31
42	-	-	.26
43	-	-	.42
44	-	-	.45

[1]Radioactivity at time of burial.

The values shown in table 10 were computed from data in table 9. The ratios should be considered approximate because of the probable errors explained in the previous section. Probable inaccurate values are the ratios of radioactivity to waste volume for trench 1 (an order of magnitude greater than most trenches) and trench 39 (an order of magnitude less than any other trench). Radioactivity data for trenches 40 through 44 are not available, but, excluding the water-holding trench 41, probably have concentrations similar to those in other common trenches. Excluding these seven trenches, the means of the ratios are: radioactivity to waste volume = 2 curies/ft^3; radioactivity to trench volume = 0.4 curies/ft^3; and waste volume to trench volume = 0.4.

The mean radioactivity concentrations apply to the bulk of the waste buried at Maxey Flats. Waste of low volume and high specific activity are buried in "hot wells," and these are not included in the calculations. Precise radioactivity data for trench 45 are not available, but it contains large quantities of high specific-activity waste. If radioactivity concentrations in "hot wells," and in trench 45, had been included in the calculations, the computed means would be greater than those stated above. Information regarding type and quantity of specific radionuclides buried at Maxey Flats are on file at the Kentucky Department for Human Resources in Frankfort, Kentucky.

Trench-water Pumpage and Processing

Water accumulates in closed burial trenches by infiltration through the caps, seepage of ground water through the regolith and rocks, or a combination of the two. Some water initially accumulated from precipitation and runoff that entered open burial trenches as they were being filled. The water pumped from the trenches is processed by evaporation (boiling), using a submerged air-propane heater, and burial of the sludge remaining after evaporation. Tritium is the predominant radionuclide released in the evaporation process. Most other radionuclides are retained in the sludge. Montgomery and others (1977) and Blanchard and others (1978) describe the evaportor effluent in detail.

Most trenches were first pumped at the beginning of a trench-dewatering operation in late 1972 and 1973, but infiltrating water continued to accumulate after they were pumped. Frequent pumping and processing of trench water is now an expensive routine maintenance operation.

Holding tanks were used to temporarily store water that had been removed from trenches, particularly when large volumes were pumped in 1973. These tanks were surrounded by an earth berm to contain any spills of radioactive water. Several spills have contaminated the bottom of the berm area, so that rainwater falling into it is now evaporated with the trench water (Montgomery and others, 1977). The berm and water are shown as Pond A on plate 1. Most holding tanks are now inside a building, and this pond is being eliminated. Other ponds containing a mixture of rainwater and trench water are those shown as Ponds B and C.

The volume of water pumped from trenches and ponds, from 1973 through 1979, is shown in figure 17. Total pumpage was 4,929,590 gal from trenches and 1,234,450 gal from ponds. The potential maximum rate of removal cannot be deduced from the graph. Some of the reasons for this are: the limited capacity of the evaporator to vaporize the water (1 to 5 gal/min); much of the water pumped in 1973 was stored in holding tanks and processed in later years because of the limited evaporation rate; most water processed in 1975 was from trenches 40 and 42, and from holding tanks; and, after 1977, pumpage from most trenches was reduced in order to evaporate water in ponds A, B, and C.

The maximum volume of water that may be pumped is also limited because the slotted sections of old riser pipes in some trenches are plugged. New, 18-in.-diameter riser pipes were driven to the bottoms of trenches 1S, 3, 5S, 7, 10, 15, 25, 28, 29, and 35 in November 1977. With the exception of the pipe in trench 1S, which is the only one in the trench, the new pipes were installed to replace old, 2-to 3-in.-diameter plugged pipes. All "B" riser pipes shown for these trenches in plate 1 are the new pipes.

The effect on yield from some trenches, due to installation of the new pipes, is best illustrated by pumping data for trench 35 (fig. 17). Pumpage was 14,700 gal in 1973. The old pipe evidently became plugged because frequent pumping produced only 210 gal between 1973 and 1977. From 1977 through 1979, 476,420 gal were pumped from the new pipe. Similar examples are trenches 10, 15, and 26. Installation of the new pipes did not always result in higher yields. Both new pipes in trenches 28 and 29 yielded only 200 gal from 1977 through 1979. These pipes evidently have poor connection with water in the trench, or the combination of waste and backfill in the vicinity of the pipes has very low hydraulic conductivity.

Total pumpage shown at the top of figure 17 indicates that the highest-yielding trenches are numbers 10, 19S, 26, 27, 32, 35, and 40. The caps on these trenches may be more permeable than others. Factors that also influence the volume pumped are: the degree of connection of the riser pipes to water in the trenches; the necessity for using much of the evaporator capacity for eliminating water from ponds (thereby restricting pumpage from trenches); differences in trench sizes and specfic yield of the waste; and the fact that much of the water in trench 40 (with less amounts in others) was due to direct precipitation into the trench when it was open. Considering these factors, there is apparently no direct relationship between pumpage data and relative hydraulic conductivity of the trench caps.

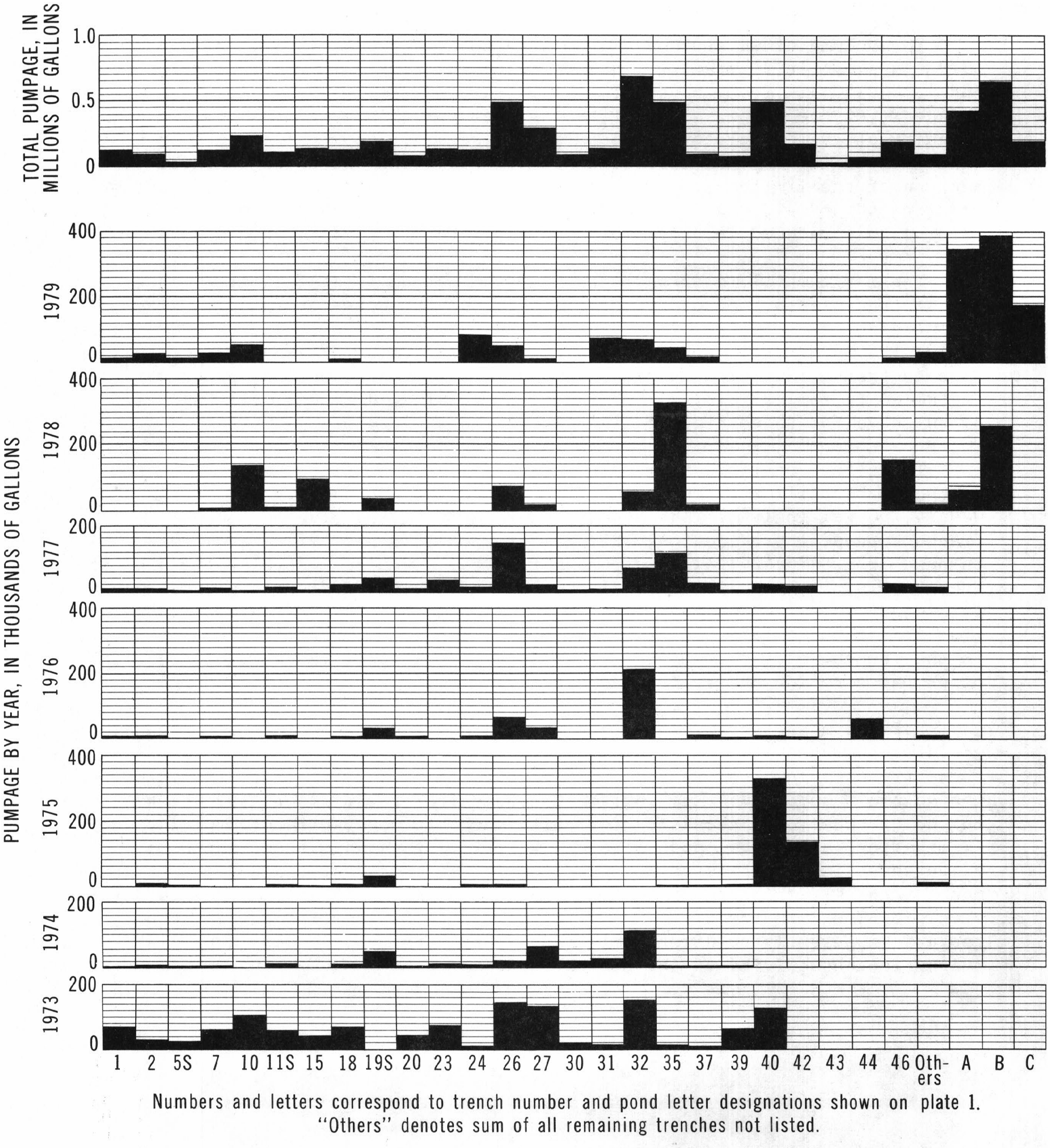


Figure 17.-- Pumpage from trenches and ponds. Data from the Kentucky Department for Human Resources (1980).

Chemical Composition of Trench Water

Descriptions of the principal-ion, radionuclide, and organic chemistry of trench water are given by Weiss and Colombo (1980). Only a brief discussion of that report is given here.

A general survey of water quality in the trenches was conducted in June 1977, when 46 samples were collected from 33 trenches. Samples were collected from separate pipes in the same trench where possible. Portions used for dissolved organic carbon analysis were filtered through 0.45-micrometer silver membrane filters, and immediately stored on ice. Radiochemical samples were acidified with 35 ml of concentrated nitric acid at the time of collection, except for a portion of untreated water used for tritium analysis. These were not filtered, so values for radioactivity represent both dissolved and particulate fractions. Concentrations of radioactivity between samples range more than four orders of magnitude (table 11).

TABLE 11.--Ranges of water-quality measurements from 33 trenches

[Data from Weiss and Colombo, 1980]

Measurement[1]	Range
pH	2.2 to 12.4
Specific conductance (umhos/cm at 25°C)	2.8×10^2 to 3.9×10^4
Dissolved organic carbon (mg/L)	<1.0 to 6.0×10^3
Gross alpha (pCi/L)	<2.0×10^2 to 6.4×10^5
Gross beta (pCi/L)	2.0×10^3 to 5.7×10^7
Gross gamma (relative counts per minute)	<1.0 to 1.6×10^4
Tritium (pCi/L)	2.5×10^5 to 7.4×10^9

[1]Analyses on unfiltered samples, except those for dissolved organic carbon.

Water samples from eight trenches were analyzed for specific radionuclides. These were: tritium; strontium-90; plutonium-238, -239, and -240; americium-241; and gamma emitters (of which cobalt-60, cesium-134 and -137 were found to be above minimum-detectable limits). Iron-hydroxide precipitated when trench water was exposed to air, so samples were collected, filtered, acidified, and analyzed in an anoxic environment. Samples were filtered through 0.45-micrometer membrane filters and acidified in the field to pH <2.0, except for an untreated portion used for tritium analysis. Tritium was the predominant radionuclide, with concentrations at least an order of magnitude greater than any other isotope (table 12). Cesium-134 was the least abundant isotope.

TABLE 12.--Radiochemical analyses of water from eight trenches[1]

[Data from Weiss and Colombo, 1980]

Trench	Date (month/ year)	Tritium (pCi/L)	Strontium-90 (pCi/L)	Plutonium-238 (pCi/L)	Plutonium[2] (pCi/L)	Americium-241 (pCi/L)	Cobalt-60 (pCi/L)	Cesium-137 (pCi/L)
2	9/76	2.5 E7 (<1)	6.8 E3 (<1)	3.8 E3 (2.7)	4.1 E2 (8.6)	4.3 E3 (3.9)	1.4 E4 (1.9)	<100
2	7/77	2.1 E7 (<1)	3.6 E3 (10)	9.4 E3 (10)	2.8 E2 (10)	2.9 E3 (8.9)	1.0 E4 (4.5)	N.D.
7	9/76	4.4 E8 (<1)	2.0 E6 (<1)	5.0 E0 (20)	<1	<20	2.5 E3 (5.1)	4.6 E3 (2.9)
18	9/76	4.5 E8 (<1)	4.7 E4 (<1)	5.9 E2 (5.9)	5.1 E1 (20)	<20	2.2 E4 (1.5)	4.9 E3 (3.0)
19S	9/76	6.9 E7 (<1)	2.6 E5 (<1)	1.7 E5 (7.6)	2.1 E4 (24)	7.7 E2 (7.0)	1.3 E3 (23)	3.2 E3 (9.8)
19S	5/78	6.8 E7 (<1)	2.9 E5 (10)	2.1 E5 (10)	8.4 E2 (10)	1.5 E3 (17)	2.5 E3 (11)	1.0 E4 (3.8)
26	9/76	2.0 E8 (<1)	3.5 E4 (<1)	3.1 E4 (6.8)	2.7 E3 (2.2)	1.0 E3 (5.7)	1.3 E3 (6.8)	7.5 E3 (2.0)
26	7/77	1.3 E8 (<1)	3.0 E4 (10)	1.3 E5 (10)	3.5 E3 (10)	N.D.	1.4 E3 (14)	5.3 E3 (5.7)
27	9/76	3.1 E8 (<1)	2.0 E5 (<1)	1.3 E4 (3.1)	1.7 E3 (13)	1.5 E4 (3.8)	2.0 E4 (3.2)	2.3 E4 (2.4)
27	5/78	5.9 E8 (<1)	2.1 E5 (10)	4.1 E3 (10)	6.7 E2 (10)	1.4 E3 (17)	1.3 E3 (21)	8.0 E3 (4.6)
32	9/76	2.1 E8 (<1)	3.8 E5 (<1)	3.6 E3 (4.2)	1.1 E2 (25)	<40	6.0 E3 (5.6)	6.0 E3 (4.6)
32	7/77	2.3 E9 (<1)	5.4 E5 (<10)	1.1 E5 (10)	2.9 E3 (10)	N.D.	3.5 E3 (8.1)	4.8 E3 (5.5)
37	9/76	1.1 E7 (<1)	1.9 E3 (<1)	1.8 E4 (1.0)	3.1 E2 (2.6)	2.8 E4 (1.0)	5.0 E4 (1.0)	9.8 E3 (2.1)

[1]N.D. - not detected. E - exponent of base 10 (1 E2 = 1 X 10^2). Numbers in parentheses are ±2 sigma percent counting uncertainties. Samples contained <100 pCi/L Cesium-134, except: trench 26 on 9/76, 310 (18); trench 32 on 9/76, 420 (24); and trench 37 on 9/76, 1700 (4.3).

[2]Plutonium-239 and -240.

Radionuclide concentrations differ between trenches, and change with time in the same trench (table 12). Larger concentrations in some trenches are probably due to: the type, quantity, and physical and chemical form of the isotopes buried; and the physical and chemical form of the non-radioactive waste.

Results of analyses for principal ions in trench-water are shown in table 13. The results show significant cation-anion imbalances, as well as discrepancies in total dissolved solids compared to concentrations of individual ions. The samples were some of the first collected for analysis of principal ions in trench water at Maxey Flats. Several procedural problems were identified after the initial analyses: colorimetric procedures for chlorides and sulfates were questionable, due to interference from other components; and alkalinity titration was found not to be an accurate method for determining bicarbonate in trench water (R. Pietrzak, Brookhaven National Laboratory, written commun., August 1981). Ion-chromatographic and carbon-dioxide-probe methods were later employed (after completion of this hydrologic study), which resulted in more accurate analyses. The improved procedures, and analytical results from later sampling, are given by Czscinski and Weiss (1981).

Sodium and bicarbonate are the predominant ions shown in table 13. The large concentrations of iron are probably due to decomposition of steel drums used to contain the waste during shipment.

Forty-eight organic compounds were identified in the trench water. Concentrations of individual compounds were less than 10 mg/L in most samples (Weiss and Colombo, 1980).

TABLE 13.--Principal-ion analyses of water from eight trenches

[Data from Weiss and Colombo, 1980, except their values for alkalinity as calcium carbonate are converted to bicarbonate. See additional comments in text regarding these analyses.]

Trench	Date sampled	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Iron (mg/L)	Bicarbonate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Nitrogen[1] (mg/L)	DOC[2] (mg/L)	Dissolved solids (mg/L)	pH
2	9/76	29	79	66	700	40	1,900	310	11	<0.50	210	2,160	6.7
2	7/77	20	41	35	1,300	28	1,670	230	<5	.08	90	2,740	7.4
7	9/76	130	73	140	240	61	1,330	220	<10	<.05	250	1,410	6.9
18	9/76	14	160	50	540	33	2,500	310	18	<.05	500	2,240	7.0
19S	9/76	58	130	25	100	150	1,190	150	<10	<.05	620	1,670	6.6
19S	5/78	50	124	12	650	115	1,110	140	<5	<.10	500	2,100	6.9
26	9/76	31	130	39	240	65	1,610	290	<10	<.05	950	1,580	6.8
26	7/77	45	87	27	270	110	1,050	210	<1	<.04	770	1,150	7.3
27	9/76	600	430	120	670	1,200	527	4,200	69	1.6	730	7,620	6.0
27	5/78	240	255	36	450	1,150	402	3,900	<5	<.10	540	8,400	6.6
32	9/76	75	230	210	700	16	3,320	370	11	<.05	790	3,810	7.3
32	7/77	65	320	280	1,900	32	3,170	580	<1	<.04	990	3,590	7.9
37	9/76	250	730	20	680	1,100	152	180	8,000	13	3,300	11,200	5.1

[1]Nitrite plus nitrate.
[2]Dissolved organic carbon.

HYDROLOGY OF THE SHALLOW SUBSURFACE

This section relates to the regolith, and to the bedrock above the shale-sandstone sequence at the base of the Nancy and top of the Farmers Members in the trench area. Most discussion applies to the regolith because most trenches are located in this strata. The discussion is separated from later sections involving both shallow and deep rocks because of the particular hydrologic problems involved in the shallow zone, especially those relating to water in trenches.

Rocks Exposed in Trenches

Four geologic sections were made of the regolith and rocks above the shale-sandstone sequence at the base of the Nancy and top of the Farmers Members, principally to show the relative positions of the sandstone marker beds and the trench bottoms (plate 2). The tops of some wells and riser pipes in the diagram appear to be below ground level. This is because ground level is taken along the line of section, and some wells and riser pipes are off the line.

Altitudes and thicknesses of the sanstone marker beds were measured only at well UB1-A, open trench 46, and an outcrop near well 4E. Accuracy is ±0.5 ft. Altitudes and thicknesses of these beds at other wells were determined from gamma-ray geophysical logs. The latter altitudes have maximum error of about ±5 ft, but most are probably accurate to about ±3 ft. Thicknesses of the beds were obtained from lithologic descriptions of wells 1 through 8 (Walker, 1962) and E wells (Emcon Associates, 1975).

The approximate thickness of the trench caps was determined by estimating the altitude of the original (pre-burial) land surface from well and trench data. The present land surface at the E wells is probably about the same as the original because most were drilled on the perimeter of the filled trench area. It is different at wells 1 through 8 because they were drilled in the trench area before burial and trench capping began. The original land surface at wells 1 through 8 was approximated by adding the depth of the sandstone marker beds below land surface, as given in the lithologic descriptions, to the altitude of the beds determined by geophysical logging and levelling.

Altitudes of the original land surface at most trench riser pipes are shown as "+" symbols on plate 2, and were obtained by adding the reported trench depths from table 9 to the measured altitudes of the bottoms of the pipes. Altitudes of pipes in trenches 1 through 23 are given in appendix 8 and those in trenches 24 through 45 are given in appendix 9. Pipe depths and trench depths are assumed to be equal. This may not be the case in some trenches because some pipes are bent or broken, partially filled with sediment, and may not extend to trench bottoms. The approximate position of the original land surface was sketched in, weighting the more-accurate altitudes at the well locations. Thickness of the trench caps over most of the area is about 6 ft.

The amount of error between the measured altitudes of some riser-pipe bottoms and the actual trench bottoms may be estimated by noting the difference between the dashed line, representing the original land surface, and the "+" symbols on plate 2. For example, the dashed line is about 6 ft below the "+" symbol at pipes 36-A and 36-B (section A-A'). A -6 ft correction would put the bottom of the riser pipe very near the lower sandstone marker bed, which is the probable position of the trench bottom. A similar correction could be made for riser pipe 31-B. The method does not work as well for some pipes, such as most of those shown on the left side of section B-B'. The original land surface may have been lower than estimated in this area, or some soil may have been removed before reported trench depths were measured.

The bottoms of most trenches are at the lower sandstone marker bed (plate 2), so most waste is buried in regolith. The bottoms of riser pipes in trenches 18 and 19S are higher than most others. The bases of the trenches are probably at the lower sandstone marker bed, however, because recently installed riser pipes are about 10 to 12 ft greater in depth than those shown in plate 2 (J. Razor, Hittman Nuclear and Development Corp., verbal commun., October 1982). Trench 41 (now filled with regolith) and slit trenches in 33L probably bottom at the upper sandstone marker bed. Trenches 40, 42, 43, and 44 were dug to within a few feet of the shale-sandstone sequence at the base of the Nancy and top of the Farmers Members, so they are open to the regolith and unweathered part of the Nancy Member.

Water Levels in Trenches

Much, probably most, of the water that accumulated prior to 1973 was from leakage through the trench caps, or from direct rainfall into the open trenches. If water levels in the trenches are related to a water table in the rocks, those obtained after initial pumpage would therefore be more representative than earlier levels. Plate 2 shows the ranges of water levels in the trenches after initial pumpage, through December 1979. Also shown are the ranges of water levels in wells 1 through 8 and UB1-A, for the period August through December 1979. Little or no pumpage was done on most trenches (except numbers 40 and 42) during the latter months of 1975, so water levels which may not be entirely related to pumping are those shown for January 1976.

Water levels in most trenches shown in plate 2 do not appear to be located at any specific horizon, but several are between altitudes 1035 and 1040 ft. The latter levels may correspond to a water table in the regolith just above the lower sandstone marker bed, or they may simply be located in the lower part of the riser pipes because of frequent pumping. Because most of the burial area is underlain by trenches, the upper part of the ground-water system has probably been considerably altered from its former, natural state. The present upper water table may be very irregular in shape because water in the trenches may cause local ground-water mounds, or pumping may cause local depressions.

Hydrographs of eight trenches are shown in figure 18. Water-level data were collected from two pipes in trench 7 to observe effects from pumping. Only 14 weeks of record were collected from trench 1S and riser pipe B in trench 7, and data could not be obtained for trench 35 during March 1980.

Most hydrographs (except those for trenches 28 and 29) show persistent, long-term rises after pumping. Most also show very short-term (days) rises superimposed on the long-term trends, and rapid rises and falls at the higher levels due to changes in barometric pressure. Hydrographs for pipes in trenches 28 and 29 are different than others. These pipes probably have poor hydraulic connection with water in the trenches, becuase yield from the pipes is very low, as was explained earlier. The water levels in the two pipes are probably not representative of those in the trenches for most of the time. None of the hydrographs show effects of pumping from other trenches, even though 3 and 7 are adjacent to each other, as are 10 and 15 (see plate 1).

A cone of depression probably develops in the waste when pumping trench 3, and possibly trench 7, because recovery is more rapid shortly after pumping than during later periods. Some of the early recovery may also be due to slow drainage of the waste in the zone of lowered water level. Most recovery is probably due to infiltration through the trench caps, with possibly some flow from the regolith. Recovery after pumping in trenches 10, 15, and 35 is practically linear on rectangular plots, indicating insignificant development of a cone of depression. There may be little change in head with distance from the point of pumping in these three trenches because pumping rates are small (1 to 5 gal/min) and the hydraulic conductivity of the waste is probably large.

The rapid, short-term rises in water levels correspond to individual rainfall events, as can be seen by comparison of the daily rainfall plot (fig. 5) with the hydrographs. Most noticeable are those in early December 1978 (7.16 in. rainfall during a 7-day period), mid-January 1979 (1.44 in. rainfall during a 3-day period) and late February 1979 (2.3 in. rainfall during a 5-day period). As will be shown on hydrographs in the next section, the water level in a well finished in the regolith (UB1-A) does not rise rapidly during rainfall events, nor does it continue to rise. This indicates that most water in the trenches is due to infiltration through the caps, rather than flow from the regolith.

Some trenches show more response to individual rainfall events than do others. During the period November 1978 through February 1979, the following percentages of water-level rises were due to short-term events: trench 10 - 75 percent, trench 35 - 55 percent, trenches 3 and 7 - 40 percent, and trench 15 - 20 percent. The greater responses in some trenches may indicate relatively greater hydraulic conductivity of the trench caps. The comparison is rather crude, however, because the differences in magnitudes of water-level rises may also be related to differences in specific yield of the waste.

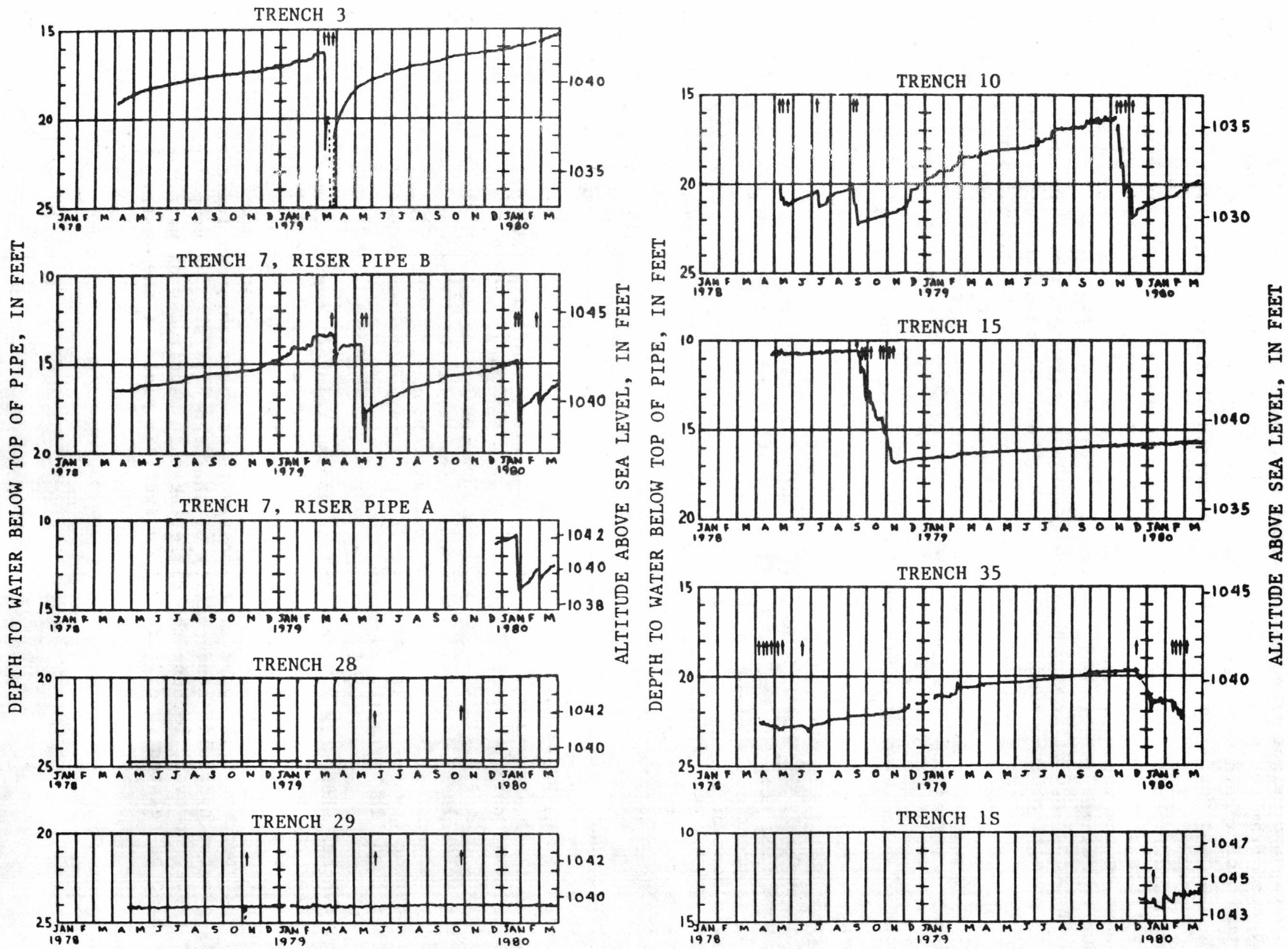


Figure 18.-- Hydrographs of eight trenches. Arrows denote pumpage. Line represents continuous water-level data, dashed where approximated.

Some short-term rises also have corresponding rapid falls in water level Examples in figure 18 are trench 10 in early July 1979, trench 35 in late February 1979, and trench 1S several times in early 1980. These rises are probably due to infiltration of rainfall and runoff at the riser pipes, followed by decline as the water moves from the pipes into the waste. The 6-week decline in trench 1S during December 1979 and January 1980 is much longer than the examples for trenches 10 and 35. The trench was pumped once during the period of record (only 5 gal were removed on January 14, 1980), so the declines are not due to pumping. They may indicate loss of some water from the trench to the regolith.

Shorter (hours) rises and falls at higher water levels in most trenches correspond to changes in barometric pressure. This probably results from compression of air between the bottom of the cap and the water in the trench, after submersion of the slots in the riser pipe.

Water levels were obtained from two pipes in the same trench only at trench 7. Pumping from pipe B in January and February 1980 caused corresponding lowering of water levels in pipe A. Precise comparisons of water levels in the pipes could not be made because water-level floats were removed during pumping.

Water Levels in Shallow Wells and Position of the Upper Water Table

Continuous water-level data were collected from wells 1 through 8 (except number 2) and well UB1-A. Well 2 had casing too badly bent for collection of data. Hydrographs of the wells are shown in figure 19. The frequent, rapid rises in wells 1 through 8 occurred during rainfall events. The wells are not cemented, so water from ground surface probably seeps into the casing-borehole annuli. This occurred so freqently in wells 4 and 6 that data collection was discontinued after 4 months. Well UB1-A is cemented from ground surface to the top of the upper sandstone marker bed, so is sealed from surface runoff. Short-term, small fluctuations in UB1-A correspond to changes in barometric pressure. The unusual hydrograph for well 7 may be due to occassional periods of surface runoff accumulating in the well, followed by natural sealing of the casing-borehole annulus as bedrock or regolith is wetted and expanded by the infiltrating water. The accumulated water "slug" then slowly infiltrates the adjacent rocks during the time the well is sealed.

Although water-level data from most shallow wells are of limited use, probably due to flow of surface water down the outside of the casings, those in wells 3, 5, 8, and UB1-A indicate a water table in the lower part of the regolith. Well 8 is the only shallow well, excluding number 7, located away from the trenches (see plate 1). It is therefore useful for estimating the positon of the water table where influence from water in trenches is less than at other shallow wells. The water level in well 8 is at the top of the lower sandstone marker bed. The levels in wells 3 and UB1-A (section B-B' on plate 2) range from 3 to 5 ft above the bed, and the level in well 5 is as much as 10 ft above the bed.

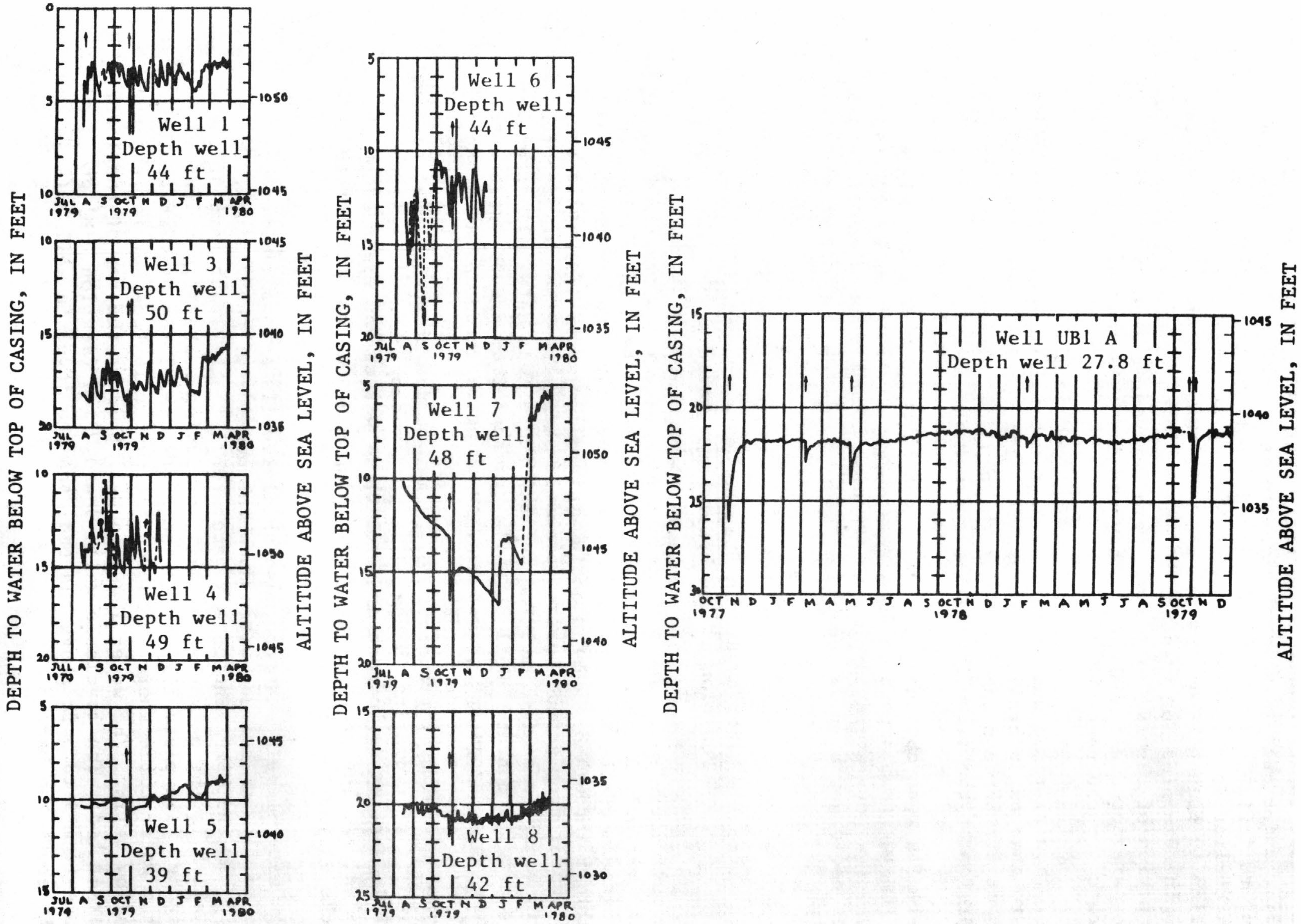


Figure 19.— Hydrographs of shallow wells. Depth referenced to top of casing. Arrows denote discharges. Line represents continuous water-level data, dashed where approximated.

The exact position of the water table may be different than indicated by the well data because heads in the regolith are composited in the open intervals. The heads likely decrease with depth because flow is downward (as well as lateral) toward deeper, saturated rocks. The actual position of the uppermost water table open to the well would therefore be higher than indicated by well data. No wells are completed above the lower sandstone marker bed, so the precise position of the water table is not known. Using the data available, it is concluded that the upper water table is as much as 10 ft above the lower sandstone marker bed, at altitude of about 1,035 to 1,040 ft.

Responses to trench pumping and long-term rises in trench-water levels are not apparent on the hydrograph of well UB1-A, even for trenches very near the well (10 and 15), as may be seen by comparing figures 18 and 19. Data collection from other wells was too short-term, and water levels fluctuated too freqently, for such a comparison. The water-level data from well UB1-A probably reflect a composite of heads due to the effect of several trenches, and the time lag between head changes in trenches and responses in the well may be large.

The heads in trenches are assumed to partly, and possibly completely, control the position of the water table at the bottom of the regolith in the trench area, even though response to head changes in trenches is not readily apparent in well UB1-A. The assumption is based on the fact that nearly all of the area is underlain by trenches, and is supported by greater water-level altitudes in wells 3, 5, and UB1-A, as compared to well 8. These data indicate water-table mounding in the trench area.

The statement was made in a previous section that the irregular water levels in the trenches did not appear to correspond to any particular horizon. With the conclusion from well data that the water table is at an altitude of about 1,035 to 1,040 ft, it may be seen in figure 18 that levels in several trenches are at the water table. The shape of the water table is likely to be very irregular, however, due to influence of different heads in trenches. Data from only four wells, and from many constantly changing water levels in trenches, are insufficient to construct a meaningful potentiometric-surface map of the area.

Seepage through Trench Caps and Specific Yield of Waste in Trench 10

Trench-pumpage and water-level data were used to compute rate of seepage into trenches. Computation consisted of dividing time for water-level recovery into volume pumped, then normalizing to unit area of trench cap by dividing trench area (as computed from data in table 9) into the result. The units are the same as those for hydraulic conductivity, but the values do not represent this parameter because: caps are probably not completely saturated; hydraulic gradients may not be 1/1; flow may not be perpendicular to the surfaces of trench-caps; and some flow into the trenches may not be from the caps.

The value computed is an effective rate of water transmission into the trenches, and is called seepage rate here. It is useful for estimating and comparing rates of water accumulation in the trenches, but it combines several features of the trench cap, such as: type of opening in which flow occurs (capillary and fracture); type of flow (saturated and unsaturated); topographic gradient of the surface; and hydraulic conductivity.

The seepage rate results from both near-surface flow through the cap and deeper flow either into, or out of, the regolith. Since both near-surface and deeper flow occur simultaneously, they cannot be separated with available data.

Flow through trench caps is probably much greater than that between regolith and trenches shown in figure 18, with the possible exception of trench 1S. Greater flow through the caps is indicated by (a) rapid rises in trench-water levels due to rainfall events, which account for much of the recovery -- these rapid rises do not occur in the regolith, as indicated by water-level data from well UB1-A, and (b) little or no rise occurred in most trenches during periods of slight rainfall in late January to early February 1979, and throughout March 1979, which cause the slopes of the hydrographs for most trenches to be zero, and only slightly negative in trenches 10 and 35. For purposes of estimating rates of flow through caps, water accumulation in trenches 3, 7, 10, 15, and 35 is assumed to be due only to flow through the caps. Water accumulation in trenches other than those shown on figure 18 is probably also due primarily to flow through the caps because other trenches are similarly constructed and have similar capping material.

Rates of accumulation and leakage for the trenches analyzed are shown in table 14. Values are given for two pumping periods in trench 10. Recovery rates were used to extrapolate water levels to pre-pumping levels for those trenches in which recovery was incomplete. The trenches, and rates and periods during which the rates were obtained, are: trench 7 - 0.0087 ft/d for October 1979 through January 1980; trench 15 - 0.0016 ft/d for March 1979 through March 1980; and trench 35 - 0.0033 ft/d for May and June 1978.

The seepage rates should be considered approximate, and the accumulation rates are mean daily rates only for the depths and periods of recovery used. Constant recovery rates were used to extrapolate water levels to pre-pumping levels, and this implies constant recharge and constant specific yield of the waste. Actually, recovery rate and recharge vary with changes in rainfall. As an example, if the recovery rate for trench 10 during October and November 1978 (0.084 ft/d) had been used for extrapolation, the leakage rate would have been 0.0011 ft/d, rather than the 0.0023 ft/d measured. Specific yield could change because of waste subsidence, and may also change with trench depth.

TABLE 14.--Seepage rates for caps on five trenches

[Pumpage data from Kentucky Department for Human Resources, 1980, rounded to nearest 10 ft^3.]

Trench	Date pumped (month/yr)	Volume pumped (ft^3)	Time for recovery (d)	Accumulation rate (ft^3/d)	Trench cap area (ft^2)	Seepage rate (ft/d)
3	3/79	820	267	3.1	3,750	0.00082
7	5/79	2,500	400	6.3	3,375	.0019
10	7/78	860	49	17.6	9,000	.0020
10	9/78	2,000	93	21.5	9,000	.0024
15	9/78-12/78	12,540	3,700	3.4	15,000	.00023
35	4/78-6/78	5,210	139	37.5	21,000	.0018

Maximum and minumum leakage rates in table 14 differ by almost an order of magnitude. The possible maximum and minimum total infiltration in the trench area could be computed by use of the leakage rates, if the values represent the range for all trenches. The cap area of common trenches computed from dimensions in table 9 is 534,000 ft^2, excluding all "L" trenches, and trenches 41, 45, and 46. Multiplying this area by the minimun and maximum leakage rates in table 14 gives a possible infiltration rate between 45,000 and 470,000 ft^3/yr. The values have little statistical meaning, however, because only 5 of 34 common trenches were analyzed. Also, precipitation for 1978 and 1979 was 11.5 in. greater than normal. Total leakage is probably less for years with normal rainfall.

Specific yield (S_y) of the waste was computed only for trench 10 because linear recovery indicated uniform specific yield. The 2,000 ft^3 pumped in September 1978 caused 2.1 ft of drawdown. Area (plan view) of the trench is 9,000 ft^2. The dewatered volume of waste was $(9,000\ ft^2)(2.1\ ft) = 18,000\ ft^3$, so S_y was about $(2,000\ ft^3)/(18,000\ ft^3) = 0.1$. The S_y of other trenches could not be computed because: the change in saturated thickness from point of pumping could not be determined in trenches 3 and 7 (recovery was nonlinear on a rectangular plot, and only one point for measurement of water level was available); significant accumulation of infiltrated water may have occurred during long periods of pumping in trench 35; and recovery was incomplete in trench 15. Complete recovery should be observed before computation because changes in recovery rate could indicate changes in specific yield.

Radionuclides in the Upper Part of the Regolith

Concentrations of selected radionuclides were determined for the near-surface materials at the UA and UB well sites prior to drilling. Those from the UA site were collected at ground surface and from a depth of 3 ft. Three to four holes were augered within a radius of 10 ft from each intended UB well location to insure that a trench would not be encountered during later air-rotary drilling. The holes extended to the upper sandstone marker bed, which was at a depth of about 10 to 12 ft below ground level. Samples were collected at depths of 5 ft and 10 ft.

Results of analyses from the UA well site are given in table 15, which also includes values for a background sample located 4 mi north of the burial site. Cobalt-60 was not detected. Radium-226 occurs naturally in the soils at Maxey Flats, and concentrations shown are considered to be at background levels. Cesium-137 concentrations were greater 4 mi from the burial site than at the UA well site, and are probably due to atmospheric fallout from weapons testing. The plutonium is probably from weapons-testing fallout.

TABLE 15.--Radiochemical analyses of soil samples from the UA well site and from background soil

[Numbers in parentheses are possible errors due to counting uncertainty. NA means not analyzed. Analyses by U.S. Environmental Protection Agency.]

Sampling site[1]	Depth[2] (ft)	Cesium-137 (pCi/g)	Radium-226 (pCi/g)	Plutonium-238 (pCi/g)	Plutonium-239 (pCi/g)
Background	0	1.88 (0.06)	5.1 (0.9)	NA	NA
UA	0	0.58 (0.04)	3.0 (0.6)	0.004 (0.002)	0.014 (0.004)
UA	3	<.02	2.2 (0.5)	<.003	<.002

[1]Background site located 4 mi north of burial site. UA site at UA wells.
[2]Referenced to ground level.

Samples from augerholes at the UB well site were analyzed and described by Blanchard and others (1978). A summary of the analyses are given in table 16. Cesium-137 concentrations are at or near background. The presence of cobalt-60 and greater concentrations of plutonium in some samples, as compared to those at the UA well site, indicate contamination of the regolith below ground level at the UB wells, however.

Median concentrations of cesium-137 at depth 5 ft were greater than those at depth 10 ft (table 16). Much of the regolith in the UB well area, particularly above depths of about 5 to 10 ft, had been excavated and later compacted as trench caps. Small quantities of radioactive material may have been spilled during waste burial, and mixed with the compacted soil.

Decreasing concentrations of cesium-137 with increasing depth support this possibility. The outer surfaces of some samples from depth may have been slightly contaminated by contacting the upper part of the hole during augering operations.

TABLE 16.--Summary of radiochemical analyses for regolith samples from the UB well site

[Data from Blanchard and others, 1978]

	Range of concentration[2]				
Depth[1] (ft)	Cobalt-60 (pCi/g)	Cesium-137 (pCi/g)	Radium-226 (pCi/g)	Plutonium-238 (pCi/g)	Plutonium-239 (pCi/g)
5	<0.03- 3.7 (0.1)	<0.03- 2.27 (0.06)	2.0 (0.9)- 3.8 (0.2)	0.008 (0.002)- 2.6 (0.2)	<0.002- .17 (0.02)
10	.03 (0.02)- 1.4 (0.1)	<.04- .12 (0.05)	1.3 (0.8)- 3.6 (0.9)	<.06- .15 (0.02)	<.003- .008 (0.003)
Median of 5-ft-depth samples	.13	.12	2.6	.05	.003
Median of 10-ft-depth samples	.10	<.06	2.6	.04	.004

[1]Referenced to ground level.
[2]Numbers in parentheses are possible errors due to counting uncertainty. Thirteen samples from each depth were analyzed, except only five samples from depth 5 ft and four samples from depth 10 ft were analyzed for plutonium.

Rate of Radionuclide Movement through the Lower Sandstone Marker Bed

Above-background concentrations of gamma activity were found in late summer of 1977 by personnel employed by Nuclear Engineering Company. The activity was detected in water, and on solids, at an empty trench (number 46) located at the southeast corner of the burial site. A survey of the area in August 1977 showed that the activity was from the lower sandstone marker bed, at a depth of 20 ft below ground level. Twelve small trenches were excavated to the shale underlying the bed, in an area around the southeast end of trench 46 (fig. 20). They were dug by Nuclear Engineering Company, with the purpose of identifying the extent of leakage and concentration of radionuclides.

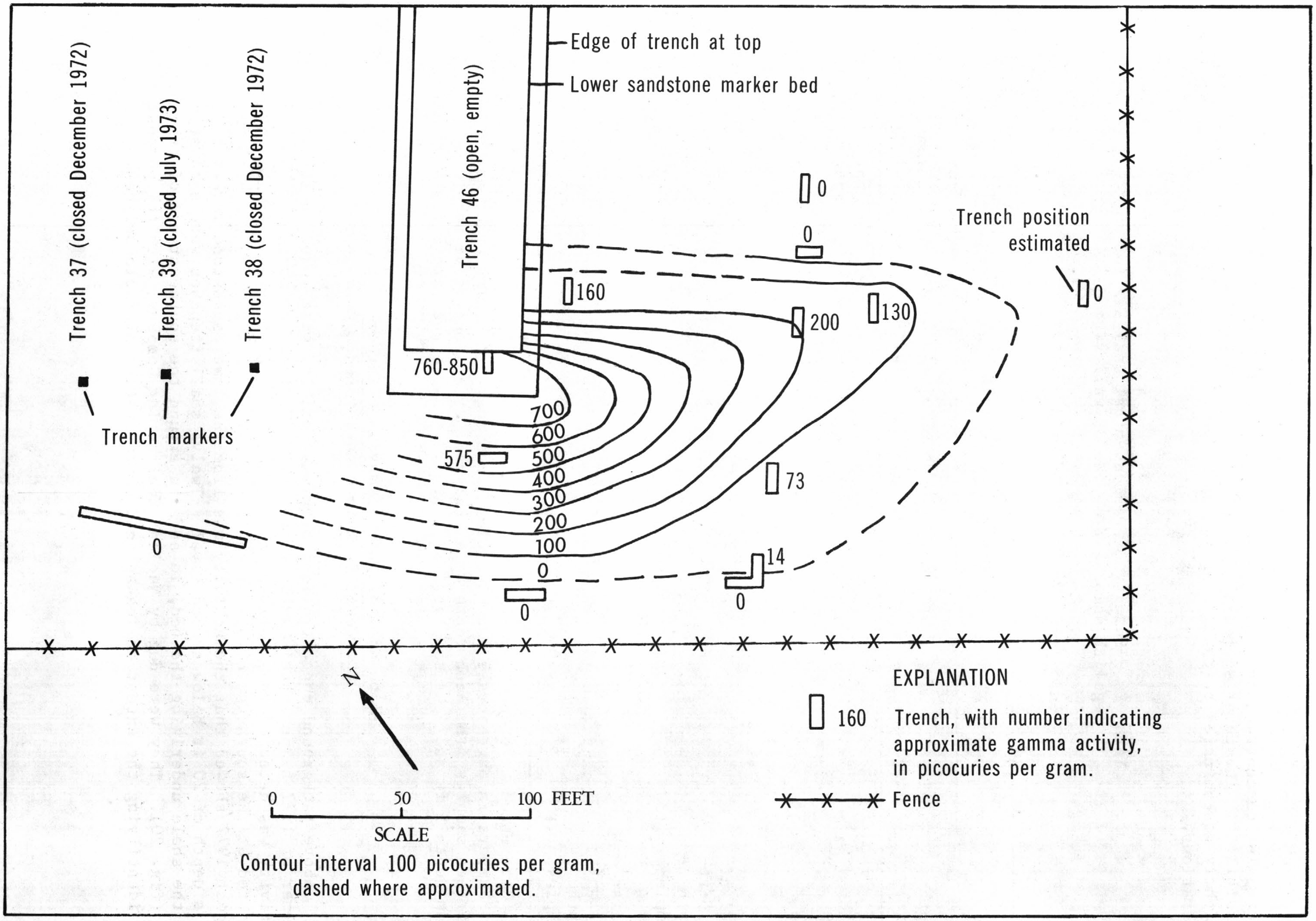


Figure 20.-- Subsurface gamma activity near trench 46. All values refer to above-background activity. Data and modified base map reproduced by permission of Nuclear Engineering Co. (written commun., April 1980).

Only cobalt-60 and manganese-54 were identified. Concentrations were measured in soil samples by use of a multi-channel system containing a sodium-iodide detector. Measurements were semi-quantitative because samples were not standardized (Nuclear Engineering Company, written commun., April 1980). Although not accurate, the concentrations were useful for area-to-area comparisons, and for defining the boundaries of the radionuclide leakage. Activity was found only in fractures in the lower sandstone marker bed, and on narrow lines on the top of the underlying shale where the fractures terminated. The activity was in clay from the overlying weathered shale, which largely filled the sandstone fractures. No activity was found in the regolith directly above the sandstone bed. The waste radionuclides had evidently sorbed onto the clay as trench water flowed laterally through fractures in the sandstone bed.

The area of gamma activity was in the form of an ellipse, or plume, with activity decreasing toward the south and east (fig. 20). The fenceline shown at the bottom of the diagram has remained as shown, but that on the right side has been extended 90 ft to the east since the diagram was made (see plate 1). Maximum extent of the plume is assumed to be the zero contour on the diagram, near the estimated trench position at the fenceline. The source of the radionuclides may have been nearby trenches 37, 38, and 39, or possibly older, more distant trenches to the northwest, such as 25 or 26 (see plate 1).

Trench 25 was closed 9.3 years, and trench 38 closed 4.8 years (closure dates given in table 9), prior to mapping the extent of the leakage. Distances of the boundaries of these trenches from the maximum extent of the plume were 440 ft for trench 25 and 270 ft for trench 38. Assuming migration of radionuclides began at the time of trench closure, maximum effective velocities were therefore: 47 ft/yr, assuming trench 25 was the source; or 56 ft/yr, assuming trench 38 was the source. It appears that the effective velocity of radionuclide movement is, therefore, about 50 ft/yr.

The effective velocity of 50 ft/yr is a mean for radionuclide movement along the axis of the plume. The actual velocity of an ion moving through a set of fractures is greater because the path traced by an ion is more tortuous than is the axis of the plume. Of equal importance, the 50 ft/yr effective velocity applies to the mobility of cobalt-60 and manganese-54, not necessarily to ground water (or to other radionuclides).

The velocity of a radionuclide front is usually less than that of water because of sorption during flow. Tritium would be the most suitable radionuclide tracer, but the large concentrations released from the waste-water evaporator cause tritium data from Maxey Flats to be of little value for this purpose. The 50 ft/yr effective velocity of the cobalt-60 and manganese-54 is therefore used as a minimum velocity of ground water in the lower sandstone marker bed. It is the only ground-water velocity estimated from field data.

HYDROLOGY OF THE LOWER PART OF THE REGOLITH AND BEDROCK

Geologic Sections and Positions of Fractures in Wells

Figure 21 is a geologic section from ground level to the upper part of the Crab Orchard Formation. Cemented sections, ranges of water-level fluctuations, and positions of fractures in wells are shown. Head decreases with depth, indicating a downward component of flow, but perched water tables may be present in any of the strata.

Unusual features are dry wells in some strata which are probably saturated. For example, water levels in UA3 and 14E indicate at least some rocks in the lower part of the Nancy and upper part of the Farmers Members are saturated. Well UB1 is open to the same strata, but is dry. A similar situation is shown for the Henley Bed of the Farmers Member, Sunbury Shale, and Bedford Shale at wells UA2 and UB4. The absence of water in some wells may be due to lack of intersection with a fracture, or completion in strata which are saturated in some areas but not in others.

Borehole televiewer logs were made in several wells to determine positions of fractures. The recorded signal must be transmitted through fluid other than gas, so only water-filled parts of wells can be logged. Wells UA1 and UA2 were filled with water before logging. Others were logged below the natural water levels and may contain undetected fractures at higher levels.

No fractures were observed in wells UA1 and UA2, but fractures too small for resolution by the logging equipment could be present. Wells and intervals of altitude in which fractures were detected are: 14E - 993 to 995 ft and 986 to 988 ft, UA3 - 995 to 996 ft, UA4 - 726 to 727 ft, and UB2 - 750 to 755 ft.

A series of geologic sections which give more detail than figure 21 of the strata above the Sunbury Shale in the trench area are shown on plate 3. The bottoms of many wells are in the Sunbury Shale, including wells 4E and 9E. Well 5E is open only to the Ohio Shale. Obvious features of water levels are: those in wells 1 through 8 are at high altitudes and show large fluctuations; they decrease with depth; and some in wells finished in the same strata have very different levels, such as 13E and 14E.

The high levels in wells 1 through 8 result from a water table in the regolith, and the large ranges are due to infiltration of surface water into the wells. Differences in water levels in other wells are related to whether or not a fracture is exposed in the well, number of fractures intersected, vertical gradients, and presence of unsaturated zones at depth. Specific problems regarding interpretation of water levels are discussed in the following section.

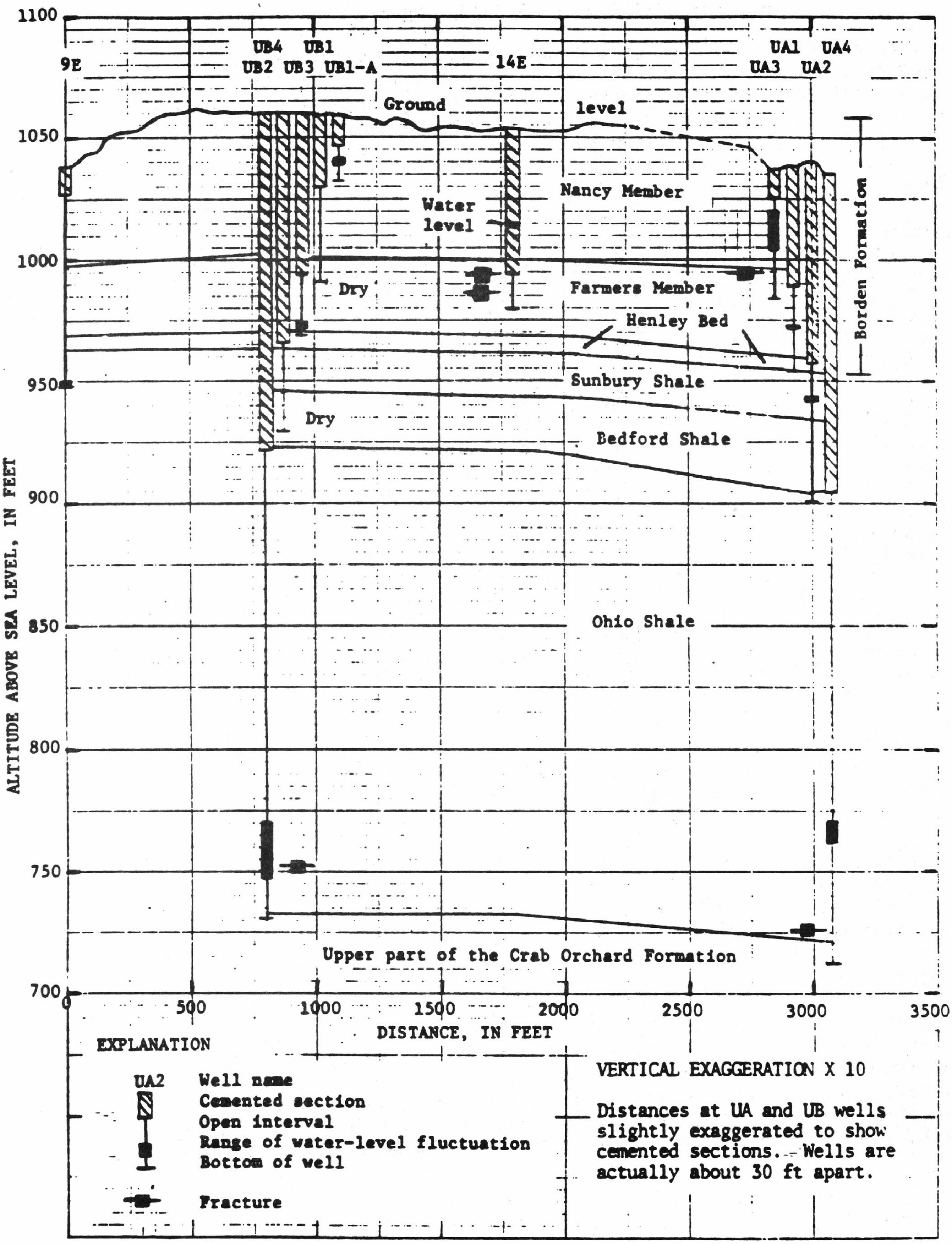


Figure 21.-- Geologic section of the Maxey Flats site, showing water levels in wells 9E and 14E, UA wells, and UB wells.

Problems Related to Interpretation of Water-level Data

Accurate description of the ground-water system at Maxey Flats by use of water-level data collected during this study is difficult, primarily because virtually all ground-water flow occurs in fractures. Extremely small flow may occur in the interstitial pore space comprising the unfractured bulk of the rock, but this flow is not readily measured in wells. The necessity for completing wells open to depth intervals of many feet also precludes accurate description of the system.

The water table is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water (Lohman and others, 1972). When interstitial hydraulic conductivity is small, as is the case in the unfractured part of the rocks at Maxey Flats, accurate location of the water table is difficult. Months to years are sometimes required for a measureable volume of water to enter a well completed in the unfractured part of the rocks.

A process of consecutive drilling through short intervals and waiting for water-level recovery would have to be done many times to accurately locate the water table. Because such drilling is not economically practical, wells are completed below the water table, and some are open to more than one hydrologic unit. The water levels therefore represent a composite of all heads to which the wells are open. They are below the water table at Maxey Flats because heads decrease with depth.

Wells at Maxey Flats that are open to fractures accumulate water that reaches static level in much less time than those open to unfractured rock. The more rapid recovery does not necessarily result in accurate location of the water table, however. A well and fracture are usually not perfectly vertical, so they intersect for only a short (a few feet) distance. The chance of the two intersecting exactly at the water table are very small. Wells open to rocks in which flow is predominantly downward and lateral, such as those at Maxey Flats, therefore encounter heads in the saturated part of the fracture which are: less than at the water table; and composited in the open interval. The resulting water level is below the water table.

The water level represents the composite of the heads in all fractures encountered, if more than one fracture is open to the well. Water levels would have to be obtained from several wells, open only to narrow intervals in single continuous (both horizontally and vertically) fractures, to accurately describe the flow in a widely spaced fracture system - a difficult task, and nearly impossible to verify.

Hydraulic gradients are not known because heads are composited in the wells. This results in uncertainty about the positions of perched water tables at depth, and directions of ground-water flow. Gradients, positions of water tables, and directions of flow can therefore only be estimated. Idiosyncrosies of water levels in several wells, and their possible causes, are explained before the data are used to describe the ground-water system.

Water Levels

Continuous water-level data were collected from UA and UB wells, and from some E wells. Other data were collected about twice-monthly. Hydrographs of wells open to less than four hydrologic units are described in this section. Those for wells open to all rocks from the regolith to the upper part of the Sunbury Shale are shown in appendices 10 and 11.

Long periods (years) of concurrent water-level record from many wells, preferably without drawdown from sampling, would be required before rigorous interpretation of the data could be made. Samples of approximately 1 to 2 gal were collected about twice-monthly from many wells. The levels in most of these wells did not completely recover until sampling was temporarily discontinued. Stable levels may not have been measured in wells 6E and 13E, even during the period of discontinued sampling.

All well hydrographs are plotted as follows. Noon-daily readings from continuous data are shown as a continuous curve, except where dashes are used to show approximate levels when data loss occurred. Periodic data from taped measurements are plotted as "+" symbols. These are connected with a smooth curve when measurements are less than six weeks apart. Approximate levels during longer periods between measurements, or during recovery from sampling, are shown as dashed lines. All depths are referenced to the tops of casings and altitudes are referenced to the NGVD of 1929.

Wells Open to the Nancy Member and Upper Part of the Farmers Member of the Borden Formation

Hydrographs of wells completed in the unweathered part of the Nancy Member and the shale-sandstone sequence at the base of the Nancy and top of the Farmers Members are shown in figure 22. The rise in water level in well UA3 during 1977 and 1978 is due to above-normal rainfall (see fig. 5). The nearly constant water level in well 14E may be due to hydraulic connection with a more permeable fracture system than at well UA3, which results in rapid discharge of infiltrating water. Well UB1 was dry after completion. After 5 gal of water were added to the well, the water level declined continuously until the well was again dry. Evidently, the Nancy and upper part of the Farmers Members are locally unsaturated at this well.

Wells 6E and 11E are open to about the same rocks as those shown in figure 22, but are also open to the lower sandstone marker bed. The water level in well 11E rises many feet during the winter (fig. 23), then declines during the spring and summer. Well 6E showed only two large increases in water level. One of these was in autumn, when no corresponding rise occurred in 11E.

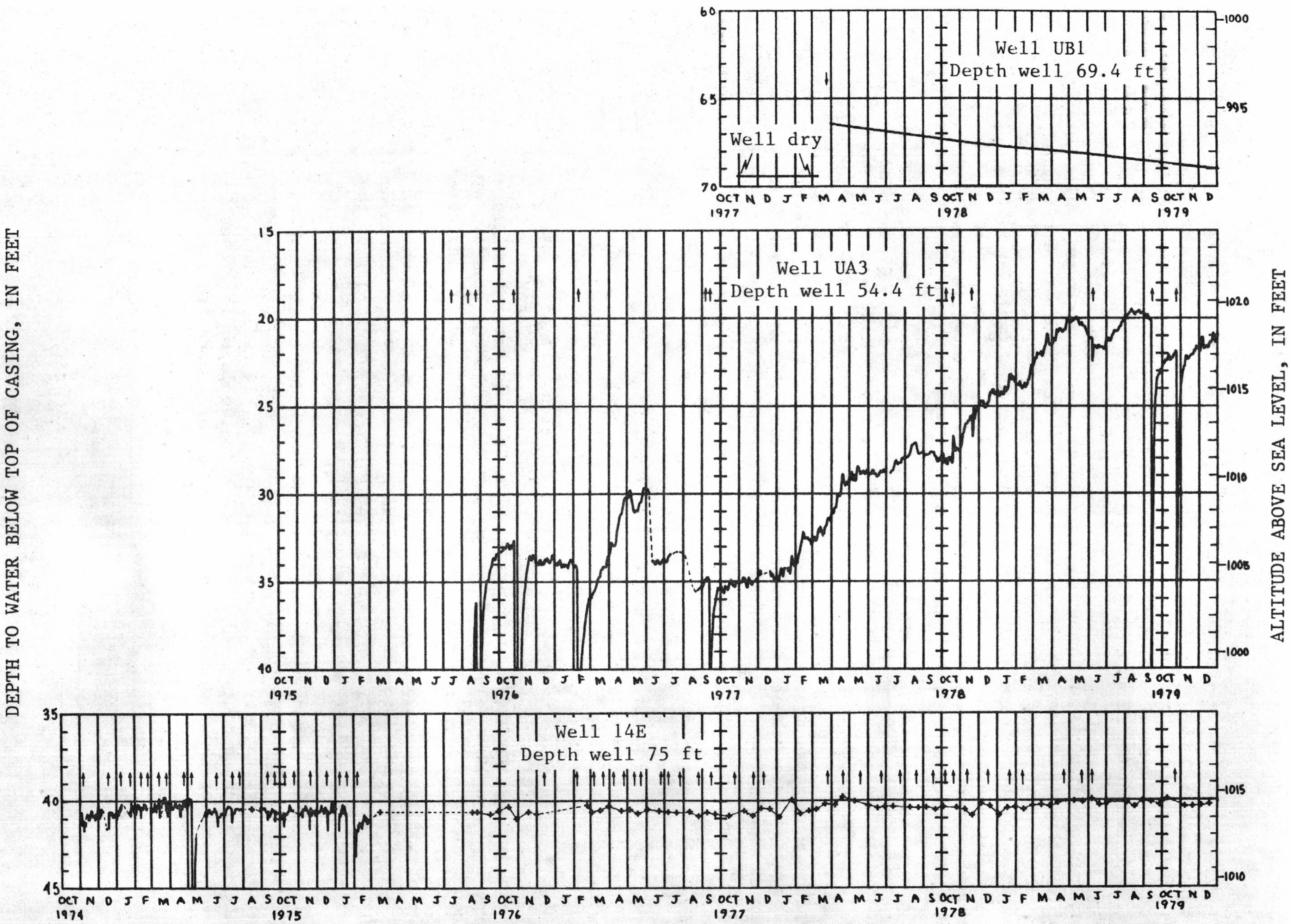


Figure 22.-- Hydrographs of wells open to the unweathered part of the Nancy Member and upper part of the Farmers Member of the Borden Formation. Depth referenced to top of casing. Upward-pointing arrows denote discharges and downward-pointing arrows denote charges. Line represents continuous water-level data, dashed where approximated. Cross represents single measurement.

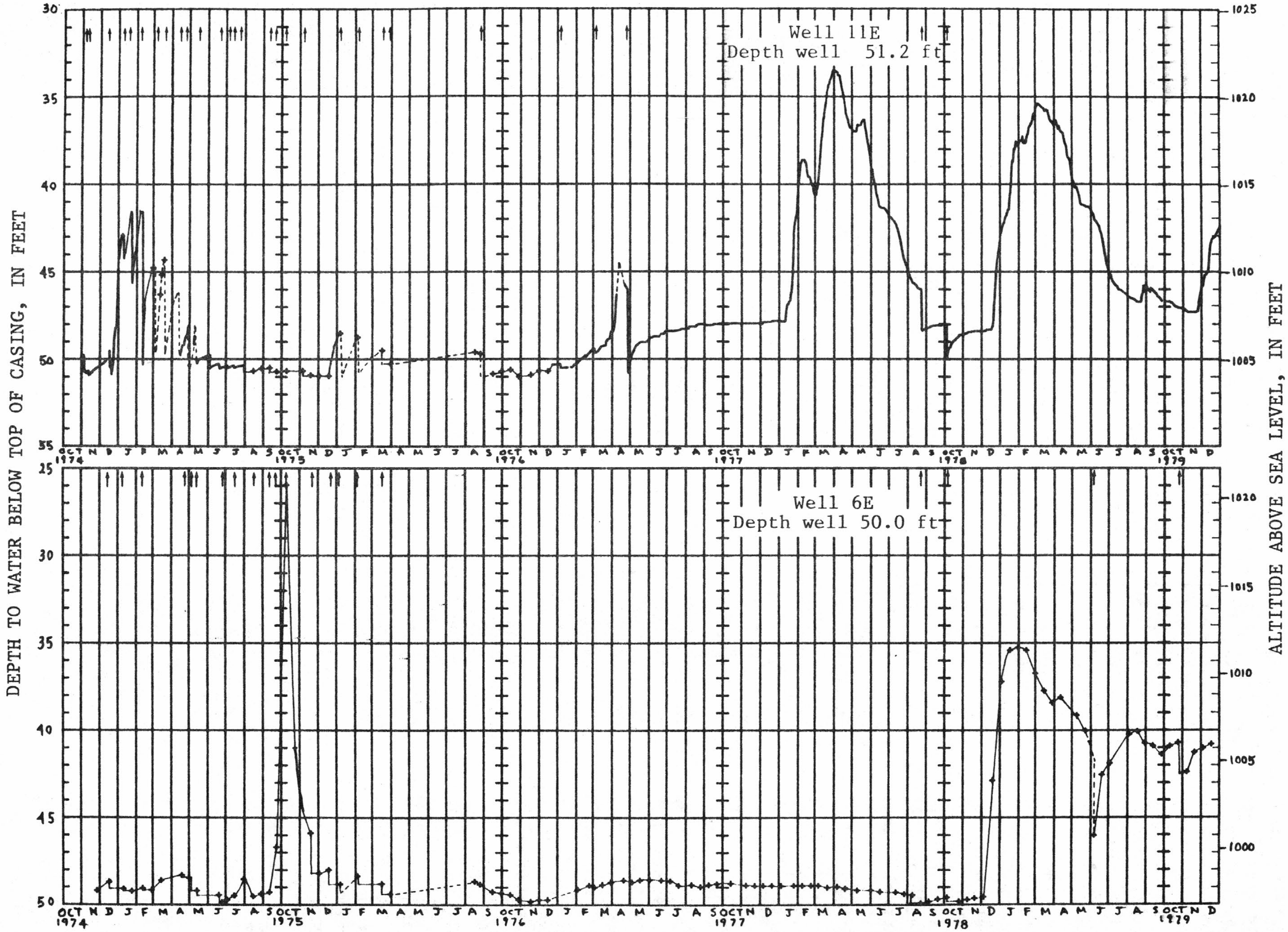


Figure 23.--- Hydrographs of wells open to the lower sandstone marker bed of the Nancy Member to the upper part of the Farmers Member of the Borden Formation. Depth referenced to top of casing. Arrows denote discharges. Line represents continuous water-level data, dashed where approximated. Cross represents single measurement.

The water levels in 6E and 11E would probably remain near the bottoms of the wells, if they were tightly cemented from ground level to rocks below the lower sandstone marker bed. The mean specific conductance of water from well 11E increases during periods of high water level from about 3,000 to about 4,000 umhos/cm, which indicates that the large rises in water level are not caused by seepage of surface water into the well. Evidently, ground water enters the upper part of the well from the lower sandstone marker bed during wet winter months of low evapotranspiration, and flows out of the lower part of the well into the deeper rocks.

The mean specific conductance of water from well 6E rapidly decreases during periods of high water level, from a mean of about 1800 to about 300 umhos/cm. Water from ground surface evidently leaks past the cemented section during months of unusually large rainfall, and temporarily accumulates at the bottom of the well. Rainfall in September and October 1975 was about 3 in. above normal for each month, and was about 6 in. above normal in December 1978 (see table 1). These periods correspond with large rises in water levels in well 6E.

Wells Open to the Lower Part of the Farmers Member of the Borden Formation

Hydrographs of wells open only to the lower part of the Farmers Member are shown in figure 24. Because no fractures were observed on borehole televiewer logs of well UA1, the slow rate of recovery (0.02 ft/d) during 1976 may have been due to flow from unfractured rock, or from fractures too small for resolution by the logging equipment. An attempt was made to connect the well with interconnected fractures in May 1977, when explosive charges were used to perforate the entire open-hole interval. Rate of water accumulation remained the same after perforation, indicating lack of fracture connection. Water was therefore added and withdrawn until a stable level was obtained.

Well UB3 remained dry for five months after drilling. Water was added to see if an induced head would decline, indicating unsaturated rocks. Rather than declining, the water level rose at a very slow rate (0.006 ft/d). Evidently the small volume of water that entered the well after drilling could not be measured because: the borehole wall had been dried during air drilling, and water that entered the well later may have been sorbed onto the dry borehole wall; or the water may have been of insufficient volume to saturate a small amount of cuttings that may have been at the bottom of the well. No stable head data are available for well UB3. Complete recovery from sampling may not have occurred in well 13E, but nearly stable head data were obtained when sampling was temporarily discontinued in 1977.

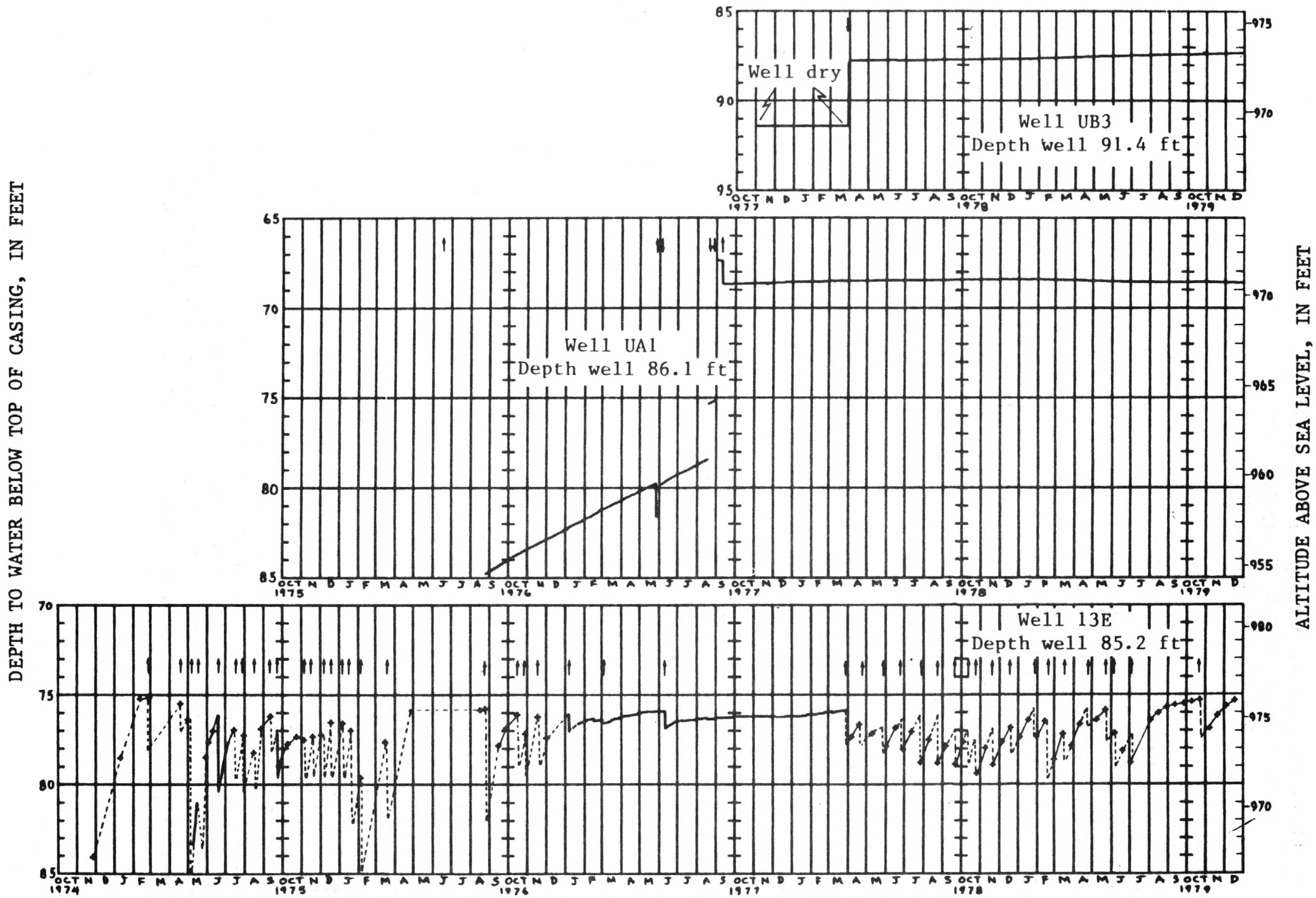


Figure 24.-- Hydrographs of wells open to the lower part of the Farmers Member of the Borden Formation. Depth referenced to top of casing. Upward-pointing arrows denote discharges and downward-pointing arrows denote charges. Line represents continuous water-level data, dashed where approximated. Cross represents single measurement.

Wells Open to the Henley Bed of the Farmers Member of the Borden Formation, Sunbury Shale, and Bedford Shale

Water-level data from well UA2 (fig. 25) best illustrate the difference in recovery rates between wells completed in the unfractured part of the rocks, as compared to those open to fractures. A few inches of drilling fluid remained in the hole for seven months after completion of drilling. Little or no water entered the well during this time. Water was poured into the well three times to see if higher heads would decline, but they remained stable. The entire open-hole interval was perforated with explosive charges in May 1977. The shot-holes evidently connected with one or more fractures because the water-level recovered in 14 months.

The upper part of the hydrograph of well UA2, and hydrographs of two other wells completed in shales underlying the Farmers Member, are shown in figure 26. Well 3E is open only to the upper 4 ft of the Bedford Shale. Well UB4 was drilled 3 ft into the top of the Ohio Shale, and was dry after completion. Water was poured into well UB4, and it flowed into the rocks until the hole was again dry. The well had evidently exposed an unsaturated fracture at the top of the Ohio Shale. The bottom 7.3 ft was cemented, and water was added again. The water level did not decline, nor did it recover after a withdrawal. It is assumed that well UB4 would have accumulated water if it had intercepted a fracture because: UA2 showed similar, initial lack of water-level response before connection with a saturated fracture in the Sunbury Shale; and the water level in 3E recovers after sampling, which indicates a saturated zone in the Sunbury Shale. Because fractures in these shales are saturated, it is assumed that the unfractured part of the rocks are also saturated.

The initial absence of water in wells UA2 and UB4 illustrates two important points. One is that almost no flow occurs in the unfractured part of the saturated rocks, at least in the three shales open to these wells. The second is that the cement used in these wells has produced a very tight seal from water in overlying rocks (water from the lower sandstone marker bed entered both wells before cementing), so other UA and UB wells are probably also tightly sealed.

Wells Open to the Ohio Shale

Hydrographs of wells completed in the Ohio Shale are shown in figure 27. Water-level fluctuations over periods of several months correspond to departures from normal rainfall, combined with seasonal changes. Rises and declines of several feet sometimes occur in well UB2 over short periods (hours to days). Examples of rapid increases are those in March, May, and December 1978. These rises correspond to periods of large rainfall (see daily rainfall in fig. 5), but occur much more rapidly, and with greater magnitude, than in other wells. Examples of rapid declines are those in September and October 1978, and April 1979.

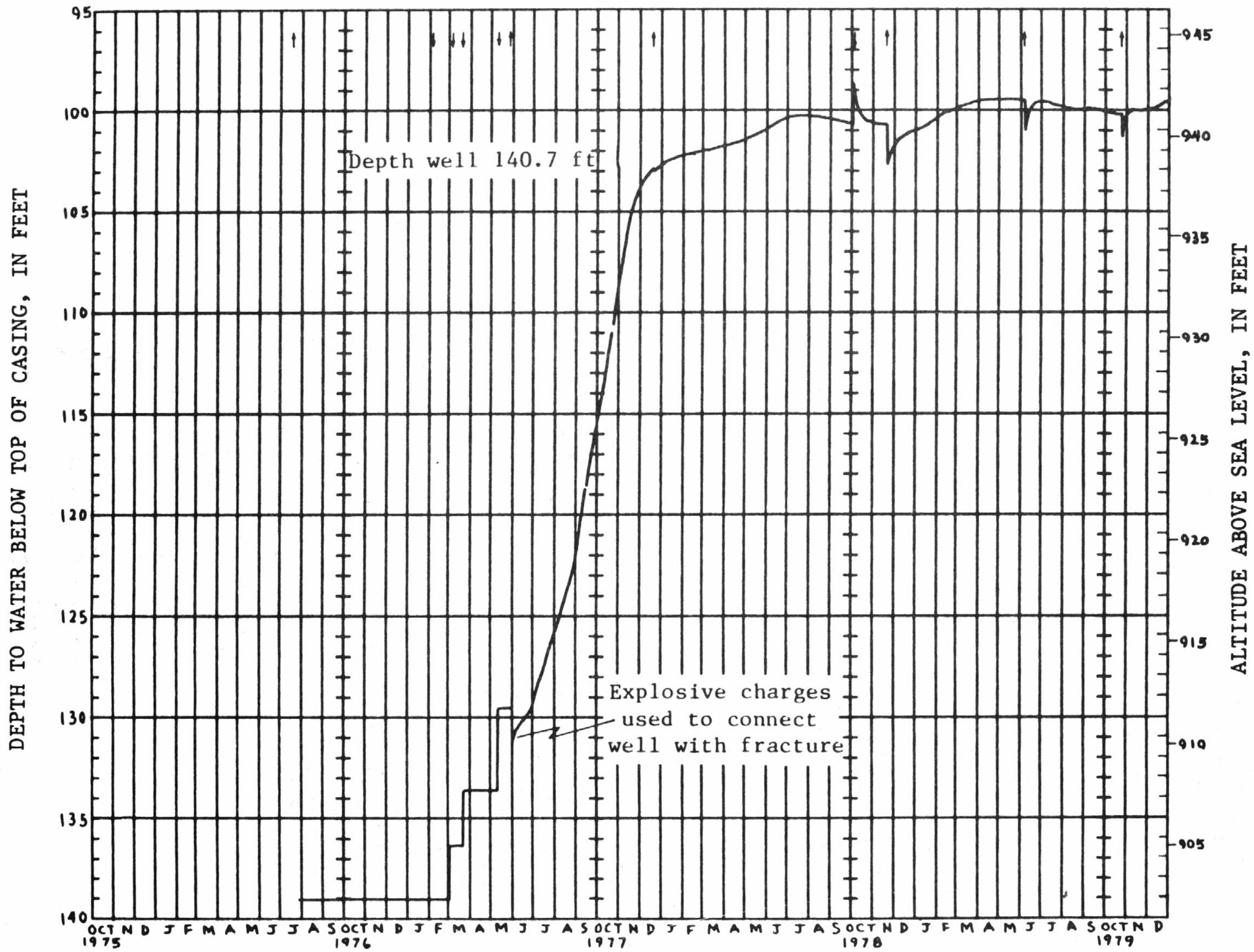


Figure 25.-- Hydrograph of well UA2. Depth referenced to top of casing. Upward-pointing arrows denote discharges and downward-pointing arrows denote charges. Well is open to the Henley Bed of the Farmers Member of the Borden Formation, Sunbury Shale, and Bedford Shale.

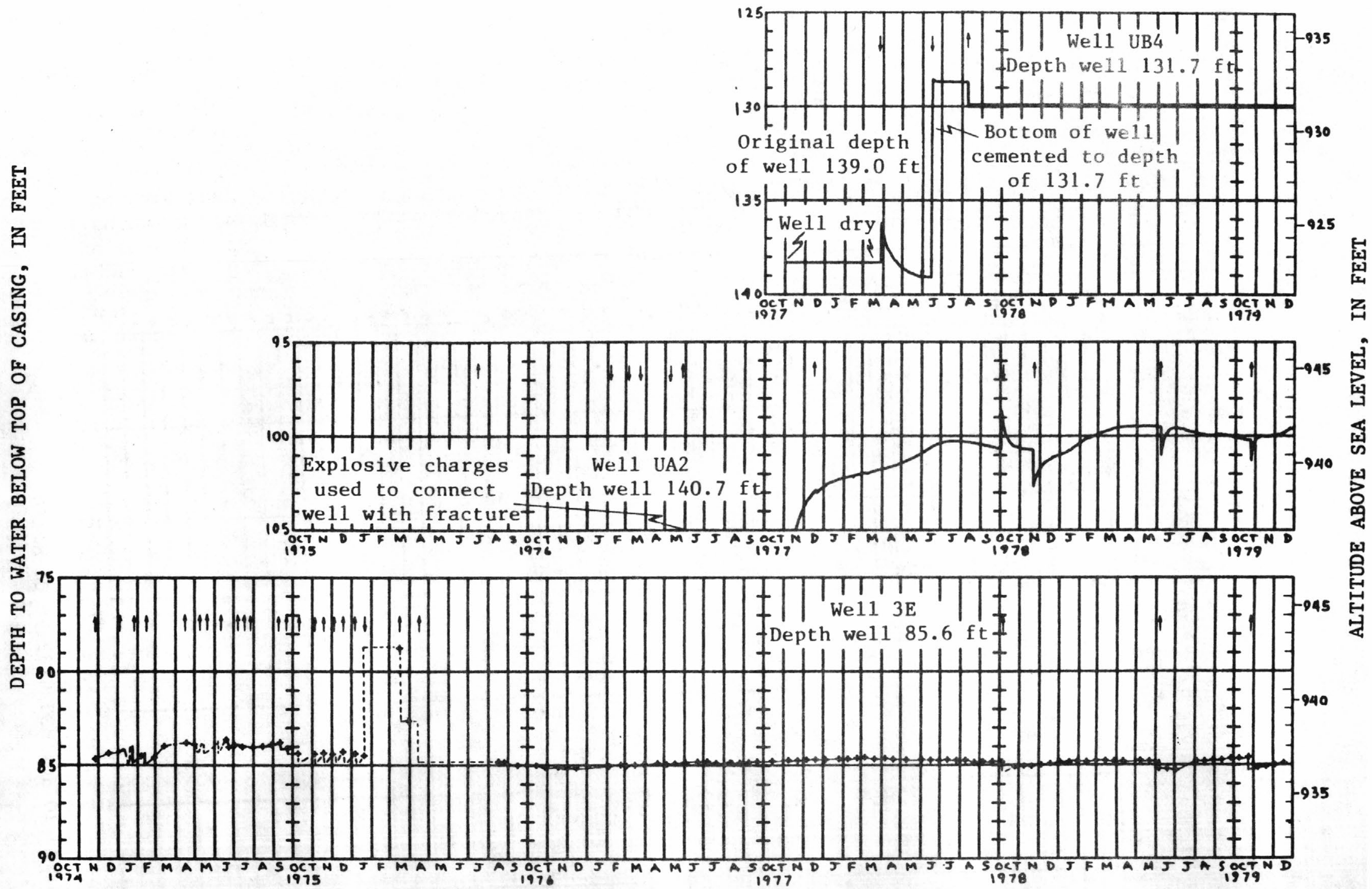


Figure 26.-- Hydrographs of wells open to the Henley Bed of the Farmers Member of the Borden Formation, Sunbury Shale, and Bedford Shale. Well 3E is open only to the upper 4 ft of the Bedford Shale. Depth referenced to top of casing. Upward-pointing arrows denote discharges and downward-pointing arrows denote charges. Line denotes continuous water-level data, dashed where approximated. Cross denotes single measurement.

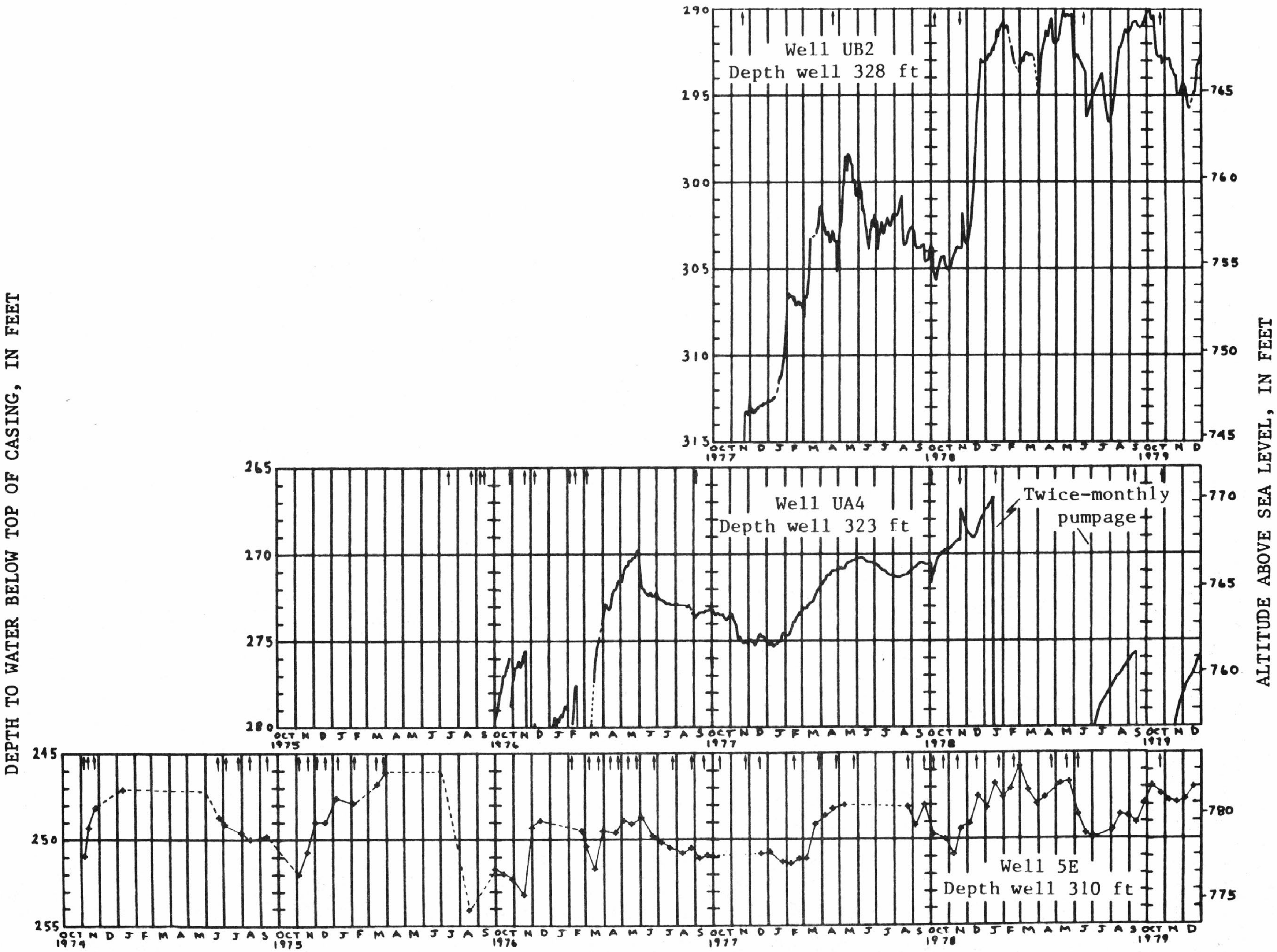


Figure 27.-- Hydrographs of wells open to the Ohio Shale. Depth referenced to top of casing. Upward-pointing arrows denote discharges and downward-pointing arrows denote charges. Line denotes continuous water-level data, dashed where approximated. Cross denotes single measurement.

The water-level declines are usually more rapid than the rises, dropping as much as 2 ft in 36 hours. Changes of this magnitude (other than recovery from sampling) occur over periods of weeks to months in other wells at Maxey Flats. Reasons for the rapid declines are not known. They do not correspond to changes in barometric pressure, phases of the moon (earth tides), nor to a specific depth in the well.

Positions of Water Tables and Saturated Zones in Bedrock

The uppermost water table is located at the base of the regolith in the trench area, as discussed in a previous section. Decreasing heads with depth in bedrock wells may indicate perched water tables, or may result from vertical gradients in saturated rocks. The rock units adjacent to water levels in wells, wells in which the water levels were obtained, and maximum and minimum water-level altitudes during October 1978 (October 1977 in well 13E) are: lower part of the Nancy Member - UA3, 6E, 11E and 14E - 997 to 1,014 ft; lower part of the Farmers Member - UA1 and 13E - 971 to 975 ft; Sunbury Shale - UA2 and 3E - 937 to 941 ft; and Ohio Shale - UA4, UB2 and 5E - 755 to 779 ft. All of the water levels cited probably reflect composite heads, as explained previously. That is, the water level measured is probably lower than the actual level of the water table.

Vertical gradient is obtained for a saturated medium by computing the ratio of difference in heads to vertical distance between points of head measurement. This is not appropriate for Maxey Flats well data because all rocks between points of measurement may not be saturated and heads are composited. It is referred to here simply as the head to depth ratio.

Table 17 shows head to depth ratios for UA wells and wells in the trench area. Water levels were obtained in October 1978, except that in well 13E was obtained in October 1977. Composite heads were measured in the entire open sections of the wells, so the depth of the point used in computing the head to depth ratio is not necessarily the precise depth at which the measured head would be produced if the well were open only to a narrow interval. The bottoms of the wells were used as points of head measurement in 3E (depth 85.6 ft) and 13E (depth 85.2 ft) because depths to water-yielding zones are unknown in these wells. Measuring points in other wells correspond to likely positions of water-yielding zones, as follow: the bottom of the lower sandstone marker bed in UB1-A; the center of the lower fracture (although both fractures may be water-yielding) in 14E; and the center of the single fracture in UB2. Altitudes of the latter three points are shown on figure 21.

TABLE 17.--Head to depth ratios for wells at Maxey Flats

Rocks open to wells[1]	Ratio for trench-area wells	Ratio for UA wells[2]	Trench-area wells compared	UA wells compared
LSM - LN	0.55	-	UB1-A, 14E	-
LSM - LF	0.97	-	UB1-A, 13E	-
LSM - HSB	1.1	-	UB1-A, 3E	-
LSM - O	1.0	-	UB1-A, UB2	-
LN - LF	2.0	0.93	14E, 13E	UA3, UA1
LN - HSB	1.5	.74	14E, 3E	UA3, UA2
LN - O	1.1	.91	14E, UB2	UA3, UA4
LF - HSB	1.2	.58	13E, 3E	UA1, UA2
LF - O	1.0	.90	13E, UB2	UA1, UA4
HSB - O	1.0	1.0	3E, UB2	UA2, UA4

[1]Inclusive, except only upper 3 ft of Bedford Shale open to well 3E. LSM - lower sandstone marker bed of Nancy Member; LN - lower part of Nancy Member; LF - lower part of the Farmers Member; HSB - Henley Bed of Farmers Member, Sunbury Shale, and Bedford Shale; and O - Ohio Shale.

[2]UA wells not open to lower sandstone marker bed.

Ideally, vertical head distribution should be measured at one location, such as at the cluster of UA wells. The larger head to depth ratios for trench-area wells may be due to error introduced by measuring heads at different locations because some horizontal components are included. Most important, however, is that only seven of the sixteen ratios in table 17 have values less than 1.0.

Hydraulic gradients in the vertical direction may exceed 1.0 in a ground-water system that contains more than one stratum because the heads in a more-permeable upper stratum may be sufficient to cause flow through a less-permeable lower stratum in which vertical gradients are greater than 1.0. Head to depth ratios greater than 1.0 may indicate saturated-unsaturated conditions, however; that is, the presence of an unsaturated interval between two saturated intervals. Although positions of saturated and unsaturated zones cannot be accurately determined from the well data, it is assumed that intervals in which head to depth ratios exceed 1.0 may contain unsaturated intervals.

Ratios with values less than 1.0 do not necessarily indicate completely saturated rocks. The value of 0.55 for the unweathered part of the Nancy Member indicates saturated conditions in the rocks at some locations, but loss of water that was poured into well UB1 indicates they are unsaturated at the UB wells. The value of 0.58 for the interval from the lower part of the Farmers Member to the base of the Bedford Shale could indicate a completely saturated interval, but the Sunbury Shale has a greater fracture intensity (0.35/ft) than the overlying lower part of the Farmers Member (0.18/ft) or the underlying Bedford Shale (0.06/ft). Water may therefore discharge from the Sunbury Shale at a more rapid rate than is required to keep it completely saturated, resulting in dewatering of the upper part of the formation.

The upper part of the Ohio Shale probably contains unsaturated intervals, because: the head to depth ratio = 1.0 at both UA and trench-area well sites; the upper part of the Crab Orchard Formation is probably the lower hydrologic boundary of the flow system, so flow would presumably be nearly horizontal and gradients in the vertical direction would presumably be small; and water poured into the top of the Ohio Shale at UB4 drained from the well. The upper part of the formation probably contains one or more perched water tables because ground water entered wells UA4 and UB2 during drilling, when they were open only to the upper 110 ft of Ohio Shale.

In summary, the ground-water system at Maxey Flats probably consists of sequences of saturated and unsaturated zones, with more than one seqence in some hydrologic units. The thicknesses of unsaturated zones may change with time, and from place to place. The unsaturated zones are probably less than a few tens of feet thick in most rocks, and possibly only a few feet thick in some.

The lower sandstone marker bed is saturated. The unweathered part of the Nancy Member may be saturated in some areas, but not in others. Most rocks between the lower part of the Farmers Member and Ohio Shale are probably saturated, with the possible exception of the upper part of the Sunbury Shale. Other saturated zones, which possibly contain unsaturated intervals, are the lower part of the Nancy and upper part of the Farmers Members, and the Ohio Shale. Altitudes of approximate water-table postitions are given at the beginning of this section. Data are insufficient to construct accurate potentiometric surface maps of this complex system.

Responses of Water Levels in Wells to Changes in Rainfall

The hydrograph of well UA3 (open to the Nancy Member) is similar in shape to those of wells UA4, UB2, and 5E (all open to the Ohio Shale), even though it is completed at much shallower depth. Water-level changes in the wells have different magnitudes, but they are usually in the same direction and occur at about the same time. The changes are related to varying rates of precipitation and infiltration, but rises and declines in the lower formations may be due to head changes in the colluvium on the hillsides.

Hydrographs of wells UA3 and UA4 are shown with a plot of accumulated departure from normal monthly rainfall in figure 28. Normal monthly rainfall at Farmers, Kentucky (see table 1) was used because only 6 years of precipitation data were available at Maxey Flats. Differences between monthly normals at Farmers and monthly values at Maxey Flats were accumulated to produce the plot.

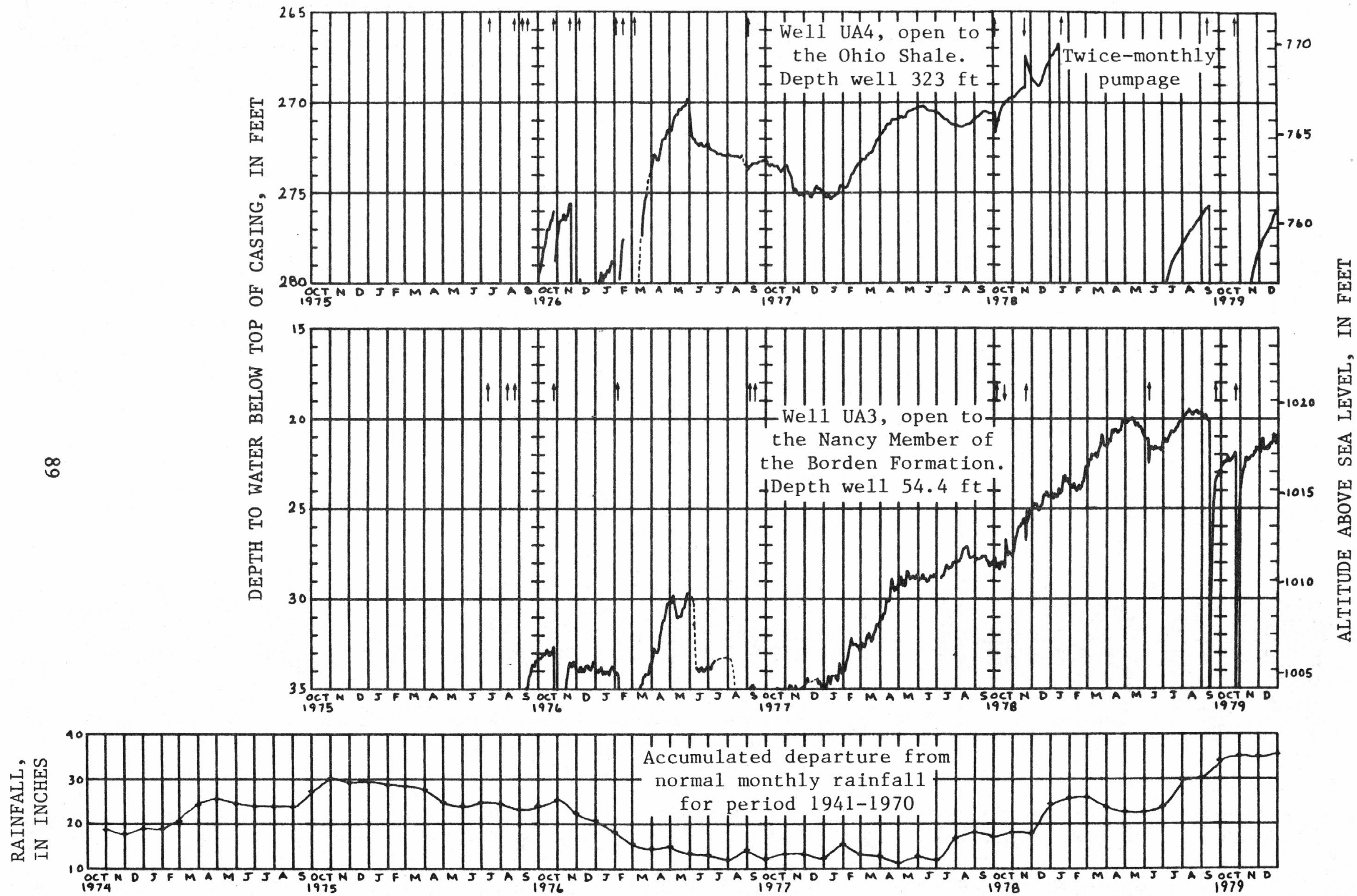


Figure 28.-- Accumulated departure from normal monthly rainfall at Maxey Flats with hydrographs of wells UA3 and UA4. Depth referenced to top of casing. Upward-pointing arrows denote discharges and downward-pointing arrows denote charges. Lines on hydrographs denote continuous water-level data, dashed where approximated.

Various time shifts were applied to the accumulated departure plot, relative to the well hydrographs, in an attempt to determine the time lag between changes in rainfall and corresponding changes in water level. None of the shifts matched the hydrographs as well as not applying any shift. For example, if above-normal rainfall in July 1978 is assumed to correspond to the water-level rises in October 1978, there are no increases in rainfall to account for water-level rises from February through August 1978.

Some water-level rises obviously occured when there were no corresponding periods of above-normal rainfall, even when the accumulated-departure plot and hydrographs were matched with no time lag (fig. 28). The rises occurred during months of low evapotranspiration, beginning between November and March. The water levels declined during months of high evapotranspiration (June through November) in 1976 and 1977, but the declines during 1978 may have been prevented because rainfall was above normal in July and August. A similar situation occurred in well UA3 due to above-normal rainfall from June through October of 1979. Frequent pumping prevented complete recovery in well UA4 during 1979.

Many months are probably required for infiltration of rainwater on the hilltop to change heads at depth because unsaturated intervals are present in the rocks. Head changes apparently occur almost simultaneously in the Nancy Member and Ohio Shale, however. Those in the Ohio Shale may be caused by head changes in the colluvium, and possibly the shallow weathered rock underlying the colluvium, on the hillsides. The saturation of the colluvium could cause a "damming" effect, keeping back flow which might ordinarily discharge from the shale, thereby increasing storage and head in the shale. If this were the case, the magnitudes of the water-level rises would be related to the amount and duration of head increases in the colluvium, storage coefficient of the rock, and later infiltration of rainfall from the hilltop through the underlying saturated-unsaturated sequences of rock.

Head change in colluvium is one explanation of why there is apparently little or no time lag between recharge events and changes in water levels at depth. Another reason may be that both precipitation and water-level data have not been collected long enough at Maxey Flats to determine the time relationship between the two.

Core Analyses

Mineralogic analyses of cores from well UA4 (table 18) are semi-quantitative, and percentage totals between 90 and 105 are common. The low percentages (72 and 64 percent) in table 18 are probably also due to the semi-quantitative method of analysis. The analyses were performed on bulk samples from cores, and do not necessarily represent mineralogic composition of materials along surfaces of water-bearing fractures.

The amphibole is probably hornblende, and the mixed-layer clay mineral is probably illite-montmorillonite (U.S. Geological Survey hydrologic laboratory, written commun., August 1978). Most shales at Maxey Flats are primarily composed of quartz and illite, with less amounts of mixed-layer clay minerals. The single sample of sandstone (from the Farmers Member) is mostly feldspar and quartz. Pyrite occurs in the shales as both nodules and disseminated specks, which may account for the percentage differences in samples from the Ohio Shale.

The sample from depth 143.0 ft (table 18) had similar physical appearance to other black shale samples from the Ohio Shale, yet had very different percentages of plagioclase feldspar and illite. Samples from other shale beds in the Ohio Shale (depth 308.2 ft) and upper part of the Crab Orchard Formation (depth 320.5 ft) were greenish-gray and softer than black shale samples, but had similar mineralogic composition to black shales. Evidently, physical appearances do not necessarily mean mineralogic differences in rocks from the two formations.

Grain size, total porosity, and hydraulic conductivity (K) were determined on cores from wells UB1 and UB2. The analyses were performed by a commercial laboratory. Total and effective interstitial porosity of core samples from well UA4 were determined by a U.S. Geological Survey laboratory. Values obtained from all analyses are estimates because the coring process usually alters the rock, and field conditions cannot be duplicated accurately in the laboratory. Samples were competent, so disturbance would probably tend to increase the actual in-place properties.

Samples were tested for hydraulic conductivity by use of laboratory water with similar ionic concentrations as formation water. Testing was done with a permeameter under a confining pressure of 200 $lb/in.^2$, and 100-$lb/in.^2$ pore fluid pressure. Hydraulic conductivity in the horizontal direction was not determined for most samples obtained from below the Farmers Member because horizontal cracks due to dessication or stress relief developed in the cores. Porosity was determined by mercury injection. Parts of the cores were ground and sieved through a 0.78-in. screen. Particle size was determined on the sieved portion by gravimetric methods.

TABLE 18.--Mineralogic analyses of core samples from Maxey Flats well UA4

[Samples analyzed by x-ray diffraction, and are semi-quantitative. Values except depth are percent of total mineral content. Analyses by U.S. Geological Survey laboratory.]

Rock unit[1]	Depth[2] (ft)	Quartz	Potassium feldspar	Plagioclase feldspar	Pyrite	Amphibole	Dolomite	Chlorite	Kaolinite	Illite	Montmorillonite	Mixed-layer clay minerals	Total
WN	9.5	33	1	3	0	0	0	0	6	46	0	8	97
WN	10.8	56	1	5	0	0	0	0	9	21	0	0	92
UN	21.1	29	0	4	0	0	0	0	9	38	0	13	93
F	64.5	26	8	29	0	5	0	<1	2	2	0	<1	72
H	84.8	24	<1	3	5	0	0	3	8	37	0	22	102
S	87.6	17	0	1	15	0	0	1	6	38	0	20	98
B	113.0	29	<1	3	12	0	0	1	8	45	0	6	104
O	134.6	15	0	1	38	0	0	2	2	19	0	26	103
O	143.0	17	5	33	0	5	0	<1	1	1	1	1	64
O	183.7	23	0	1	8	0	0	3	2	34	0	26	97
O	188.0	22	1	3	0	0	0	2	4	46	0	9	87
O	227.2	28	0	3	15	0	0	<1	4	31	0	25	106
O	269.0	24	<1	2	15	0	0	2	1	29	0	27	100
O[3]	308.2	21	0	3	8	0	0	2	5	36	0	12	87
UCO	320.5	24	0	0	18	0	9	1	9	45	0	5	111

[1]WN - weathered part of Nancy Member of Borden Formation (shale), UN - unweathered part of Nancy Member of Borden Formation (shale), F - Farmers Member of Borden Formation (sandstone), H - Henley Bed of Farmers Member of Borden Formation (shale), S - Sunbury Shale, B - Bedford Shale, O - Ohio Shale, and UCO - upper part of Crab Orchard Formation (shale).

[2]To top of sample, and referenced to ground level.

[3]Greenish-gray shale bed in predominantly black Ohio Shale.

Results of UB1 and UB2 core analyses are given in table 19. The unusually large horizontal K values (relative to those from other samples) for the unweathered part of the Nancy Member and the greenish-gray clayey shale bed in the Ohio Shale may be due to small fractures produced by drilling, core removal, or core analysis. All other values for K are small, and most are less in the vertical direction.

TABLE 19.--Grain size, total porosity, and hydraulic properties of cores from wells UB1 and UB2

[K is hydraulic conductivity. Dash means not tested.]

Well	Rock unit[1]	Depth[2] (ft)	Median grain size (in)	Total porosity (percent)	Vertical K (ft/d)	Horizontal K (ft/d)
UB1	WN	15.3	6×10^{-4}	15	3.2×10^{-6}	2.7×10^{-6}
UB2	UN[3]	21.3	-	-	8.6×10^{-6}	1.5×10^{-5}
UB1	LSM	25.6	1×10^{-2}	11	6.8×10^{-6}	8.1×10^{-6}
UB1	UN	33.0	2×10^{-3}	10	6.5×10^{-6}	1.3×10^{-3}
UB1	F	68.7	2×10^{-2}	11	4.3×10^{-6}	5.1×10^{-6}
UB2	H	90.7	-	-	1.1×10^{-6}	-
UB2	S	110.6	-	-	2.7×10^{-7}	-
UB2	B	114.1	8×10^{-3}	6.5	5.4×10^{-6}	-
UB2	O	146.8	4×10^{-2}	4.0	2.7×10^{-7}	-
UB2	O[4]	184.2	-	-	1.4×10^{-4}	-
UB2	UCO	328.4	-	-	4.1×10^{-6}	1.1×10^{-5}

[1]LSM - lower sandstone marker bed, WN - weathered part of Nancy Member (shale), UN - unweathered part of Nancy Member (shale), F - Farmers Member (sandstone), H - Henley Bed of Farmers Member (shale), S - Sunbury Shale, B - Bedford Shale, O - Ohio Shale, and UCO - upper part of Crab Orchard Formation (shale).

[2]To top of sample, and referenced to ground level.

[3]Unweathered zone in mostly weathered part of Nancy Member.

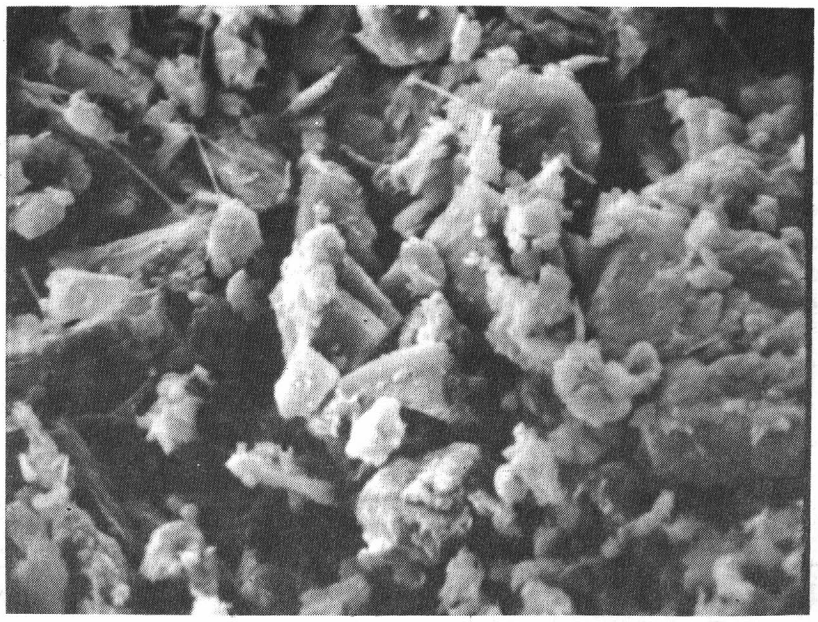
[4]Greenish-gray, clayey shale bed in predominantly black Ohio Shale.

Crushing and sieving cores for grain-size analysis may result in aggregates being measured, rather than individual particles. Most of the median grain sizes in table 19 are about one to two orders of magnitude greater than those of individual particles, as indicated by photographs of three samples (fig. 29). Only very small parts of the samples are visible, however, and many such photographs would be required to make an accurate size determination. Median grain size for the three samples, as determined from the photographs, are: 3×10^{-4} in. for the lower sandstone marker bed and Farmers Member; and 2×10^{-4} in. for the unweathered part of the Nancy Member (from depth 33.0 to 33.8 ft). All three samples are very close to the size-classification limit between very fine-grained sandstone and siltstone, which is 2×10^{-4} in.

0 500 1000

SCALE, IN MILLIONTHS OF AN INCH

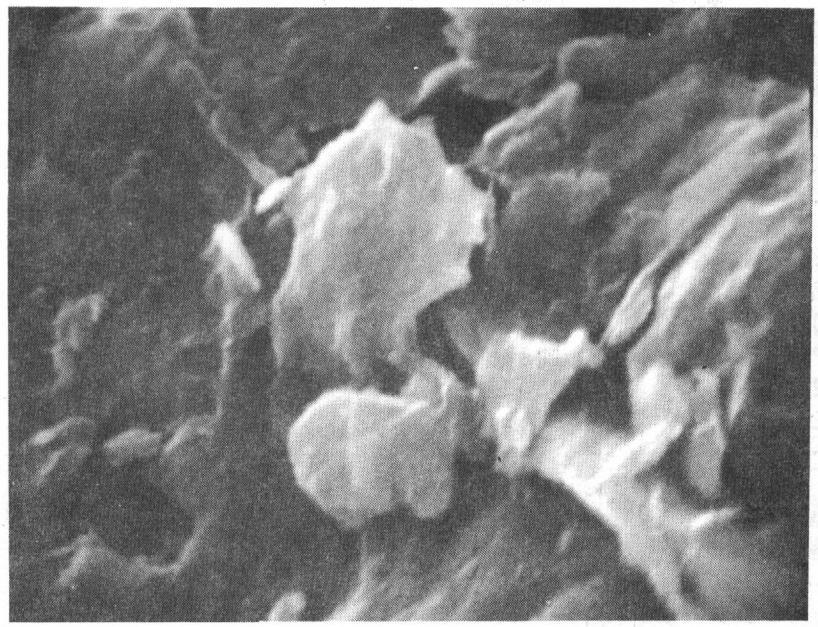
Lower sandstone marker bed of the Nancy Member



0 100 200

SCALE, IN MILLIONTHS OF AN INCH

Unweathered part of the Nancy Member



0 200 400

SCALE, IN MILLIONTHS OF AN INCH

Farmers Member

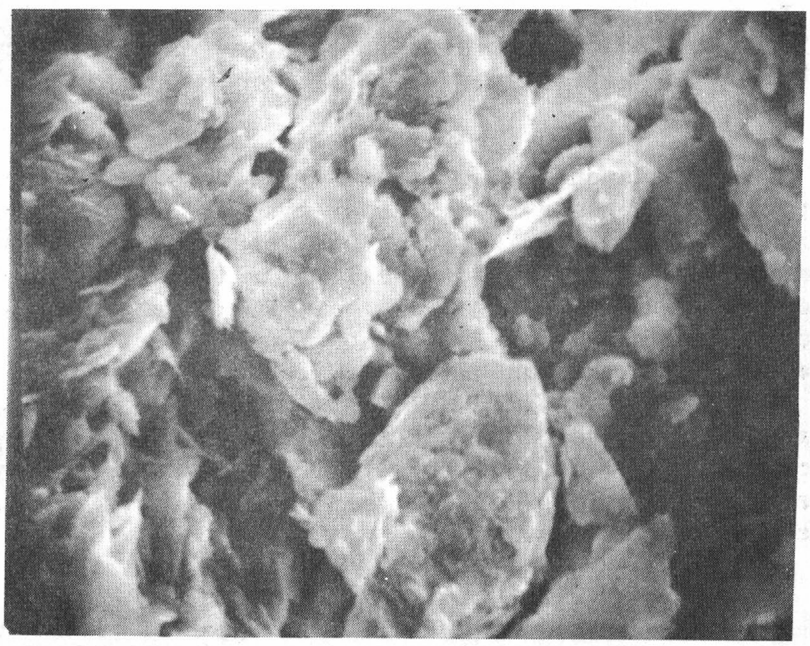


Figure 29.-- Cores from members of the Borden Formation viewed through a scanning electron miscroscope.

Most pore spaces are about one-half the size of the particles, and are sparsely located throughout the samples (fig. 29). Most particles in the shales and silty sandstones are tabular rather than spherical, which accounts for their poor hydraulic interconnection. The sparsity of pores and their small spaces indicate that area for water flux in the unfractured rock is very small. The small area, and the tortuous flow that is likely to occur around the tabular particles, are reflected in the low values of K.

Effective porosity is extremely small in bedrock samples, and is about an order of magnitude less than total porosity (table 20). Porosities of the weathered part of the Nancy Member of the Borden Formation are probably greater than those in bedrock, due to small, closely spaced (about 2 to 6 in. apart) fractures produced by the weathering process. The samples were poorly cohesive, however, and may have been altered during coring or testing. Values shown in table 20 may therefore be too large, particularly for the sample from depth 10.8 ft, and that shown in table 19 for depth 15.3 ft is probably a better approximation of total porosity for the regolith.

TABLE 20.--Total and effective porosities of cores from Maxey Flats well UA4

Rock unit[1]	Depth[2] (ft)	Total porosity (percent)	Effective porosity (percent)
WN	9.5	18.0	8.3
WN	10.8	28.0	24
UN	21.1	13.0	5.9
F	64.5	3.8	0.09
H	84.8	5.6	.60
S	87.6	14.0	1.4
B	113.0	5.7	.81
O	134.6	16.0	.18
O	183.7	11.0	.20
O	227.2	6.1	.16
O	308.2	6.8	.33

[1]WN - weathered part of Nancy Member (shale), UN - unweathered part of Nancy Member (shale), F - Farmers Member (sandstone), H - Henley Bed of Farmers Member (shale), S - Sunbury Shale, B - Bedford Shale, and O - Ohio Shale.

[2]To top of sample, and referenced to ground level.

Original pore space in the very fine grained sandstone of the Farmers Member is almost filled by secondary quartz, which results in the low total porosity shown in table 20. Microscopic examination of shales below the Farmers Member did not show significant differences in total porosity, and values of effective porosity greater than about 0.8 percent may be due to alteration of the cores.

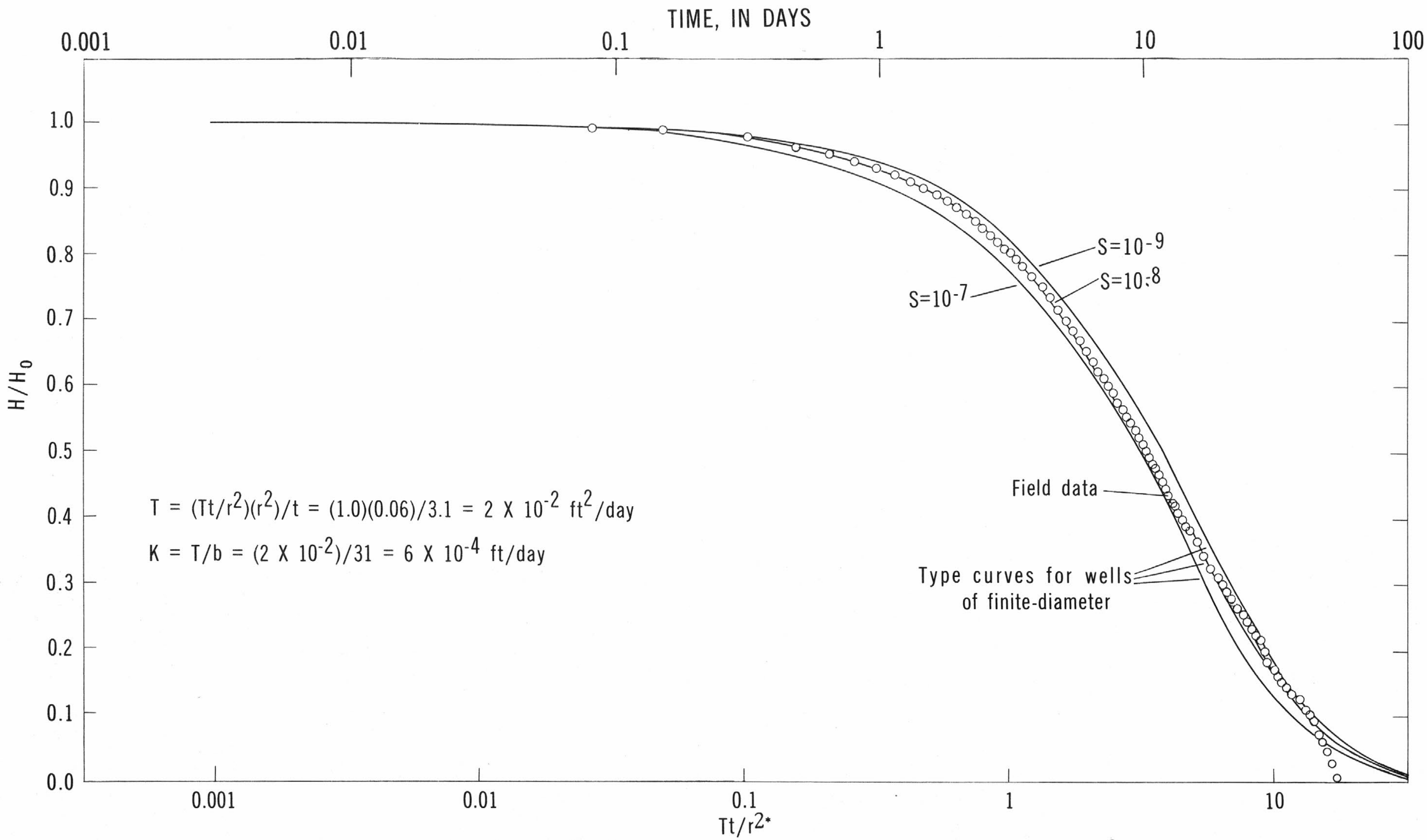
Aquifer Tests

Transmissivity (T) is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient. The hydraulic conductivity (K) of an aquifer is obtained by dividing the saturated thickness (b) of the aquifer, perpendicular to flow, into T. Values of b used here are the intervals between the initial water levels in the wells and the well bottoms. Aquifer tests were conducted by rapid (less than one-half hour) water withdrawals, or by installation of a large float to displace the water. Both types of stress are virtually instantaneous, compared to the days or weeks required for recovery.

The method of analysis used to determine T was that described by Cooper and others (1967), and Papadopulos and others (1973) for response of a finite-diameter well to an instantaneous charge of water. It involves: plotting recovery as H/H_o and time, where H is the head at some time t after initial charge or discharge at the well and H_o is the initial change in water level; and matching the recovery plot with type curves of H/H_o and Tt/r^2, where T is transmissivity, t is time, and r is the radius of the well. Each type curve represents a different value for the storage coefficient (S). The method is very insensitive for determining S because of the similar shapes of the curves. Values of this parameter obtained by curve matching ranged as much as 3 orders of magnitude for the same test, so they are not used in the report.

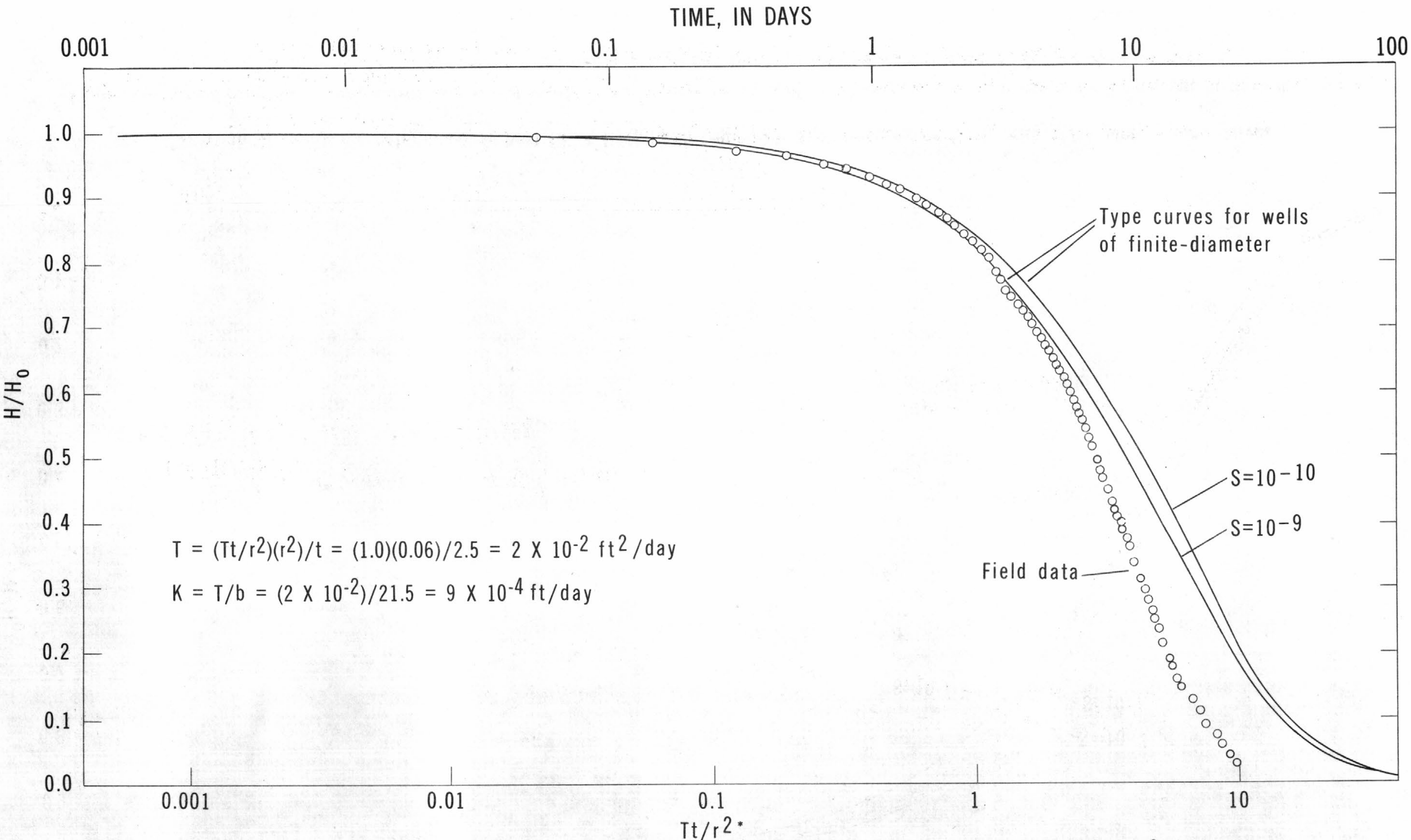
For this type of analysis, the medium tested is assumed to be confined, homogeneous, and isotropic; the well must fully penetrate the aquifer; recovery of head in the well must be a function of head in the aquifer; and recovery of head must follow according to the differential equation governing nonsteady, radial flow of confined ground water. Probably none of the conditions are fully met, except that recovery of head in the well is a function of head in the aquifer. The analysis for both T and K assumes uniform transmission of water through the rocks. At Maxey Flats, all the water may enter a well through one or two narrow fractures exposed for only a few feet, and flow is in the same direction as the fracture orientation.

Results of tests for wells UB1-A and UA2 matched type curves reasonably well. An example of one test for well UA2 is shown in figure 30. Tests for other wells usually did not match the curves after the first few days of recovery, as shown for well UA3 (fig. 31). Similar poor results were obtained by using a method of analysis described by Hvorslev (1951), in which straight-line recessions are drawn through semi-log plots of recovery data. Confined conditions and fully penetrating wells are not required in this method, but it does not take into account the compressibility of the aquifer or the water. Results from the curve-matching method are therefore used.



*Position of this scale determined by best fit of H/H_0 with time plot, superimposed on H/H_0 with Tt/r^2 plot of type curves.

Figure 30.-- Semi-logarithmic hydrograph of water-level recovery from aquifer test of well UA2, compared to type curves for aquifer test of finite-diameter wells. Well is open to the Henley Bed of the Farmers Member of the Borden Formation, Sunbury Shale, and Bedford Shale.



*Position of this scale determined by best fit of H/H_0 with time plot, superimposed on H/H_0 with Tt/r^2 plot of type curves.

Figure 31.-- Semi-logarithmic hydrograph of water-level recovery from aquifer test of well UA3, compared to type curves for aquifer test of finite-diameter wells. Well is open to the Nancy Member of the Borden Formation.

A summary of the aquifer tests is given in table 21, and includes multiple tests in most wells. Only the early part of the recovery data were used for analysis of tests in which recovery was incomplete. Different tests in the same well produced different results, with the exception of those from well UA2. This may be due to: poor matches with type curves; or changes in hydraulic conductivity in the narrow fracture openings due to stresses in the rock, such as might be produced by changes in barometric pressure, earth tides, or microseismic activity.

TABLE 21.--Summary of aquifer tests

Rock units tested[1]	Well	Change in water level[2] (ft)	Time for recovery (d)	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)
LSM	UB1-A	-1.07	I	6×10^{-2}	1×10^{-2}
LSM	UB1-A	-2.30	13	3×10^{-2}	5×10^{-3}
LN-UF	UA3	-19.80	30	2×10^{-2}	9×10^{-4}
LN-UF	UA3	+1.62	I	7×10^{-2}	3×10^{-3}
LN-UF	UA3	-18.54	30	6×10^{-2}	2×10^{-3}
LN-UF	14E	-33.80	I	2×10^{-1}	1×10^{-2}
LF	UA1	-16.34	I	4×10^{-4}	2×10^{-5}
HSB	UA2	+2.05	50	2×10^{-2}	6×10^{-4}
HSB	UA2	-1.93	54	2×10^{-2}	6×10^{-4}
HSB	UA2	-1.56	50	2×10^{-2}	6×10^{-4}
O	UA4	+1.92	I	2×10^{-2}	4×10^{-4}
O	UA4	-1.17	9	5×10^{-2}	1×10^{-3}

[1]LSM - lower sandstone marker bed of Nancy Member; LN - lower part of Nancy Member; UF - upper part of Farmers Member; LF - lower part of Farmers Member; HSB - Henley Bed of Farmers Member, Sunbury Shale, and Bedford Shale; and O - Ohio Shale.

[2]Negative sign means discharge. Positive sign means charge. I means incomplete recovery.

Most values for K obtained by aquifer testing (table 21) are about two to three orders of magnitude greater than those obtained by core analyses (table 19). The differences are due to aquifer tests including the fractured part of the rocks. The aquifer tests do not measure the K of fractures alone, because thickness of the water-yielding strata is assumed equal to the water-filled interval in the well rather than the width of the fracture opening. Differences between the K of a fracture and K of unfractured rock could therefore be several orders of magnitude.

The results in table 21 are only estimates of the water-transmitting properties of the rocks because: hydraulic conditions do not meet the requirements for the method of analysis; slightly different results are obtained for tests in the same well; and single-well tests reflect conditions immediately around the well bore, rather than a large volume of the aquifer. They indicate, however, that rocks underlying the Maxey Flats burial site have low transmissivity. The data in tables 19 and 21 indicate that this transmissivity is due primarily to flow through interconnected fractures, rather than to flow through interstices.

Principal-ion Chemistry

Water-quality samples were usually collected with a bailer. All water was not completely removed from wells prior to sampling because too much head data would have been lost. Samples may therefore not be completely representative of water in the aquifer, due to long residence time of the water in the wells. Water-quality (including radiochemical) analyses of samples from well UB2 are not included in the report because non-native water was injected during drilling, and a significant quantity remained in the well after completion.

Results of analyses for wells open to specific rocks are given in table 22, and those for wells open to all rocks from the regolith to the upper part of the Sunbury Shale are given in appendix 12. Water quality changes with time, particularly in wells UA3, UA4, 3E, and 5E. The variations may result from different residence times of water in the wells, and changes in recharge rates to the rocks.

The two very different analyses for well 11E probably result from mixing of water from the lower part of the Nancy Member with water from the lower sandstone marker bed. The quality of water in well 11E is, however, a mixture of natural ground water and trench water, as will be explained in the next section.

TABLE 22.—Principal-ion analyses of water from wells open to specific rock units

[NA means not analyzed. Analyses by U.S. Geological Survey laboratory.]

Rocks open to well[1]	Well	Date sampled	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Bicarbonate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	Silica (mg/L)	Dissolved solids (mg/L)	pH
SSM	UB1-A	2/79	110	250	13	430	57	360	1,700	0	0.68	19	3,320	6.1
SSM	UB1-A	10/79	120	250	12	410	49	290	1,700	0.02	.06	18	3,260	6.5
LSM-LN	6E	10/78	140	130	9.0	95	730	51	520	NA	NA	8.8	NA	NA
LSM-LN	11E	3/75	150	270	14	150	360	87	1,300	.03	.92	9.1	2,500	6.4
LSM-LN	11E	4/77	280	490	21	230	480	120	2,200	.01	1.09	7.6	4,350	6.6
LN-UF	UA3	10/78	280	430	37	350	590	77	2,400	NA	NA	7.9	4,430	NA
LN-UF	UA3	6/79	180	350	18	280	530	67	2,000	0	0	9.7	3,980	7.0
LN-UF	UA3	10/79	200	370	17	270	560	67	1,900	.01	.19	9.3	3,700	6.8
LN-UF	14E	3/75	82	59	7.5	220	820	51	210	.06	.15	13	1,070	7.0
LN-UF	14E	10/78	84	61	8.0	290	830	57	240	0	.27	13	1,100	NA
LN-UF	14E	6/79	73	59	8.0	240	830	56	220	.01	.65	12	1,170	7.5
LN-UF	14E	10/79	79	54	7.8	230	860	56	210	.02	.61	14	1,080	7.3
LF	UA1	5/77	16	7.1	6.0	360	610	160	140	1.8	.50	5.4	1,040	7.2
LF	13E	3/75	67	39	8.0	260	350	110	470	.01	4.8	9.6	1,200	7.5
LF	13E	10/78	40	23	8.0	380	440	110	420	.03	3.6	7.5	1,180	NA
LF	13E	2/79	40	23	7.6	330	430	100	410	NA	NA	7.1	1,180	6.9
LF	13E	6/79	38	22	7.1	390	450	110	460	.01	3.8	6.8	1,360	7.7
LF	13E	10/79	39	22	7.5	320	420	97	390	.03	3.4	7.9	1,120	7.7
HSB	UA2	6/79	10	2.4	5.2	540	1,090	150	120	0	.06	8.5	1,400	8.1
HSB	UA2	10/79	9.0	2.1	5.3	540	1,080	150	160	.01	.14	9.0	1,420	8.3
HSB	3E	10/78	110	64	37	1,400	490	43	2,900	NA	NA	9.6	5,200	NA
HSB	3E	6/79	37	70	13	1,200	410	35	2,800	NA	NA	10	4,390	7.7
HSB	3E	10/79	68	37	15	1,100	460	34	2,000	NA	NA	14	4,010	7.7
O	UA4	1/79	930	250	22	7,500	400	13,000	47	NA	NA	6.5	22,300	7.3
O	UA4	6/79	830	470	31	6,300	320	13,000	59	.01	0	6.5	22,000	7.1
O	UA4	10/79	940	250	37	6,600	400	11,000	94	.01	.01	3.2	21,500	8.1
O	5E	6/75	64	18	18	1,800	730	2,400	10	0	.04	8.3	4,450	7.2
O	5E	10/78	100	31	24	2,400	700	3,500	30	0	.01	7.9	6,210	NA
O	5E	6/79	57	37	12	1,600	880	2,300	14	NA	NA	8.2	4,370	7.5
O	5E	10/79	64	19	14	1,700	870	2,300	11	.02	.33	8.6	4,630	7.8

[1]SSM - upper and lower sandstone marker beds; LSM - lower sandstone marker bed; LN - lower part of Nancy Member; UF - upper part of Farmers Member; LF - lower part of Farmers Member; HSB - Henley Bed of Farmers Member, Sunbury Shale, and Bedford Shale; and O - Ohio Shale.

Differences in water quality between most wells are probably due to a combination of: water-transmitting properties of the rocks in the vicinity of the wells, particularly the degree of fracture connection; and different water quality in different strata. Mean concentration of principal ions in water from wells completed below the lower sandstone marker bed were grouped by rock unit and water accumulation rate after 1.5-gal withdrawals (table 23). This rate was used for comparison because transmissivity could not be determined for wells 3E and 5E. Time for recovery in well 3E was estimated as 700 days, by straight-line extrapolation of recovery from a 0.25-gal withdrawal in October 1978.

TABLE 23.--Water accumulation rates and mean concentrations of principal ions in water from wells open to specific rock units

Rocks open to well[1]	Well	Accumulation rate[2] (gal/d)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Bicarbonate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Dissolved solids (mg/L)
LN-UF	14E	2×10^{0}	79	58	250	840	55	220	1,110
LN-UF	UA3	1×10^{-1}	220	380	300	560	70	2,100	4,040
LF	UA1	3×10^{-2}	16	7.1	360	610	160	140	1,040
LF	13E	2×10^{-2}	45	26	340	420	110	430	1,210
HSB	UA2	5×10^{-2}	10	2.3	540	1,100	150	140	1,410
HSB	3E	2×10^{-3}	72	57	1,200	450	37	2,600	4,530
O	5E	2×10^{0}	71	26	1,900	800	2,600	16	4,920
O	UA4	2×10^{-1}	900	320	6,800	370	12,000	67	21,900

[1]LN - lower part of Nancy Member; UF - upper part of Farmers Member; LF - lower part of Farmers Member; HSB - Henley Bed of Farmers Member, Sunbury Shale, and Bedford Shale; and O - Ohio Shale.

[2]Mean volume of water per day accumulated after 1.5-gal withdrawal.

Water from wells with accumulation rates lower than another well completed in the same stratum generally has greater concentrations of most principal ions. This may be due to a slower rate of water movement, or more contact of water with rocks, than in the more-permeable strata. These allow greater reaction of water with minerals comprising the rocks. Water in rocks below the upper part of the Farmers Member generally has greater sodium and chloride, particularly in the Ohio Shale (table 23).

Table 23 may be used for comparison to show that water from bedrock contains concentrations of ions about an order of magnitude greater than stream water during low flow (table 7) and water from shallow wells completed in alluvium (table 8). The lower concentrations show that most base flow and water in alluvium originates from near-surface sources, rather than from bedrock. Analyses of water from wells 1 through 8 (results of which are probably influenced by flow of surface water down the casing-borhole annuli) are shown in appendix 13.

Principal cations and anions were ranked, from greatest to least concentration, with separate rock units and wells (table 24). There is poor consistency of water type in different rock strata at Maxey Flats, at least for rocks above the lower part of the Farmers Member. Part of the inconsistency may be due to: insufficient sites for data collection; an insufficient number of samples collected from the sites available; different rates of flow (table 23); and infiltration of shallow water down the boreholes of some wells. In general, however, the data indicate that water from:

(a) rocks above the lower part of the Farmers Member has no single predominant cation, but bicarbonate is usually the predominant anion;
(b) rocks between the upper part of the Farmers Member and the top of the Ohio Shale has no single predominant anion, but sodium-calcium-magnesium is usually the cation rank (greatest to least);
(c) the Ohio Shale has sodium and chloride as predominant ions, and their concentrations are several times greater than the next-most abundant cation or anion.

The greater abundance of bicarbonates in water from upper rocks at Maxey Flats (particularly those that are more permeable than others), the change in rank of bicarbonate and sulfate in water from rocks at intermediate depth, and the predominance of chlorides in water from deep rocks is similar to an anion "metamorphism" observed by Chebatarev (1955) from analysis of 10,000 water samples from Australia. The "metamorphism," with increasing length of flowpath and increasing age, results in the sequence: bicarbonate -- bicarbonate + sulfate -- sulfate + bicarbonate -- sulfate + chloride -- chloride + sulfate -- chloride. The relative solubility of ions and type of host rock are factors that influence the sequence. Sodium and chloride tend to stay in solution, whereas other ions precipitate more readily.

The rocks at Maxey Flats have low percentages of chloride-producing minerals (see table 18), so they probably have less influence than length of flowpath and ground-water velocity in producing chlorides. The predominance of chlorides in water from deeper rocks could also be due to slow diffusion of very old, saline water from semi-isolated pores into water moving through fractures.

Assuming that length of flowpath is less of a factor than rate of water movement in increasing chloride concentrations in the ground water at Maxey Flats, and either anion diffusion or anion "metamorphism" account for the concentrations, then these concentrations give an indication of relative rates of ground-water movement. Fastest flow would therefore be in rocks above the lower part of the Farmers Member, slower flow in rocks between the upper part of the Farmers Member and top of the Ohio Shale, and slowest flow in the Ohio Shale.

TABLE 24.--Rank of principal ions in water from wells on the burial site

Rocks open to well[1]	Well[2]	Rank[3]	
		Cations	Anions
SSM	UB1-A	Sodium-magnesium-calcium	Sulfate-chloride-bicarbonate
SSM-LN	6E	Calcium-magnesium-sodium	Bicarbonate-sulfate-chloride
SSM-LN	11E	Magnesium-(calcium-sodium)	Sulfate-bicarbonate-chloride
SSM-LN	1	Sodium-calcium-magnesium	Bicarbonate-chloride-sulfate
SSM-LN	2	Calcium-sodium-magnesium	Bicarbonate-chloride -
SSM-LN	3	Sodium-magnesium-calcium	Bicarbonate-sulfate-chloride
SSM-LN	5	Sodium-calcium-magnesium	Bicarbonate-chloride-sulfate
SSM-LN	6	Calcium-sodium-magnesium	Bicarbonate-sulfate-chloride
SSM-LN	7	Sodium-calcium-magnesium	Sulfate-bicarbonate-chloride
SSM-LN	8	Calcium-sodium-magnesium	Sulfate-bicarbonate-chloride
LN-UF	14E	Sodium-calcium-magnesium	Bicarbonate-sulfate-chloride
LN-UF	UA3	Magnesium-sodium-calcium	Sulfate-bicarbonate-chloride
LF	UA1	Sodium-calcium-magnesium	Bicarbonate-chloride-sulfate
LF	13E	Sodium-calcium-magnesium	/Sulfate-bicarbonate/-chloride
HSB	UA2	Sodium-calcium-magnesium	Bicarbonate-/chloride-sulfate/
HSB	3E	Sodium-/calcium-magnesium/	Sulfate-bicarbonate-chloride
O	5E	Sodium-calcium-magnesium	Chloride-bicarbonate-sulfate
O	UA4	Sodium-calcium-magnesium	Chloride-bicarbonate-sulfate

[1]SSM - upper and lower sandstone marker beds; LN - lower part of Nancy Member; UF - upper part of Farmers Member, LF - lower part of Farmers Member; HSB - Henley Bed of Farmers Member, Sunbury Shale, and Bedford Shale; and O - Ohio Shale.

[2]Water quality in wells 6E, 11E, and 1 through 8 may be influenced by infiltration of shallow water down well bore.

[3]Greatest to least concentration, in mg/L. Ions in parentheses have equal rank. Ions between slashes have different rank for different samples from same well.

Low-level tritium analyses were completed for water samples from wells UA3 and UA4 by a U.S. Geological Survey laboratory. This was done as a first step in an attempt to determine the ages of water in the Nancy Member and Ohio Shale. Water was completely evacuated from both wells before sampling. Concentrations were 23.1 ±2.2 pCi/L in well UA3 and 52.2 ±2.9 pCi/L in well UA4. They indicate the presence of recent-age water, which was probably introduced during drilling. Therefore, age dating could not be accomplished.

Radiochemistry

Tritium in Recharge and in Water from Wells

Evaporator operation on the burial site increases ambient tritium levels in air (as water vapor) and rainfall. Concentrations in water samples from wells result from one or more of the following: infiltration of rainwater; ground-water flow from trenches; diffusion at the air-water interface in the wells; and diffusion of vapor from trenches to water in the rocks.

Rainfall samples were taken for tritium analysis from four collectors on the burial site. They were located at wells 13E, UB4, 11E, and UA2, which are given here in order of increasing distance from the evaporator. Samples were usually taken monthly, so results of analyses represent the composite concentrations at each site, in all rainfall accumulated between sampling periods.

Concentrations of tritium in rainfall range widely with location, and with time at specific locations (table 25). They are dependent on several factors, such as: length of time the evaporator was operated, variations in concentration of water processed, proximity of the sampling site to the evaporator, wind direction, and intensity and duration of rainfall. Median concentrations shown in table 25 decrease with increasing distance of sampling points from the evaporator. The maximum values are of most interest in this study, however. Assuming concentrations due to diffusion are negligible compared to those due to infiltration and flow from trenches, concentrations in ground-water samples that exceed the maximum values in table 25 indicate subsurface flow from the trenches.

Samples from wells in the trench area were analyzed for tritium as follows: most E wells about twice monthly by the Kentucky Department for Human Resources (October 1977); UB1-A once by Brookhaven National Laboratory (Weiss and Colombo, 1980); and other UB wells once or twice by Dames and Moore consulting firm (December 1977). UB1-A was the only well in the UB series that was completed before sampling. It was open to the sandstone marker beds. All other UB wells were sampled during drilling, when they were open to several rock units above the Ohio Shale. The water was probably from the lower sandstone marker bed because most wells were dry after completion in underlying rocks.

TABLE 25.--Tritium concentrations in rainfall at the Maxey Flats site

[Values in thousands of picocuries per liter. Numbers in parentheses are ± 2 sigma percent counting uncertainties; blank if unknown. Dash means no sample collected. Analyses by Brookhaven National Laboratory.]

	Rainfall sample collection site							
Composite period[1]	13E		UB4		11E		UA2	
03/09/77 to 04/20/77	153	(1.3)	-		3.87	(4.2)	<0.70	
04/20/77 to 05/17/77	26.2	(19)	-		6.36	(12)	2.01	(35)
05/17/77 to 06/20/77	28.5	(2.1)	-		27.5	(2.3)	42.7	(1.8)
06/20/77 to 07/20/77	16.5	(3.2)	-		10.8	(4.1)	10.8	(4.2)
07/20/77 to 08/25/77	49.6	(1.8)	-		2.99	(13)	1.47	(20)
08/25/77 to 09/21/77	7.75	(4.9)	-		6.29	(5.8)	3.46	(10)
09/21/77 to 10/14/77	4.36	(9.0)	-		7.28	(5.3)	<0.70	
10/14/77 to 11/22/77	7.90	(5.1)	-		13.0	(3.9)	15.3	(3.3)
11/22/77 to 12/20/77	46.8	(1.7)	-		104	(<1)	4.91	(8.1)
12/20/77 to 03/20/78	105	(<1)	46.0	(2.0)	17.2	(3.5)	-	
03/22/78 to 04/19/78	55.5	(1.6)	69.6	(1.4)	42.8	(1.9)	16.5	(3.0)
04/19/78 to 05/15/78	49.3	(1.8)	274	(<1)	86.6	(1.2)	1.70	(40)
05/15/78 to 06/16/78	183	(1.1)	36.3	(1.2)	29.0	(2.1)	88.1	(2.8)
06/16/78 to 07/12/78	22.0	(2.7)	7.41	(6.0)	4.11	(7.5)	3.71	
07/12/78 to 08/09/78	3.38	(10.1)	-		4.25	(3.8)	.591	(38)
08/09/78 to 09/05/78	6.50	(5.5)	3.12	(9.9)	5.71	(6.0)	.263	(86)
09/05/78 to 10/05/78	5.28	(6.3)	2.92	(10.6)	3.82	(10.2)	<0.24	
10/05/78 to 11/09/78	7.50	(5.2)	27.2	(2.6)	8.70	(4.5)	6.54	(6.1)
11/09/78 to 12/05/78	17.3	(2.9)	47.3	(1.7)	103	(<1)	26.9	(2.2)
12/05/78 to 02/28/79	63.0		16.0		22.0		15.0	
02/28/79 to 03/28/79	157	(1.1)	2.58	(7.7)	6.25	(5.6)	9.07	(4.7)
03/28/79 to 04/23/79	48.4	(2.0)	7.16	(5.3)	42.7	(2.2)	17.9	(3.4)
04/23/79 to 05/22/79	7.14	(11.6)	5.00	(14)	10.2	(8.5)	2.92	(27)
05/22/79 to 06/19/79	28.6	(3.2)	11.4	(5.8)	38.2	(2.7)	3.46	(14)
06/19/79 to 08/02/79	3.13	(19)	<0.62		<0.62		4.50	(16)
Range	3.13-183		<0.62-274		<0.62-104		<0.24-88.1	
Median	26.2		11.4		10.2		4.11	

[1]Time interval over which sample accumulated.

Tritium from 11E, 13E, and UB wells (table 26) exceed maximum concentrations in precipitation, showing flow of water from trenches to the wells. No conclusions are made regarding flow of tritium to other wells because levels are less than maximum levels in rainfall.

TABLE 26.--Ranges of tritium concentrations in wells on the Maxey Flats site

[Numbers in parentheses are possible errors due to counting uncertainties; blank if unknown]

Well	Ranges of tritium concentrations (pCi/L)		
1E	5,130 (280)	-	5,340 (280)
3E	380 (190)	-	7,500 (330)
[1]5E	235 (190)	-	3,160 (210)
6E	375 (180)	-	18,840 (450)
8E	<200	-	12,410 (380)
10E	660 (200)	-	40,140 (620)
11E	730,000 (2,620)	-	6,813,130 (7,940)
12E	990 (200)	-	27,050 (530)
13E	163,290 (1,250)	-	4,592,740 (6,520)
14E	620 (180)	-	19,210 (456)
UB1	4,120,000	-	4,180,000
[2]UB1-A	5,800,000		
[2]UB3	292,000,000		
[2]UB4	7,960,000		

[1]A sample collected in April 1974 contained 141,630 pCi/L, and one collected in February 1976 contained 25,790 pCi/L. These are probably not representative of the ground water because concentrations were about an order of magnitude greater than in any other sample.

[2]One sample collected.

Increases in tritium concentrations correspond to increases in well 11E water levels (fig. 32), and are probably due to partial filling of the well by water from the lower sandstone marker bed. They occur during months of low evapotranspiration and increased infiltration. The decreases are probably due to a combination of: a decrease in flow from the lower sandstone marker bed during months of decreased infiltration; and removal of some of the accumulated water by sampling, which results in mixing of the well water with water from the lower part of the Nancy Member. The tritium concentrations in well 13E (which is open only to the lower part of the Farmers Member) reflect either leakage of trench water from shallow zones along the cement bond in the well, or infiltration of trench water into the Farmers Member.

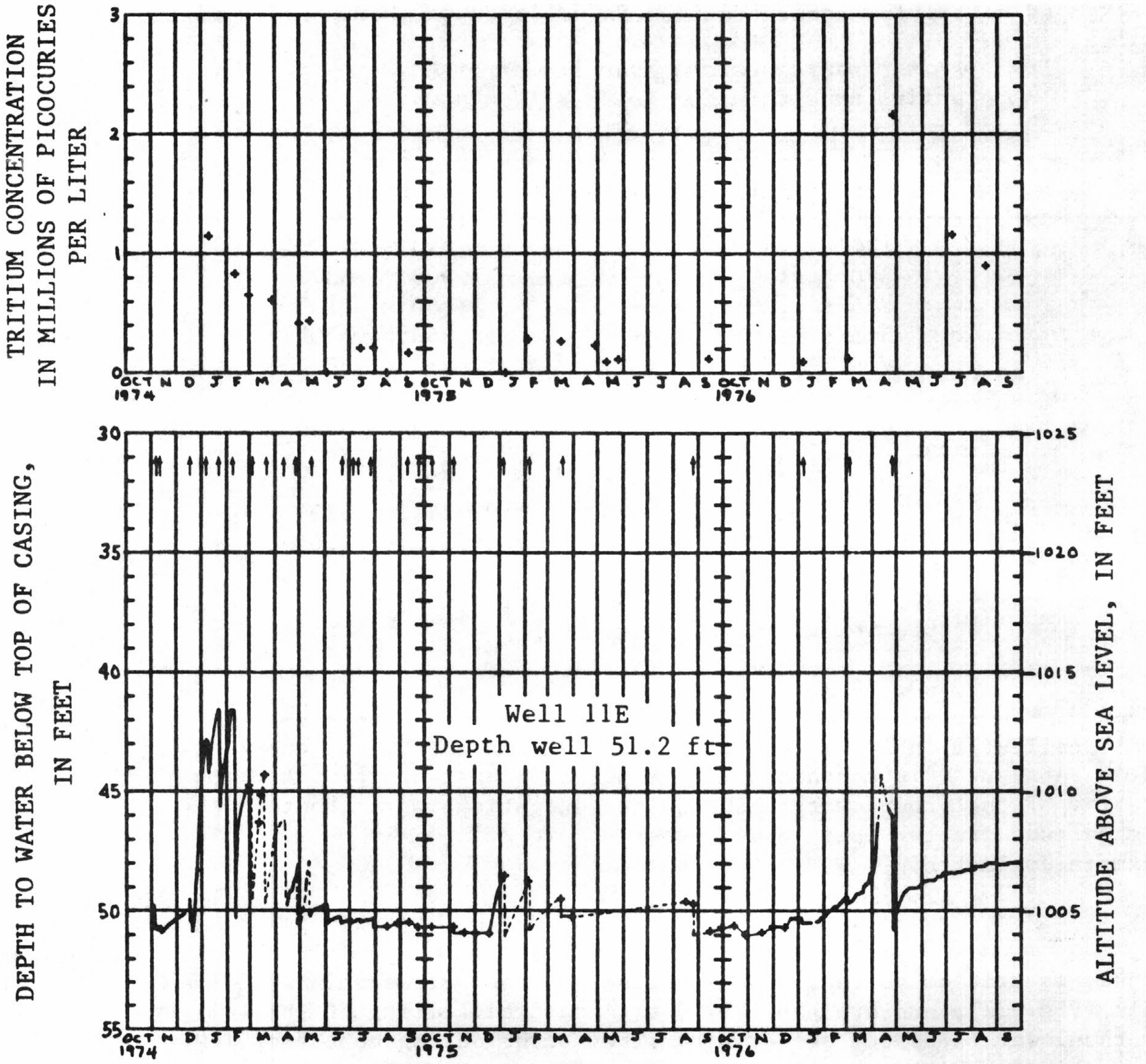


Figure 32.-- Hydrograph of well 11E with plot of tritium concentrations. Well is open to the Nancy Member of the Borden Formation. Tritium data from the Kentucky Department for Human Resources (1977). Depth referenced to top of casing. On hydrograph, line denotes continuous water-level data, dashed where approximated. Cross on hydrograph denotes single measurement. Arrows denote discharges.

A possible source for the tritium in well 13E is nearby trench 33L (see plate 1), in which 446 curies of tritium were solidified. Trench 31 is 50 ft from well 11E, and contains the greatest tritium-waste activity of any trench on the burial site - 484,224 curies (Kentucky Department for Human Resources, December 1977). The UB wells are also near trench 31, but are virtually surrounded by many other trenches, which also contain tritium and are of equal proximity.

The specific trenches from which tritium in wells originated are not known with certainty, and the higher concentrations shown in table 26 may be the result of flow from several trenches. The front of tritium flow had passed sites 13E, 11E, UB wells, and possibly other well locations, before the wells were drilled. The velocity of ground water therefore could not be computed from the data, even if specific-source trenches were known.

Trench-water flow in the burial area is apparently most prominent in the lower sandstone marker bed. Little or no water accumulated in the UB wells after completion in rocks underlying this bed (water samples taken from deeper wells, prior to well completion, were evidently from the lower sandstone marker bed), probably because they did not intersect with fractures, so no conclusion is made regarding deeper flow of trench water at this location. The tritium concentrations in well 13E indicate that trench water may have reached the lower part of the Farmers Member.

Other Radionuclides in Ground Water

Samples from most wells are of limited value in determining radiochemical quality of ground water at the burial site. Wells 1 through 8 may accumulate runoff from the contaminated soil and regolith. Many E wells are open to several rock units, including the lower part of the regolith.

Various gamma-emitting radionuclides, strontium-90, and plutonium have been found in water samples from E wells, as described by the Kentucky Department for Human Resources (1974), and Montgomery and others (1977). However, the radionuclides may have been introduced during drilling, well completion, or possibly by cross-contamination during sampling (Montgomery and others, 1977). The E wells were flushed with Morehead city water in 1976, and since that time concentrations, other than tritium, have been at or near minimum detectable limits (D. Clark, Kentucky Department for Human Resources, oral commun., November 1980).

The UB wells (except UB1-A) were sampled during drilling, primarily as a safety precaution. Most samples were centrifuged, rather than filtered, so that drilling operations would not be impeded. Only gross alpha and gross beta (and tritium) concentrations were determined. Analyses of water from wells 10E, 12E, and 14E by the Kentucky Department for Human Resources (October 1977) were used to determine background levels, which were less than about 2 pCi/L for gross alpha and about 60 pCi/L for gross beta.

Gross alpha and gross beta concentrations were considerably above background in UB wells before the wells were completed (table 27). Probably all water was from the lower sandstone marker bed, and the radiochemical analyses show flow from the trenches through this bed.

TABLE 27.--Analyses of gross alpha and gross beta in water from UB wells

[Samples centrifuged, except as noted. Numbers in parentheses are possible errors due to counting uncertainties. Data from Dames and Moore Consulting Firm, December 1977.]

Well	Date sampled	Gross alpha (pCi/L)	Gross beta (pCi/L)
UB1	10/13/77	19 (16)	165 (34)
[1]UB1	10/17/77	2,800 (400)	88,800 (1900)
UB3	10/27/77	357 (53)	510 (53)
UB4	10/20/77	12 (15)	138 (32)

[1]Filtered sample.

The probable reason for the very different results for the two samples from well UB1 is that one or more additional fractures in the lower sandstone marker bed were encountered as drilling progressed. The drillhole was 6-in. diameter when the sample with lower concentrations was collected on October 13, 1977. The upper 30 ft of the hole was later reamed to 10-in. diameter in preparation for setting casing and cementing. The sample collected October 17, 1977 was from the 10-in. hole. The fracture encountered after reaming evidently had better hydraulic connection with trenches than the first fracture, resulting in less sorption of radionuclides. The differences in radiochemical quality of the samples vividly illustrate the inhomogeneity of the flow system.

Specific-isotope analyses of water from wells UB1 (taken from the 10-in drillhole) and UB1-A are shown in table 28. Cobalt-60 was the only gamma-emitting waste isotope detected. The large differences in concentrations between the two wells are probably related to the degree of fracture connection with the trenches. The water-accumulation rate for well UB1 was about 8 gal/d, and that for well UB1-A was about 1 gal/d. The types of radionuclides shown in table 28 have been buried in many of the trenches around the UB wells. Their source and flowpath are therefore unknown.

TABLE 28.--Specific-isotope analyses of water from wells UB1 and UB1-A

[Numbers in parentheses are possible errors due to counting uncertainties. Analyses by Brookhaven National Laboratory.]

Well	Cobalt-60 (pCi/L)	Strontium-90 (pCi/L)	Plutonium-238 (pCi/L)	Plutonium-239 (pCi/L)
[1]UB1	4,680 (110)	71,000 (7100)	33 (0.33)	0.42 (0.25)
UB1-A	2,500 (63)	63 (6.3)	14 (2.2)	.54 (.59)

[1]Sample taken before well completion, and probably from lower sandstone marker bed.

Geophysical equipment was used to make downhole spectra at various depths in all UB wells after they were completed. A sodium-iodide crystal was used in the equipment, which detects only gamma-emitting radionuclides. Initial spectra were taken with a 3.5-in.-diameter by 12-in.-long sodium iodide detector, and counting time was 5 minutes. The equipment was later collimated by placing 1-in.-thick lead shields over part of a smaller-diameter detector, with a 2-in. gap between the shields. Only a few-inch interval of rock was therefore investigated at each depth. The effective geometry of the detector was then 1-in. diameter by 2-in. long, and counting time was 17 minutes. Wells, number of spectra, and depth interval (referenced to ground level) in which spectra were taken were: UB1, 29 between depths 5.7 and 63.6 ft; UB1-A, 2 at depths 13.7 and 20.3 ft; UB2, 14 between depths 5.4 and 54.6 ft; and UB4, 10 between depths 11.8 ft and 99.3 ft. Spectra were taken at the upper and lower sandstone marker beds in all wells.

Cobalt-60 was the only waste isotope identified. It was found in well UB1 only in the lower sandstone marker bed. Spectra were taken as close as 6 in. above and 6 in. below the bed, using the collimated probe, but no waste isotopes were detected at these horizons. Cobalt-60 was also detected in well UB3 at a depth of 5.4 ft, and was probably due to contamination of the regolith during waste burial or trench-dewatering operations. No waste isotopes were identified in other UB wells by geophysical logging.

Spectral logs were made in well numbers 1, 5E, 12E, and 13E during an earlier study (Zehner, 1980), and later in 3E and all UA wells. Cobalt-60, cesium-134, and cesium-137 were identified in well 12E, in the depth interval from 14 ft to 44 ft below ground level. Because drilling and well completion methods were not observed at this site, it is not known if these radionuclides entered the well by normal flow, or as a result of well construction. No waste isotopes were detected in the other wells.

CONCEPTUAL FLOW MODEL OF THE GROUND-WATER SYSTEM

A conceptual flow model was made by simplifying the complex ground-water system at Maxey Flats to an idealized, two-dimensional, cross-sectional, steady-state flow problem. Flow through individual fractures was not considered because hydrologic information for individual fractures was not avalailable. Rocks were considered to act as a porous medium over a large area. Only flow above the base of the Bedford Shale was modeled because of insufficient data for the Ohio Shale.

Directions of ground-water flow could not be accurately determined with available data. Flow over a large area is probably controlled by topography, however, because the large area (entire burial site) includes many fractures of different orientation, dip of the rocks is small (25 to 40 ft/mi), and the flow system occurs in a protruding part of a topographically isolated knob. Flow is therefore likely to extend outward from the topographic axis of the site, toward the adjacent valleys.

The equation for two-dimensional, steady-state, ground-water flow is: $(\partial/\partial z)((K_{zz})(\partial h/\partial z)) + (\partial/\partial y)((K_{yy})(\partial h/\partial y)) = 0$, where K_{zz} and K_{yy} are the hydraulic conductivites in the vertical and horizontal directions, respectively, and h is hydraulic head. The equation was solved numerically by using finite-difference approximations.

The model is a vertical cross section taken through the burial area, from the UB wells to the unnamed valley (fig. 33). Boundary conditions are as follow. The left side is a no-flow boundary corresponding to an assumed ground-water divide along the topographic axis of the hill. Heads along the lower boundary are set equal to the elevation at the base of the Bedford Shale. Heads along the water table in the regolith are assumed to vary linearly from a value corresponding to the water level in well UB1-A to a value equal to the elevation of the top of the lower sandstone marker bed at the edge of the hill. Heads at the seepage boundary along the hillside are set equal to their elevation. The equation above was then solved for head distribution.

Ratios of approximate vertical hydraulic conductivity relative to the Bedford Shale are used (fig. 33) because accurate values for hydraulic conductivity are not available. The ratios are based on fracture intensity, visual observations of discharge at outcrops, water-level recovery rates in wells, and reasonable approximations of heads in the model to head data from wells. They therefore do not correspond solely to the rank of rock units by fracture intensity, nor to estimates from aquifer tests. The discontinous character of fractures in the vertical direction results in greater horizontal hydraulic conductivity, so the ratio of horizontal to vertical hydraulic conductivity (anisotropy) is assumed to be 100. Further details regarding construction of the model are described by Pollock and Zehner (1981).

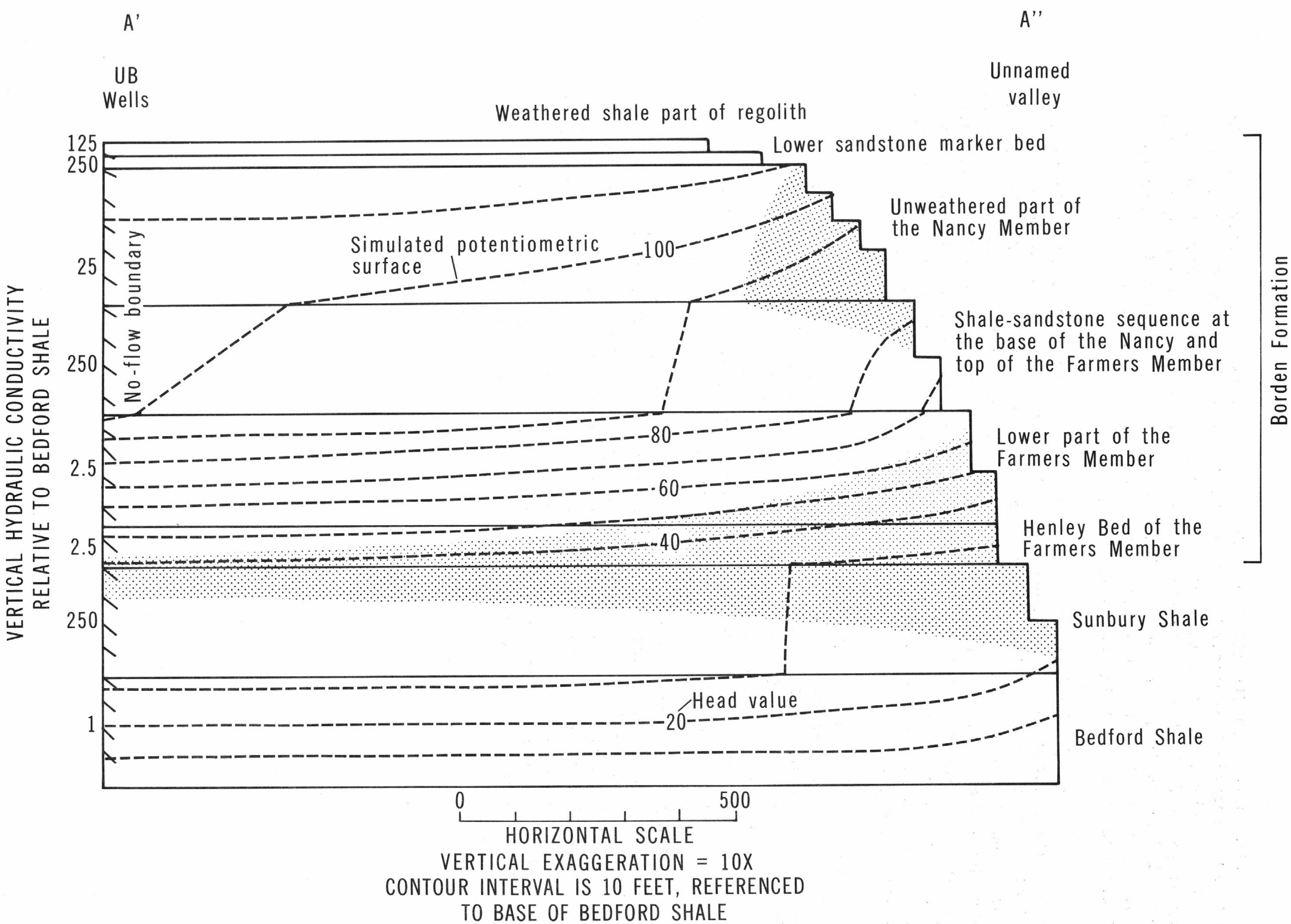


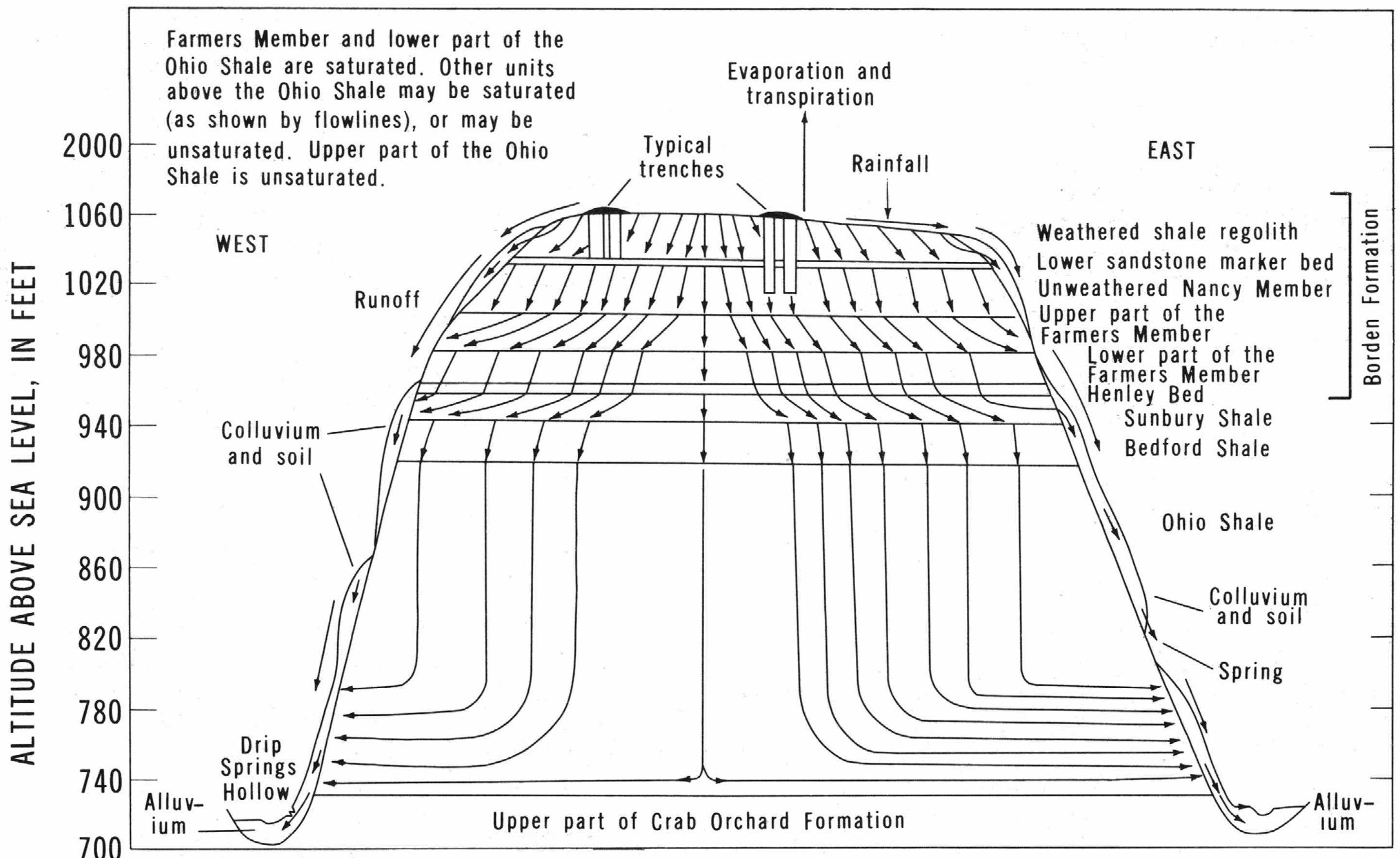
Figure 33.-- Simulated head distribution in rocks above the Ohio Shale. Stippled areas are regions where the predicted head is less than the elevation head, and are possibly unsaturated. Diagram modified from Pollock and Zehner (1981). See figure 35 for A' A'' line of section location.

Simulated head distributions show that flow is nearly vertical in the poorly permeable unweathered part of the Nancy Member, lower part of the Farmers Member, and Bedford Shale (fig. 33). It is nearly horizontal in the upper part of the Farmers Member and lower part of the Sunbury Shale. The stippled areas indicate regions that are possibly unsaturated. Assuming the upper part of the Ohio Shale is unsaturated, a perched water table may therefore be present in the Sunbury Shale.

Flow through the lower sandstone marker bed was primarily vertical in the model simulations, mostly because the bed was thin compared to other relatively permeable units. Significant horizontal flow through the bed is indicated by radionuclide data, however. The anisotropy of the sandstone bed may therefore be greater than 100. A model was constructed with an anisotropy of 1,000 for the bed, but results still showed predominantly vertical flow. Data are not available for obtaining a more accurate estimate of anisotropy, so results shown in figure 33 are used as the best approximations with available data.

Based on the model, about 70 percent of the water entering the top of the burial site discharges to the hillside above the lower part of the Farmers Member. Only about 10 percent of the remaining flow enters the Ohio Shale. The most active part of the flow system is therefore above the lower part of the Farmers Member, as is also indicated by water-quality data. Assuming the upper part of the Crab Orchard Formation is the lower hydrologic boundary, all ground water eventually flows to the side of the hill.

A diagrammatic section of the entire flow system, including the Ohio Shale, colluvium, and alluvium is shown in figure 34. Flow in the upper part of the unsaturated Ohio Shale is probably vertical, and nearly horizontal in the lower, saturated part of the formation. Other unsaturated zones (not shown) may be present in overlying strata, and near the hillsides. Recharge to colluvium is by infiltration of rainfall and runoff, and by discharge of water from bedrock. Water in springs is due to discharge from colluvium and bedrock. Recharge to alluvium is from overland runoff and flow from colluvium.



VERTICAL EXAGGERATION 3

Arrows below ground level represent flowlines. Length and density of flowlines do not indicate velocity or volume of flow.

Figure 34.-- Diagrammatic, hydrogeologic section of the Maxey Flats site showing hydrologic relations.

DISCHARGE FROM BEDROCK

Discharge from bedrock at Maxey Flats cannot be accurately computed with available data. An upper limit is approximated, however, so that an estimate may be made of the potential maximum flow from the trench area and its approximate dilution by surface and near-surface flow. This limit is computed by highly simplified methods and is presented for perspective, rather than as an actual value.

All ground water is assumed to flow through uniform fracture openings. Most fractures in outcrops are weathered, so their openings are probably larger than those in the subsurface. Numerous freshly exposed fractures were observed in trench walls, however. Those in bedrock, which trended perpendicular to the walls, showed minimal disturbance from excavation and stress relief. The maximum openings in these fractures were located just below the lower sandstone marker bed. Their width at this horizon was about 0.01 ft, and it decreased with depth. For purposes of approximating the upper limit of ground-water discharge, it is assumed that: all fractures above the lower part of the Farmers Member have uniform openings of 0.01 ft; surfaces of the fractures are smooth, parallel planes; and friction to flow along the planes is neglible. Discharge computation is based on the simple equation $Q = VA$, where Q is discharge, V is ground-water velocity, and A is the area of the fracture opening.

The equation above is expanded to the form $Q = (F_I)(O_L)(B)(C)$, where Q is ground-water discharge per unit drainage area, F_I is fracture intensity, O_L is outcrop length, and B is saturated thickness. The constant C = 5.4×10^{-8} in./(yr X ft), and is the product of fracture opening (0.01 ft), ground-water velocity (50 ft/yr), and the conversion factor (1.07×10^{-7} in./ft^3) for normalizing discharge to unit drainage area in the 4.01 mi^2 Rock Lick Creek basin above the gaging station near Sharkey, Kentucky. The product of F_I, O_L, B, and fracture opening gives the area through which ground water discharges.

The 50-ft/yr ground-water velocity is used in all discharge calculations, and is based on the estimated rate of cobalt-60 and manganese-54 movement through the lower sandstone marker bed near trench 46 (see discussion in the section "Rate of radionuclide movement through the lower sandstone marker bed"). This value may not be representative of maximum ground-water flow because water may move faster than the radionuclide front. Also, this lateral component of velocity may be different in other areas, or in underlying strata. The 50-ft/yr value is the most reasonable ground-water velocity obtainable from all data, however, so is used to make the best possible approximation of maximum discharge with available information.

Discharge from bedrock in the Rock Lick Creek basin is approximately perpendicular to lines shown in figure 35 because flow is probably away from topographically high areas. The lines intersect at the contact of the Nancy and Farmers Members, and their length approximates the outcrop length of these rocks. They may be considered as the tops of planes through which ground water flows. Most lines trend predominantly NNE and WNW, and are nearly perpendicular to each other. Predominant trends of most fracture sets in these rocks are similar (see figure 9), so most fractures intersect the lines at nearly right angles. This is a further indication that flow is approximately perpendicular to the lines.

Table 29 shows outcrop lengths, mean intensities of only those fracture sets approximately perpendicular to outcrops in the Rock Lick Creek basin, and approximate maximum annual ground-water discharge from bedrock. Discharge was computed from the equation above. All bedrock above the lower part of the Farmers Member is considered to be saturated. Discharge from the Nancy Member and upper part of the Farmers Member is about 70 percent of the total discharge in the ground-water system, based on the flow model discussed previously. Total discharge from all rocks (table 29) includes the remaining 30 percent from underlying stata.

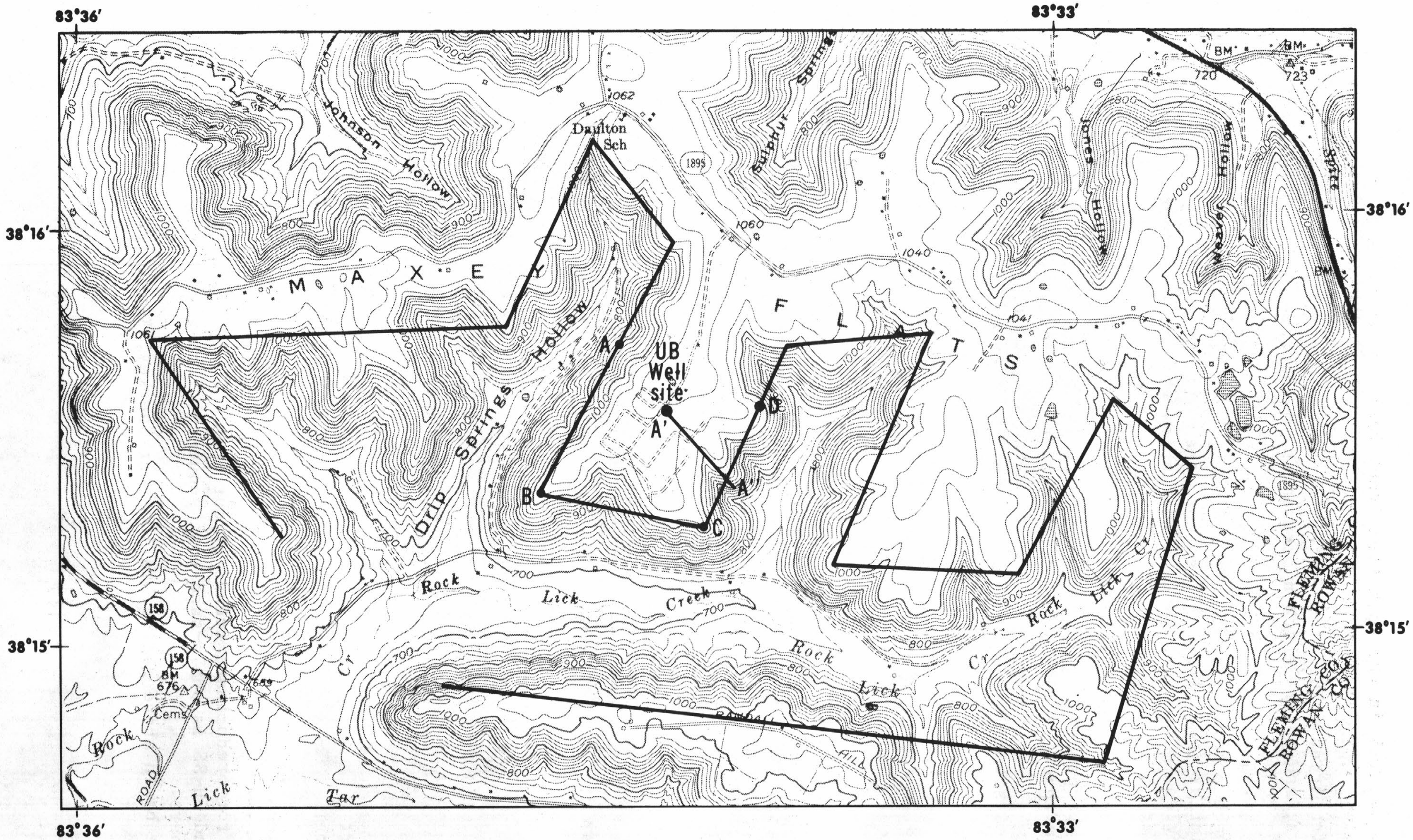
TABLE 29.--Approximate maximum annual discharge from bedrock at the Rock Lick Creek drainage basin, and at the Maxey Flats site

[F_I - fracture intensity, O_L - outcrop length, B - saturated thickness, and Q - ground-water discharge per unit drainage area. Method of computing Q explained in text.]

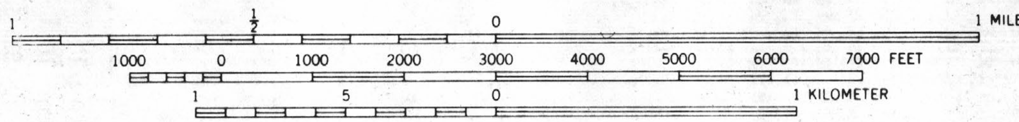
Rock unit[1]	F_I (ft^{-1})	O_L for drainage basin[2] (ft)	O_L for burial site (ft)	B (ft)	Q for drainage basin[2] (in./yr)	Q for burial site (in./yr)
WNW-trending UN	0.06	30,000	2,700	15	0.0015	0.00013
NNE-trending UN	.16	21,300	4,500	15	.0028	.00058
WNW-trending SH-SS	1.74	30,000	2,700	20	.056	.0051
NNE-trending SH-SS	.75	21,300	4,500	20	.018	.0036
Total Q from rocks above the lower part of the Farmers Member					.08	.009
Total Q from all rocks					.1	.01

[1]Directions are for predominant trends of outcrops. UN is unweathered part of Nancy Member, and SH-SS is shale-sandstone sequence at base of Nancy and top of Farmers Members.

[2]All of drainage basin above gaging station near Sharkey, Kentucky.



Base from U.S. Geological Survey Plummers Landing 1:24000, 1951, revisions as of 1979 and Farmers 1:24000, 1970.



CONTOUR INTERVAL 20 FEET

National Geodetic Vertical Datum of 1929

Figure 35.-- Approximate linearized outcrop length of the Nancy and Farmers Members of the Borden Formation in the Rock Lick Creek drainage basin. Points A, B, C, and D delineate area from which trench water could discharge from the Maxey Flats site. A' A" is line of section.

The approximate upper limit of dishcarge from bedrock in the Rock Lick Creek basin above the Sharkey gaging station is 0.1 in./yr (table 29). Mean annual base flow for the years 1974 through 1978 is 240 ft^3/s-d (table 6), which is equivalent to 2.2 in./yr. Maximum annual discharge from bedrock in the drainage basin is therefore about 5 percent of the total annual ground-water discharge. Discharge from bedrock underlying the trench area (normalized to drainage area in the 4.01 mi^2 drainage basin) is 0.01 in./yr, which is about 0.5 percent of the total annual ground-water discharge in the basin. The small percentages indicate that most ground-water discharge is from near-surface sources in the colluvium and alluvium, rather than from bedrock.

Total discharge from all rocks would be about twice that shown in table 29, if Q were computed for saturated rocks underlying the Farmers Member by the equation above, rather than by using the 30 percent value from the flow model. Water-quality data indicate that the most active part of the flow system is in the upper rocks, however. Fracture openings may be less than 0.01 ft in the deeper rocks, resulting in less discharge. The 30 percent value obtained from the flow model is therefore used.

The maximum ground-water discharge from the upper rocks in the Rock Lick Creek drainage basin may also be approximated by using aquifer-test data, and assuming that: all bedrock above the lower part of the Farmers Member is saturated and has equal hydraulic conductivity; and the head distribution in the shale-sandstone sequence at the base of the Nancy and top of the Farmers Members, as shown in figure 33, is also present in the upper part of the Nancy Member. From table 21, the mean hydraulic conductivity (K) from all tests in these two rock units is 0.004 ft/d. Horizontal hydraulic gradient (I) is 0.02 ft/ft between the left and right flow boundaries in figure 33. Saturated thickness is 35 ft and total outcrop length (sum of line lengths on figure 35) is 51,300 ft, so area of flow (A) is 1.8×10^6 ft^2. Approximate ground-water discharge from upper strata is therefore Q = KIA = 140 ft^3/d, which is equivalent to 0.005 in./yr.

The discharge computed from aquifer test data is considerably lower than the 0.08 in./yr computed from ground-water velocity and fracture intensity data, possibly because: results of aquifer tests represent hydraulic conditions at the well, so are poor approximations of the water-transmitting properties of the rocks as a whole; or the value computed from velocity and fracture intensity data may be greater than actual discharge. Because the potential maximum discharge is of primary interest here, the larger value is used.

The maximum flow from unfractured rocks may be estimated from results of core analyses, by assuming that all flow is horizontal and at maximum possible gradient (which is assumed to be 1 ft/ft). The mean K of cores from the unweathered part of the Nancy Member and Farmers Member (table 19) is 1×10^{-5} ft/d, excluding the anomalously large value of 1.3×10^{-3} ft/d. The large value is probably due to fractures in the sample, which may have been produced by coring or laboratory testing. Total outcrop length in the Rock

Lick Creek drainage basin above the gaging station near Sharkey, Kentucky, is 51,300 ft and saturated thickness in all rocks is about 250 ft, so A is 1.3×10^7 ft^2. The maximum discharge from unfractured rocks in the Rock Lick Creek basin is approximated as Q = KIA = 100 ft^3/d, which is equivalent to an annual discharge per unit drainage area of 0.004 in./yr. This is more than an order of magnitude lower than the approximate maximum discharge from fractured rocks, and is considered to be negligible by comparison.

DILUTION OF WATER FROM BEDROCK

Chloride concentrations in water from bedrock and alluvium are compared, as a test of the conclusion obtained from hydraulic information that 0.1 in./yr is a reasonable approximation of maximum discharge from bedrock in the Rock Lick Creek basin. Data are insufficient to determine the proportion of chloride which originates solely from the colluvium and alluvium, compared to chloride which originates solely from bedrock. For purposes of testing, although the following does not precisely represent actual conditions, assumptions are that: all chloride in alluvial water is from bedrock; lower concentration of chloride in alluvial water, as compared to bedrock water, is due to infiltration of rainfall and runoff; chloride concentration in rainfall and runoff is zero; and water from bedrock is thoroughly dispersed in the alluvium. Chloride is used for comparison because it is not readily sorbed, exchanged, or precipitated.

Chloride concentrations in all samples taken from alluvium (table 8) have a mean of 4.0 mg/L. Groups of bedrock units above the Ohio Shale, and mean chloride concentrations in these groups (computed from data in table 23), are: lower part of the Nancy Member and upper part of the Farmers Member - 62 mg/L; and lower part of the Farmers Member, Henley Bed of the Farmers Member, Sunbury Shale, and Bedford Shale - 110 mg/L.

The mean chloride concentrations in water from wells open to the Ohio Shale are 2,600 mg/L in 5E, and 12,000 mg/L in UA4 (table 23). Computing a mean for both wells is not reasonable because of their large difference. A greater percentage of discharge from the Ohio Shale would be indicated if the smaller mean were used because dilution of bedrock water would be less (since the dilution is assumed to be from rainfall and runoff that infiltrated the alluvium, and chloride in the rainfall and runoff is assumed to be zero). The lower value is used for the test because maximum ground-water discharge is of interest.

The Maxey Flats flow model indicates that 70 percent of ground-water discharge is from rocks above the lower part of the Farmers Member, 20 percent is from rocks between the upper part of the Farmers Member and the Ohio Shale, and 10 percent is from the Ohio Shale. The composite chloride concentration is therefore about (0.7)(62 mg/L) + (0.2)(110 mg/L) + (0.1)(2600 mg/L) = 300 mg/L. The 0.1-in./yr estimated maximum discharge from bedrock (table 29) is 5 percent of the total ground-water discharge in the Rock Lick Creek drainage basin, based on a mean annual base flow of 2.2 in./yr. The predicted concentration in the alluvium is therefore (0.05)(300 mg/L) = 20 mg/L, which is greater than the 4.0 mg/L mean computed from data in table 8. Water from the Ohio Shale strongly influences the results. If it were only 1 percent of total bedrock discharge, and that from the upper rocks were 79 percent instead of 70 percent, the predicted concentration in the alluvium would be 5 mg/L. This is also greater than the observed mean, however.

The 0.1-in./yr discharge from bedrock, which is estimated from fracture-intensity and ground-water velocity data, is evidently greater than that actually present because: predicted chloride concentrations in alluvial water are too large; and some, possibly most, chloride in alluvial water actually originates from the colluvium and alluvium. Because an upper limit is of interest, however, 0.1 in./yr is assumed to be the potential maximum discharge from bedrock in the Rock Lick Creek basin, and 0.01 in./yr is assumed to be the maximum discharge from rocks underlying the trench area.

Ground-water discharge is mixed with overland runoff. Dilution of the discharge from bedrock is considerable, when considered over extended periods, because the discharge from bedrock is much less than the streamflow. Dilution of discharge from rocks underlying the burial area is of interest because this dishcarge could contain trench water. Discharge from rocks underlying the burial area is diluted more than that from rocks in the entire Rock Lick Creek drainage basin, as considered for water at the gaging station, because the more limited extent of the burial area results in less ground-water discharge than that produced in the entire drainage basin. Daily streamflow is occasionally very small (hundredths of a cubic feet per second) over periods of a few days, and dilution of bedrock water could theoretically be zero during this time. Monthly data are used to compute dilution of water that discharges from bedrock because they are more representative of "average" streamflow.

The dilution factor DF is defined as $DF = (D_s - D_b)/D_b$, where D_s is stream discharge and D_b is discharge from bedrock. Excluding the 1.34 ft^3/s-d discharge for January 1977, which was affected by ice, the minimum monthly D_s for water years 1974 through 1978 was 2.67 ft^3/s-d during August 1976 (table 4). The maximum monthly D_s was 891.4 ft^3/s-d during March 1975. The mean for all months was 195.1 ft^3/s-d, as computed from the discharge totals in table 5.

The D_b in the Rock Lick Creek drainage basin above the Sharkey, Kentucky, gaging station is about 0.1 in./yr (table 29). This is equivalent to a monthly flow of 0.9 ft^3/s-d, and is assumed to be constant. Minimum, maximum, and mean DF are therefore about 2, 1,000, and 200 for water from all bedrock in the basin above the gaging station. The D_b from rocks underlying the trench area is about 0.01 in./yr (table 29), which is equivalent to 0.09 ft^3/s-d. The minimum, maximum, and mean DF for ground-water discharge from the burial area are therefore 30, 10,000, and 2,000.

The DF values given above were computed for discharge at the gaging station near Sharkey, Kentucky, because the discharge in the Rock Lick Creek drainage basin is measured only at this location. The DF for the tributaries adjacent to the burial site are probably less than those computed because stream discharge is less in the tributaries than at the gaging station.

Principal-ion, water-quality data were not collected over a sufficent range of discharges to verify the ranges of DF. Radionuclide data are not useful for this purpose because most tritium in stream water may be due to the trench-water evaporator, and other radionuclides in streams may be from the contaminated surface of the burial site. Actual dilution of discharge from bedrock is probably larger than the values given above, however, because the estimated ground-water discharge is probably too large.

WATER BALANCE

A water balance of the Maxey Flats area may be computed by the equation $P = R + ET + \Delta GW$, where P is precipitation, R is runoff, ET is evapotranspiration, and ΔGW is change in ground-water storage. The latter factor probably does not change significantly on an annual basis, and is assumed to be zero. Precipitation and runoff are measured directly, and ET is computed by difference.

Table 30 is a summary of precipitation, runoff, and ET for water years 1974 through 1978. Assuming the annual change in ground-water storage is zero, mean annual ET is 54 percent of mean annual precipitation for these years.

TABLE 30.--Water balance for the Rock Lick Creek drainage basin above the gaging station near Sharkey, Kentucky

[Values in inches]

Water year	Precipitation	Runoff	Evapotranspiration
1974	54.77	24.33	30.44
1975	54.65	30.23	24.42
1976	35.76	15.58	20.18
1977	35.85	8.96	26.89
1978	56.49	29.48	27.01
Mean	47.50	21.72	25.78

HYDROLOGIC CONSIDERATIONS REGARDING RADIONUCLIDE TRANSPORT AT MAXEY FLATS

Potential Transport Routes and Distribution

The trench caps, which are presently composed of clay and crushed shale, will probably continue to transmit water, as indicated by: the relation between rainfall and the rapid, short-term rises in water levels (see figures 5 and 18); and the persistent rises in trench-water levels (shown on figure 18). Assuming the rate of infiltration through the caps continues to exceed flow from trenches to regolith and bedrock, cessation of trench-water pumping will result in infiltrating rainfall filling the trenches, and eventual overflow. Most overflow would probably be transported from the site by overland runoff. Less overflow would probably infiltrate the upper part of the regolith, then flow through the colluvium and alluvium, and eventually discharge to streams bounding the burial site. Probably a lesser amount would flow through the subsurface directly from trenches to the hillsides via the regolith and bedrock.

Given similar hydrologic and geochemical conditions to those that existed in the past, the rate of subsurface radionuclide transport (at least for cobalt-60 and manganese-54) through the lower sandstone marker bed will be about 50 ft/yr, as indicated by data collected near trench 46 (described in the section "Rate of radionuclide movement through the lower sandstone marker bed"). Discharge of radionuclides from the subsurface will probably first appear at the level of the lower sandstone marker bed because: data collected near trench 46 indicate migration is greater horizontally through the bed, rather than vertically into underlying bedrock; and the bed is the base of most trenches (see plate 2).

The apparent absence of radionuclides in rocks underlying the lower sandstone marker bed (other than tritium at well 13E) may be due to: sorption in, and at the base of, the lower sandstone marker bed; or the difficulty of obtaining accurate water-quality data from the underlying fractured rocks. Distribution coefficents (ratios of concentrations of sorbed radionuclides per unit mass of solid to concentrations of dissolved radionuclides per unit volume of water) have not been obtained at the Maxey Flats site, and the chemical changes occurring as water moves from trenches into surrounding rocks have not been measured in detail. Studies are being conducted to determine the chemical changes (Kirby, 1982), but they have not been fully documented at this time.

Because field determinations of distribution coefficients have not been made, possible future transport of radionuclides is discussed using the "worst-case" assumption that the radionuclides will move the same as water particles; that is, by neglecting sorption. Such discussion could prove useful for considering the possible discharge of: tritium; and organically complexed radionuclides which may not be readily sorbed, such as described by Cleveland and Rees (1981) for plutonium in trench water at Maxey Flats. Neglecting sorption, radionuclides would be transported through the subsurface to the hillsides as follows: about 70 percent above the lower part of the Farmers Member (including the regolith); about 20 percent between the lower part of the Farmers Member and top of the Ohio Shale; and the remaining 10 percent between the top and bottom of the Ohio Shale. This distribution is based on a conceptual flow model of the burial site (see fig. 33).

Radionuclides transported through the subsurface would discharge either at the ground surface at outcrops, or to the colluvium. Radionuclides discharged to ground surface would be transported by runoff to nearby streams. Radionuclides discharged to colluvium would later be transported by runoff to streams, or flow into the alluvium, and then be discharged to streams. Most radionuclides would eventually be transported by flow down Rock Lick Creek because discharge is toward the valleys, and very little water moves as underflow through alluvium (see discussion in section "Base flow and underflow"). Dilution would occur in bedrock between trenches and discharge areas, at ground surface on the hillsides, and in colluvium, alluvium, and streams.

The estimated dilution of waste radionuclides discharged from bedrock is about 2,000 to one, as computed for mean monthly discharge at the gaging station on Rock Lick Creek. Actual dilution is probably greater at this location because the ratio is computed using an estimated maximum discharge from bedrock which is probably too large. On the other hand, dilution could be less than 2,000 to one locally in tributary streams adjacent to the site, or during periods of low flow (see discussion in section "Dilution of water from bedrock"). Post-dilution concentrations of radionuclides cannot be accurately determined at this time because source concentrations (representative of those near burial trenches) are not known. Samples could be obtained from discharge areas on hillsides to estimate source concentrations, although they would have undergone some dilution prior to collection. Proposed sampling sites in hillside colluvium are described in the following section.

Present and Proposed Monitoring

Surface Water

The Maxey Flats site is monitored by the Kentucky Department for Human Resources. Present sampling stations are in excellent locations for detecting surface-water transport of radionuclides. Several are in Drip Springs Hollow, both above and below the trench area, and two are in the main drainageway of the burial site. Others are above and below the confluences of the stream in the unnamed valley and Rock Lick Creek, and Rock Lick Creek and Fox Creek. Rock Lick Creek is also sampled at the gaging station near Sharkey, Kentucky. Both surface water and stream sediment are collected at the Highway 158 bridge over Rock Lick Creek (fig. 10). Sampling frequency ranges from about two to four weeks.

Future monitoring could include construction of gaging stations in Drip Springs Hollow and the unnamed valley, near the confluences of these streams with Rock Lick Creek. Radiochemical data collected at these stations could be used to compute the dissolved-radionuclide loads leaving Drip Springs Hollow and the unnamed valley. A dilution factor could be computed for each of the valleys, which presumably would be less than the 2,000 to one ratio estimated in this report for water at the gaging station on Rock Lick Creek.

Although sediment samples are taken from Rock Lick Creek, the sediment load is not measured. A sediment station could be constructed at the gaging station on this stream, so that sediment load, stream discharge, and radiochemical data could be combined to give total radionuclide load discharged from the basin, as both dissolved and particulate fractions.

Ground Water

All E-wells are used by the Kentucky Department for Human Resources for monitoring water in bedrock. Water in alluvium is sampled at all sites shown on figure 10, at the lower part of the small valley south of the burial area, and about 0.2 mi downstream from the gaging station on Rock Lick Creek. Water in colluvium on hillsides is not sampled.

Presumably, radionuclide transport would first be detected at sampling points in regolith or bedrock. Wells in the trench area should therefore continue to be sampled. However, the data obtained by sampling vertical wells at Maxey Flats will probably be of limited use in determining concentrations representative of those in water from various strata, particularly if the data are considered to be representative for a broad area of the burial site. Reasons for the limited value of the well data follow.

Most E-wells probably contain a mixture of water from different strata because most are open to several strata. An example of the mixing is shown by varying tritium concentrations in well 11E (see section "Tritium in recharge and in water from wells"). Wells open to narrow intervals are also of limited value, as shown by both radiochemical and head data. Gross alpha and gross beta concentrations increased more than two orders of magnitude in well UB1, apparently because better hydraulic connection with water from trenches was established when at least one fracture was intercepted after reaming the original diameter of the borehole from 6 to 12 in. (see section "Other radionuclides in ground water"). The radiochemical data from well UB1 show the marked heterogeneity within the strata at Maxey Flats, and illustrate the difficulty of monitoring water quality in fractured rocks. Head data from wells UA1, UA2, UB3, and UB4 show that sufficient water for sampling may not enter a well for periods of months to years after completion in saturated rocks (see section "Water levels").

Horizontal wells would probably yield samples more representative of water quality in rocks at Maxey Flats, as compared to vertical wells, because more fractures would be encountered horizontally than vertically. The disadvantages of such wells primarily relate to cost, as follow. Heavy equipment would be required for construction, which would be difficult to place and operate on the steep, densely forested hillsides around the burial site. A large number would have to be constructed, so that various hydrologic units would be sampled down the hillside, and so that the wells would be distributed laterally around the hillside. Also, a cluster of several wells might have to be constructed in the same strata so that different intervals would be open to the wells. Regarding the last point, there is uncertainty about how many fractures would have to be intercepted for the well to yield "representative" samples.

Because of the expense and difficulty in monitoring water quality in bedrock, a reasonable alternative is to sample water in the colluvium on the hillsides. Hand tools or light power equipment could be used to alleviate the problem of positioning heavy equipment on the steep slopes. Samples from wells completed in colluvium would have undergone some dilution by direct infiltration of rainfall, would constitute a mixture of discharge at the point of collection with discharge from higher rocks, and could be influenced by discharge from fractures in bedrock immediately underlying the wells. Also, radionuclide transport from trenches would probably be detected at a later time in colluvium than in bedrock. However, the colluvium would generally constitute a more homogeneous flow system than the bedrock, samples would probably be representative for determining water quality integrated from many fractures, and data would be obtained from areas very near the burial trenches which are not restricted to approach by the public.

Saturation of colluvium and shallow bedrock on hillsides was not verified during this study, but was indicated by (a) head data from wells on the hilltop, (b) the likelihood that the low hydraulic conductivity of the bedrock would cause rainfall infiltrating the shallow materials on the hillsides to saturate the more permeable colluvium, and (c) the fact that much of the hillsides are areas of discharge for water flowing from bedrock. Only a few wells should be completed on the hillsides initially, to determine the extent and duration of saturation.

Assuming extensive saturation of colluvium, wells should be located so that they are: around the burial area, thereby giving areal distribution; and down the hillside, so that discharge from various bedrock strata is sampled. Most should be located above the lower part of the Farmers Member because most bedrock discharge is from rocks overlying this stratum. Several wells should be located at the lower sandstone marker bed because this is the most likely bed from which radionuclides would first discharge. Additional wells could be constructed at the break in slope between hillsides and valley bottoms, where numerous seeps from colluvium can be observed during dry periods.

Several wells could be completed in the shallow weathered bedrock directly underlying the colluvium. Although shallow weathered bedrock is less homogeneous than the colluvium, the weathered bedrock would likely be more homogeneous than the unweathered bedrock. This is because fracturing is probably greater in the shallow materials, due to weathering processes and to stress relief. The wells could be constructed with hand tools or light power equipment, and should be located within a few feet of wells completed in colluvium so that water-quality differences (if present) between the colluvium and weathered rock may be noted.

Wells should be constructed in alluvium, to provide data on water quality in valley deposits. The data would be in addition to that obtained at existing sampling sites, but unlike all but two present sampling sites, the new wells should be located on the burial-site side of the streams. Such locations would provide data where water in alluvium is most influenced by subsurface transport of waste radionuclides. Several such wells completed in alluvium should be constructed in each of the valleys adjacent to the burial site.

Considerations Regarding Long-term Stability of the Burial Site

Erosion rates and possible erosion-preventative measures have not been described in any study conducted at Maxey Flats. They are important factors regarding long-term stability of the burial site, due to the close proximity of the trenches to the hillsides (see figure 2 and plate 1). The rates are probably large because of the 44.30-in. normal annual rainfall in the area, the type of material comprising the hill, and the steepness of the 300-foot-high hillsides.

Large erosion rates are apparent at road cuts and outcrops. Frequent maintenance is necessary to prevent highway ditches from filling with eroded materials. The shales tend to fragment quickly when exposed to the surface, apparently due to wetting and drying, and to stress relief. This is most apparent in the Nancy Member, Henley bed of the Farmers Member, and Bedford Shale. The more erosion-resistant sandstone beds first form overhanging ledges, then later break and fall as large slabs when undercut by erosion of the underlying shales. Numerous slabs from the Farmers Member can be seen on undisturbed hillsides due to this relatively rapid undercutting process. A study of slope retreat and denudation rates at Maxey Flats is essential for long-term site management.

Various methods are being considered by Kentucky agencies to reduce or eliminate infiltration into trenches, including covering trenches with cement, tile, roof structure, or dense vegetation. While description of the methods is beyond the scope of this report, changes in direction of recharge and increased erosion should be considered when such methods are employed.

Loss of virtually all recharge from the top of the hill could promote recharge to trenches from the side of the hill and increase southward ground-water flow from the area north of the burial area. Lateral recharge to trenches was not considered significant in this report because hillsides are likely to be predominantly discharge areas under present hydrologic conditions. If virtually all recharge to the trenches were to be eliminated, a barrier to such lateral flow would be necessary. A drainage ditch would probably be necessary to form such a barrier, with the ditch at the perimeter of the trench area (including the north side) and excavated to the top of the Farmers Member. The ditch should be sloped to a discharge point, filled with very permeable material, and covered with material of hydraulic conductivity at least as small as the cover over the trenches.

A cover of low hydraulic conductivity over the burial trenches will produce runoff events of greater magnitude than now occur, which will accelerate erosion of the hillsides around the trench area unless preventative measures are taken. The sediment station proposed at the beginning of this section could be used to monitor erosion rates in the Rock Lick Creek drainage basin. Additional sediment stations in the tributary valleys could be used to monitor erosion from the burial site.

SUMMARY AND CONCLUSIONS

About 4.8 million cubic feet of radioactive waste were buried at Maxey Flats until the commercial burial site was closed in 1977. The mean concentration of radioactivity in most waste was about 2 Ci/ft^3 at the time of burial, although concentrations vary considerably from trench to trench. The site is presently being decommissioned by a private firm under a contract with the State of Kentucky.

The climate of the area is humid, with normal annual precipitation at nearby Farmers, Kentucky, 44.30 in. for the period 1941 through 1970. Mean annual evapotranspiration was about 25.8 in./yr at Maxey Flats from 1974 through 1978, which was about 54 percent of the mean annual precipitation.

The burial site is located atop one of many "flat-topped" hills in the area, about 300 to 400 ft above the valley bottoms. Valleys adjacent to the burial site are: an unnamed valley to the east, the valley formed by Rock Lick Creek to the south, and Drip Springs Hollow to the west. Drainage is by Rock Lick Creek to Fox Creek, then to the Licking and Ohio Rivers.

The hillsides at Maxey Flats are covered with colluvium, which grades into alluvium in valley bottoms. The burial site is underlain by several sedimentary rock formations with very poor water-transmitting properties. They are, in descending order: the Borden Formation, consisting of the lower part of the Nancy Member, the Farmers Member, and the Henley Bed of the Farmers Member; the Sunbury, Bedford, and Ohio Shales; and the upper part of the Crab Orchard Formation. Most of the rocks are shale, except for the predominantly sandstone Farmers Member. At least eight hydrologic units are present in the strata. The most permeable rocks are thin fractured sandstones interlayered with thin shale beds, which are located at the base of the Nancy Member and top of the Farmers Member at depths of about 45 to 70 ft below ground level.

Virtually all ground-water flow in bedrock is through fractures, and the amount of fracturing is different in different stata. Greatest fracture intensity (sum of the inverse of mean fracture spacing for each fracture set) is 2.37/ft in the thin sandstone beds. Lowest is 0.06/ft in massive shales. Fractures commonly terminate at bedding planes, or have different orientation in overlying and underlying beds. Hydraulic conductivity is therefore probably greater horizontally than vertically.

Most trenches are excavated in weathered shale (regolith) of the Nancy Member, and their bases consist of a 1.5-ft-thick fractured sandstone bed (lower sandstone marker bed) at a depth of about 25 ft below ground level. Several types of radionuclides were encountered in this bed when wells were drilled in the central part of the trench area. Cobalt-60 and manganese-54 have been detected in the lower sandstone marker bed as much as 270 ft from the nearest burial trench. Estimated ground-water velocity in the horizontal direction is 50 ft/yr, based on the rate of travel of the radionuclide front at one location.

Regolith forms the sides of most trenches, and covers the top of the hill. The regolith grades laterally into colluvium. Trenches are covered with compacted shale and clay, but water infiltrates the caps and accumulates in the trench bottoms. The water is removed and disposed of by evaporation. About six million gallons of trench water and contaminated surface water were evaporated from 1973 through 1979.

Tritium is the predominant radionuclide in trench water, and ranged from 2.5×10^5 to 7.4×10^9 pCi/L for 46 samples from 33 trenches. Trench water also contained dissolved strontium-90, plutonium, americium-241, cobalt-60, cesium-134, cesium-137, and numerous organic-waste compounds.

Water levels vary considerably amoung trenches. Infiltration through trench caps is probably the principal control of the levels, as indicated by: their rapid responses to rainfall, with as much as 75 percent of the magnitude of the rises corresponding to rainfall events; and continuous water-level rises in most trenches.

The rate of infiltration into trenches is between 45,000 and 470,000 ft^3/yr, based on seepage rates computed for five trenches. The values are approximate, however, because: the number of trenches analyzed is small compared to the 47 trenches on the burial site; and rate of infiltration is probably related to the rate of precipitation, and may differ from that which occurred during the period of analysis.

Thirty wells have been completed on the burial site since 1963. Most were constructed for obtaining lithologic and general water-quality data, and are not suitable for obtaining other, more specific, hydrologic information. Nine wells were drilled during the present study, so that both head data and water-quality data could be obtained from individual hydrologic units. Limited information was obtained from these wells also because the ground-water system is in poorly permeable and fractured rocks.

Head data from wells indicate several possible saturated-unsaturated sequences in the rocks underlying the burial site. The upper water table is in the regolith, a few feet above the lower sandstone marker bed. Another water table is probably in the lower part of the Ohio Shale. The upper part of the Sunbury Shale may be unsaturated. Other local unsaturated zones may be in the unweathered part of the Nancy Member and upper part of the Farmers Member. The probable reasons for the presence of several unsaturated zones are (a) large anisotropies are produced by fracture termination or nonalignment at bedding planes, which causes both "perching" of water in the strata and lateral flow to discharge areas at hillsides, and (b) greater hydraulic conductivity of an underlying stratum may result in a discharge rate which is greater than the rate at which water is being suppied by a less permeable overlying stratum, resulting in dewatering of the upper part of the more-permeable stratum.

Ground water entering the top of the hill flows vertically through the unsaturated zones, and has both vertical and horizontal components in the saturated rocks. The predominant direction of flow through the lower sandstone marker bed is not known. Flow in other rocks is considered to be predominantly: vertical in the unweathered part of the Nancy Member, Henley Bed of the Farmers Member, and Bedford Shale; and lateral through the upper part of the Farmers Member, Sunbury Shale, and Ohio Shale. The lateral component of flow is probably away from topographically high areas, toward the adjacent valleys.

A conceptual-flow model of the burial site indicates that about 70 percent of discharge from bedrock is from rocks above the lower part of the Farmers Member, about 20 percent is from rocks between the upper part of the Farmers Member and Ohio Shale, and about 10 percent is from the Ohio Shale. All water from bedrock eventually discharges to the colluvium or ground surface on the hillsides. That which is not evaporated or transpired then flows through the valley alluvium and, eventually, into Rock Lick Creek.

Mean annual stream discharge in Rock Lick Creek above the gaging station near Sharkey, Kentucky, is 2,342 ft^3/s-d, and the mean annual base-flow component is about 240 ft^3/s-d, for the period 1974 through 1978. The potential maximum percentage of annual base flow that is due to discharge from all bedrock in the drainage basin is estimated as 5 percent, and that from rocks underlying the trench area is estimated as 0.5 percent. The remaining 95 percent of base flow is from colluvium and alluvium.

Concentrations of principal ions in base flow and in water from alluvium are similar. Water from both sources contain concentrations of dissolved solids about an order of magnitude lower than that in bedrock, and indicate that most base flow is from near-surface sources. Radiochemical quality of stream water and alluvial water are different, however. The only waste radionuclide found in alluvial water that resulted from site operation was tritium (Montgomery and others, 1977). Stream water contained both tritium and dissolved strontium-90 at a location a few hundred feet from the burial site. Other waste radionuclides in streambed sediments were found as far as 1.5 mi from the burial site.

Waste radionuclides in stream water may have moved from the burial site by way of base flow, or by way of overland runoff carrying contaminated soil from the surface of the burial site. Overland runoff is the most likely means of transport because: one radionclide found in streambed sediment had a half-life of only 35 days, indicating less travel time than would be expected in ground water; and discharge from bedrock is a very small part of total ground-water discharge, as indicated by water-chemistry data and the ratio of discharge from bedrock underlying the trench area to mean annual base flow (0.005).

Water quality shows poor relationship to rock type, but is apparently related to depth and degree of fracturing. Sodium and chloride are the predominant ions in water from the Ohio Shale, whereas calcium, magnesium, bicarbonate, and sulfate are predominant in upper rocks. Water from wells with lower rates of water accumulation generally have greater concentrations of dissolved solids. This is probably because the low rates indicate poor fracture connection and greater contact of water with rocks, resulting in greater solution of rock minerals. Chloride concentration in the Ohio Shale is on the order of thousands of milligrams per liter and is more than an order of magnitude greater than in upper rocks, indicating that the most active part of the flow system is above this formation.

Overland runoff considerably dilutes discharge from bedrock. Based on mean monthly stream discharge, the dilution factor for water from all bedrock in the Rock Lick Creek drainage basin is about 200, and that for water from rocks underlying the trench area is about 2,000. Listed below are monthly streamflow and monthly ground-water discharge (in cubic feet per second - days), from which the dilution factors were computed. The values were computed for the entire drainage area above the gaging station near Sharkey, Kentucky, except for discharge from bedrock only underlying the burial area.

Stream discharge	Base flow from bedrock and alluvium	Discharge from all bedrock in drainage basin	Discharge from bedrock only underlying burial area
195.1	20	0.9	0.09

Caps presently covering trenches will probably continue to transmit water. Overflow will result if trench-water pumping ceases. Most radionuclides in the overflow would be transported by runoff to nearby streams. Dissolved radionuclides transported through the subsurface would first flow from regolith and bedrock to the colluvium and alluvium and later be discharged to nearby streams.

Future monitoring at Maxey Flats could include: (a) construction of additional stream gaging stations, so that dissolved-radionuclide loads and dilution factors could be determined for tributary drainageways to Rock Lick Creek; (b) construction of at least one sediment station, so that particulate radionuclide load could be determined; (c) completion of wells on hillsides, so that radionuclide concentration in discharge from regolith and bedrock could be determined, and (d) construction of additional wells, so that radionuclide concentrations in alluvium on the burial-site sides of streams could be determined.

Considerations regarding long-term stability of the burial site should include: present erosion rates on the steep, predominantly shale hillsides adjacent to burial trenches; and future increases in erosion rates, which could result from planned covering of the trench area with poorly permeable material.

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APPENDIX 1.--Monthly base flow for the Sharkey, Kentucky, gaging station on Rock Lick Creek

[Values in cubic feet per second - days]

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Total
1974	0.9	3.9	4.0	40.2	40.3	57.8	48.8	21.8	17.2	18.0	11.3	14.6	280
1975	10.1	19.6	48.3	59.4	33.7	53.2	51.0	37.3	9.6	3.4	2.4	3.8	330
1976	32.9	27.3	47.8	46.8	29.6	50.1	27.7	14.5	12.5	8.2	1.4	0.3	300
1977	7.1	4.9	2.9	1.2	2.8	24.6	25.8	18.1	5.5	2.0	1.1	.6	97
1978	24.9	21.9	35.3	20.8	17.6	15.6	4.5	13.4	7.5	7.3	25.5	9.4	200

APPENDIX 2.--Altitudes and depths of wells 1 through 8

[Values in feet. Altitudes referenced to National Geodetic Vertical Datum of 1929. Dash means value unknown.]

Well	Altitude of top of casing	Approximate altitude[1] of ground level in 1963	Altitude of ground level in 1979	Depth[2] in 1963	Depth[3] in 1979
1	[4]1,054.85	1,049	1,052.7	42	32.5
2	1,054.04	-	1,050.4	42.5	30.3
3	1,055.03	1,050	1,054.2	49	37.3
4	1,064.31	1,052	1,060.8	45.5	32.5
5	1,051.81	1,053	1,051.6	39	28.0
6	1,054.60	1,052	1,053.0	42	32.8
7	1,058.66	1,054	1,055.8	44	37.3
8	1,053.72	1,051	1,052.1	41	29.8

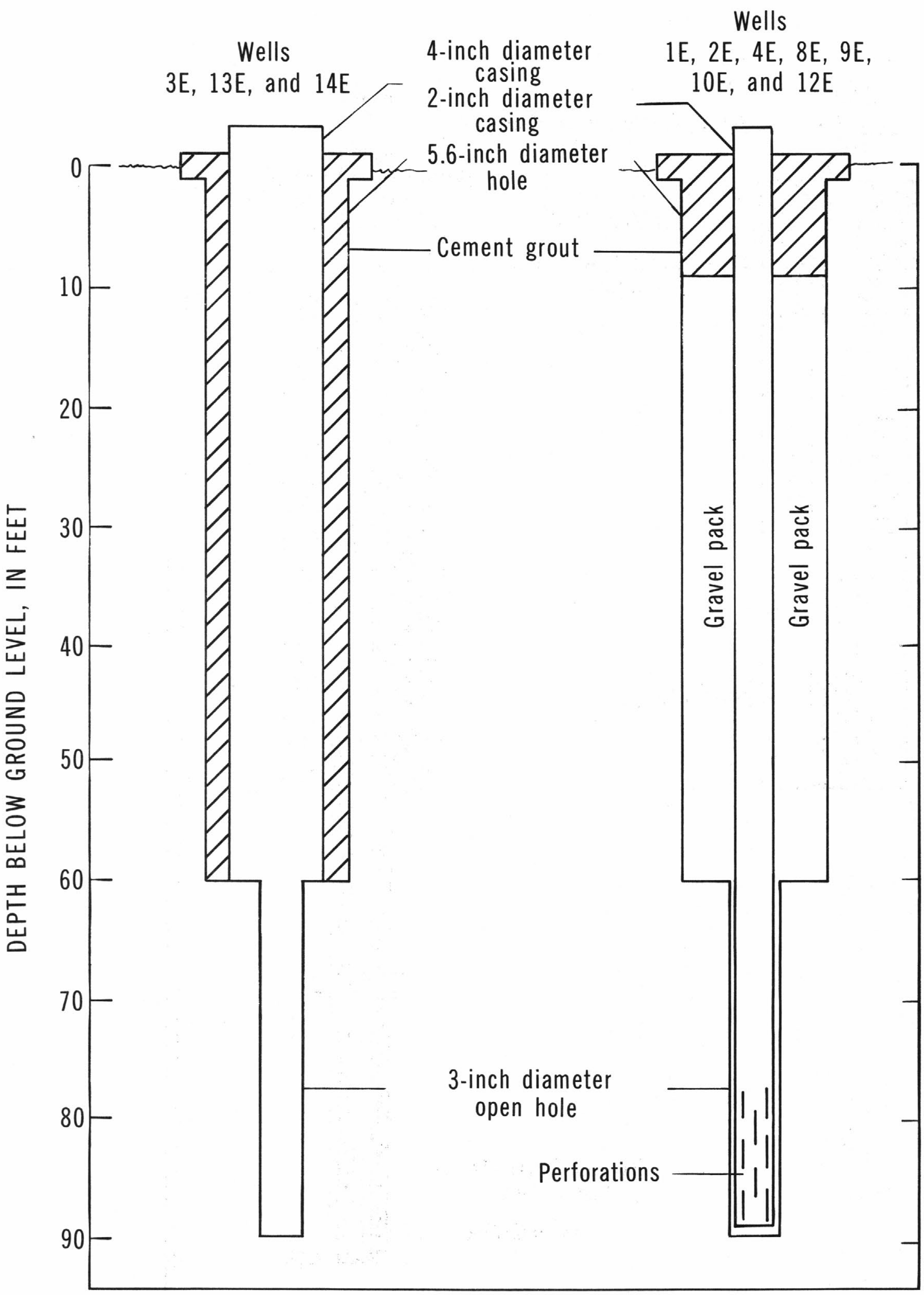
[1]Method for approximating ground-level altitude explained in text.
[2]Referenced to 1963 ground level, and taken from Walker, 1962.
[3]Referenced to tops of casings.
[4]Casing extended from 1050.65 to 1054.85 between 1975 and 1979.

APPENDIX 3.--Altitudes and depths of UA, UB, and E wells

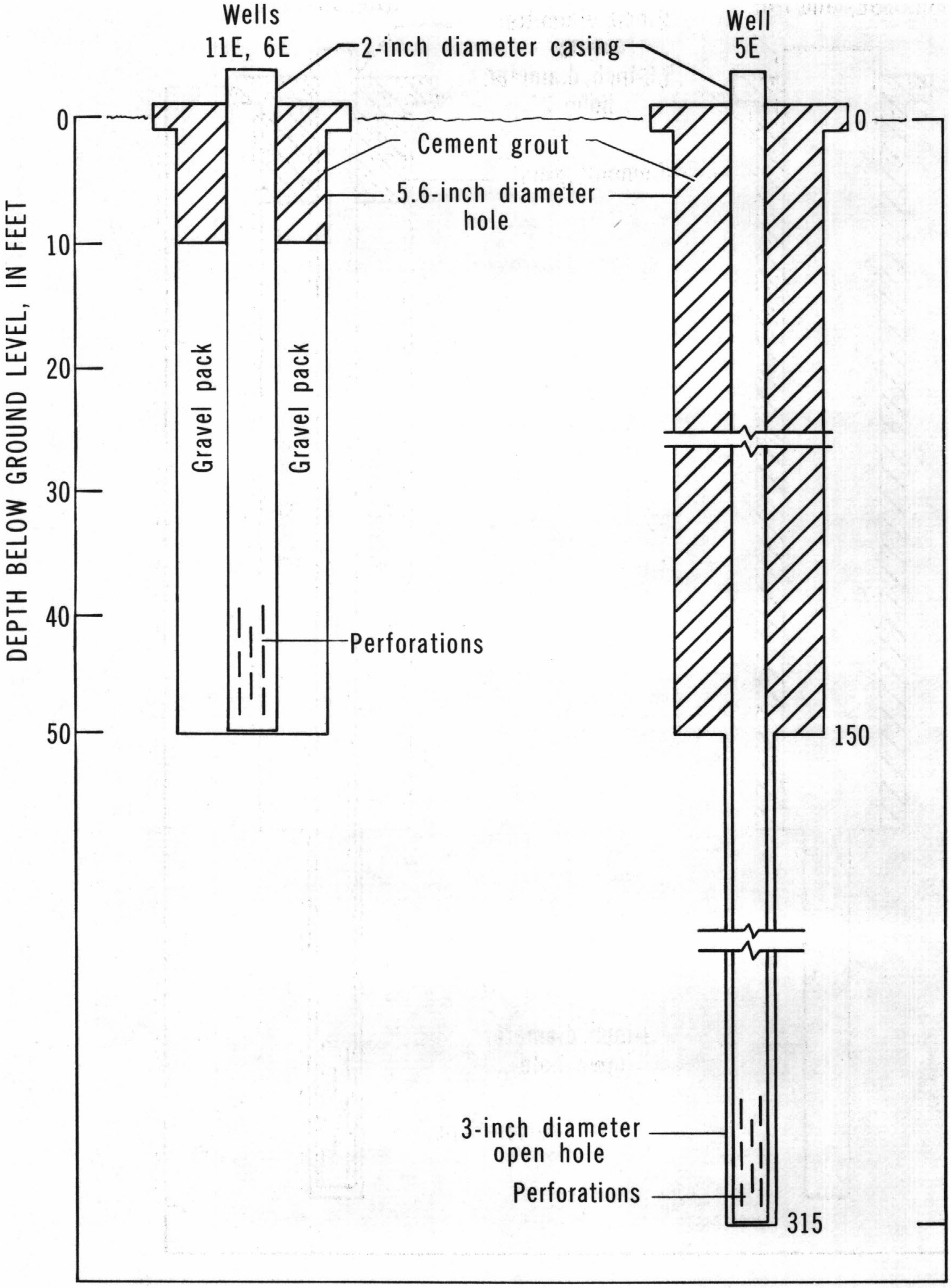
[Values in feet. Altitudes referenced to National Geodetic Vertical Datum of 1929. No well 7E.]

Well	Altitude of top of casing	Altitude of ground level	Depth[1]
UA1	1,039.43	1,038.3	[2]86.1
UA2	1,041.40	1,040.0	[3]140.7
UA3	1,039.15	1,038.2	54.4
UA4	1,036.79	1,036.2	323
UB1	1,060.49	1,059.3	69.4
UB1-A	1,060.44	1,059.1	27.8
UB2	1,059.76	1,059.5	328
UB3	1,060.49	1,059.1	91.4
UB4	1,061.34	1,060.1	[4]131.7
1E	1,042.37	1,040.8	88.4
2E	1,031.70	1,029.8	90.9
3E	1,021.67	1,021.6	85.6
4E	1,034.80	1,034.5	87.7
5E	1,028.55	1,027.7	310
6E	1,046.68	1,045.6	50.0
8E	1,045.58	1,044.4	91.0
9E	1,040.06	1,038.7	91.3
10E	1,052.03	1,050.2	92.3
11E	1,055.19	1,053.3	51.2
12E	1,050.07	1,048.7	91.7
13E	1,053.34	1,052.9	85.2
14E	1,054.59	1,054.4	75.0

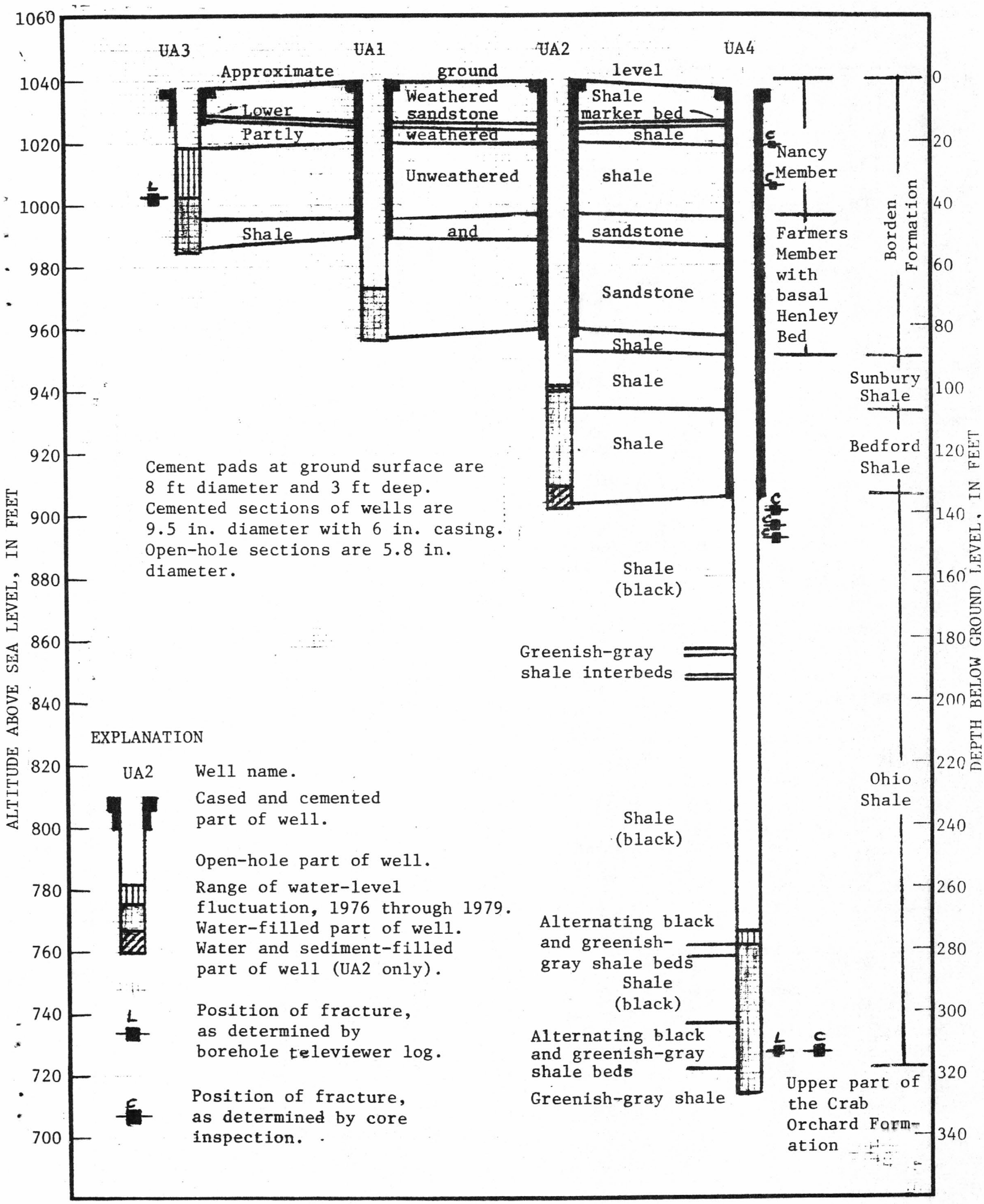
[1]Referenced to tops of casings.
[2]Original depth of hole. Debris from explosive shape charges now fill bottom 6 ft of well.
[3]Original depth of hole. Debris from explosive shape charges now fill bottom 7.8 ft of well.
[4]Original depth was 139.0 ft before bottom of well cemented.



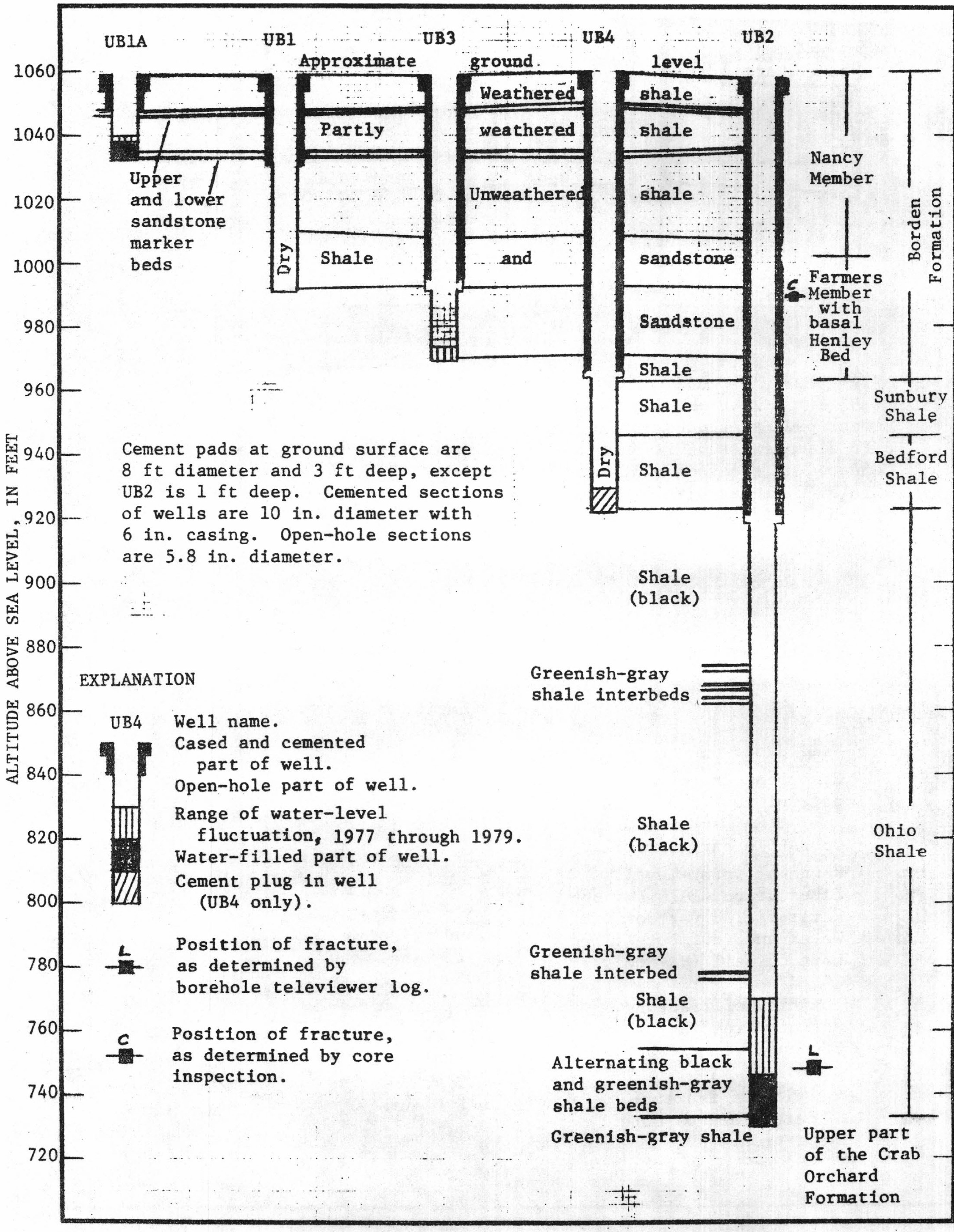
Appendix 4.-- Diagram of proposed construction for most E wells.



Appendix 5.-- Diagram of proposed construction for wells 5E, 6E and 11E.



Appendix 6.-- Construction diagram of UA wells.



Appendix 7.-- Construction diagram of UB wells.

APPENDIX 8.--Altitudes and depths of riser pipes in trenches 1 through 23

[Values in feet. Altitudes referenced to National Geodetic Vertical Datum of 1929. Dash means no measurement made.]

Pipe number[1]	Altitude of top of pipe	Altitude of ground at pipe	Altitude of bottom of pipe	Depth of pipe[2]
1	1,055.67	1,053.4	1,036.5	19.2
1S	1,057.59	1,054.5	1,041.8	15.8
2	1,052.62	1,049.9	1,036.8	15.8
3 -A	1,058.09	1,055.6	1,030.7	27.4
3 -B	1,058.05	1,055.8	1,035.1	23.0
4L	1,052.81	1,050.8	1,041.8	11.0
5S-A	1,052.62	1,051.2	1,037.0	15.6
5S-B	1,053.57	1,051.0	1,034.9	18.7
6L-A	1,051.11	1,050.4	1,044.4	6.7
6L-B	1,052.91	1,050.9	1,043.9	9.0
7 -A	1,052.74	1,051.2	1,037.8	14.9
7 -B	1,057.20	1,054.5	1,037.8	19.4
8L-A	1,050.60	1,049.3	-	-
8L-B	1,051.37	1,049.4	1,032.2	19.2
9L	1,047.40	1,046.3	1,034.8	12.6
10 -A	1,050.07	1,048.4	1,038.7	11.4
10 -B	1,051.73	1,051.2	1,029.1	22.6
11S	1,060.93	1,060.1	1,036.3	24.6
12L	1,047.84	1,047.0	1,039.5	8.3
13L	1,054.20	1,051.0	1,037.5	16.7
14L	1,054.10	1,051.3	1,037.4	16.7
15 -A	1,053.53	1,050.7	1,044.6	8.9
15 -B	1,054.47	1,054.4	1,037.1	17.4
16L	1,052.34	1,049.4	1,036.7	15.6
17L	1,054.01	1,051.6	1,036.2	17.8
18	1,063.97	1,061.7	1,043.4	20.6
19S-A	1,060.43	1,059.2	1,046.3	14.1
19S-B	1,063.49	1,059.1	1,047.5	16.0
20	1,060.36	1,060.3	1,033.1	27.3
21L	-	-	-	-
22	1,056.73	1,053.7	1,046.1	10.6
23	1,061.50	1,060.4	1,033.1	28.4

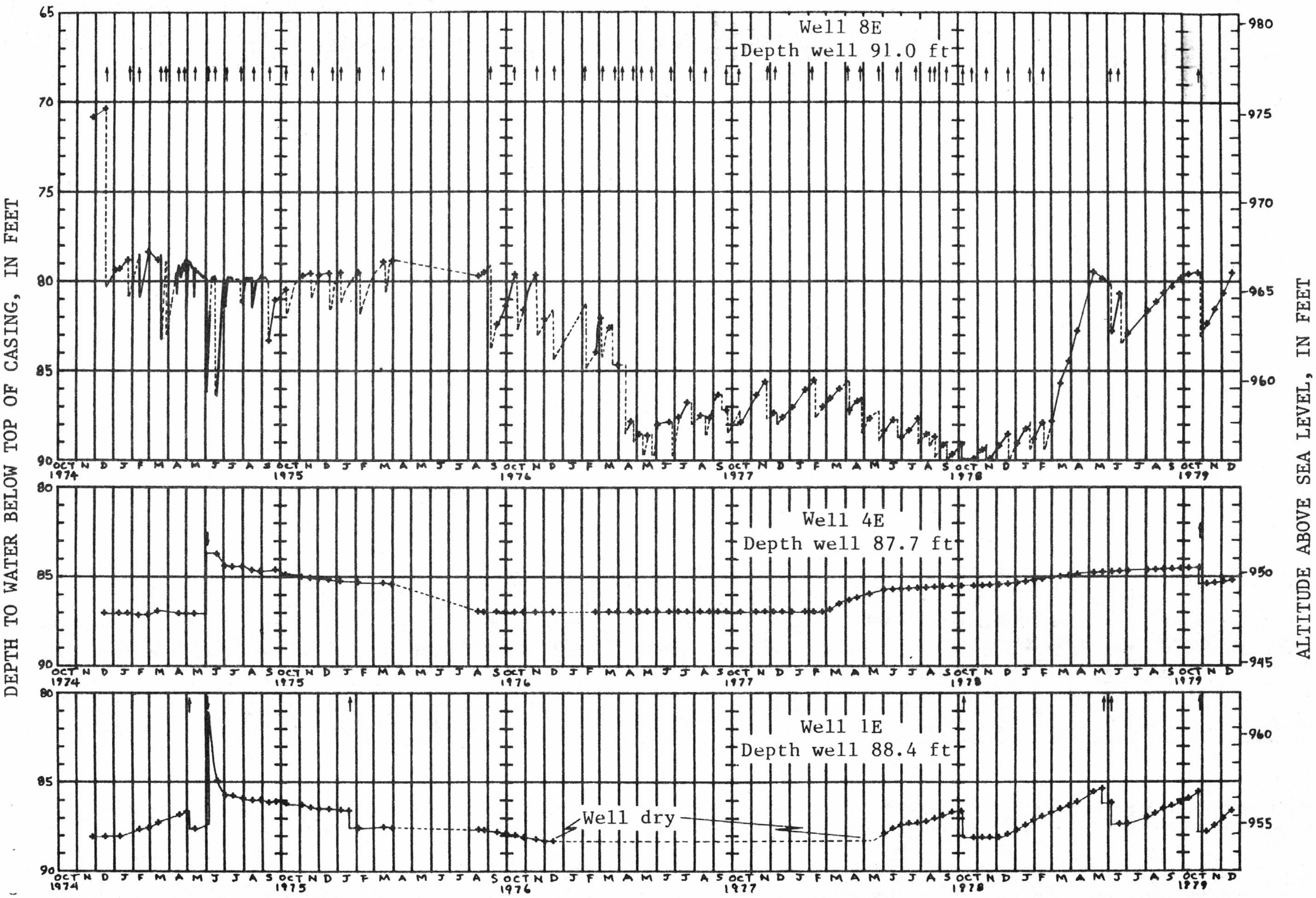
[1]Correspond to trench numbers. If more than one pipe in trench, number followed by dash and letter.
[2]Referenced to top of pipe.

APPENDIX 9.--Altitudes of riser pipes in trenches 24 through 45

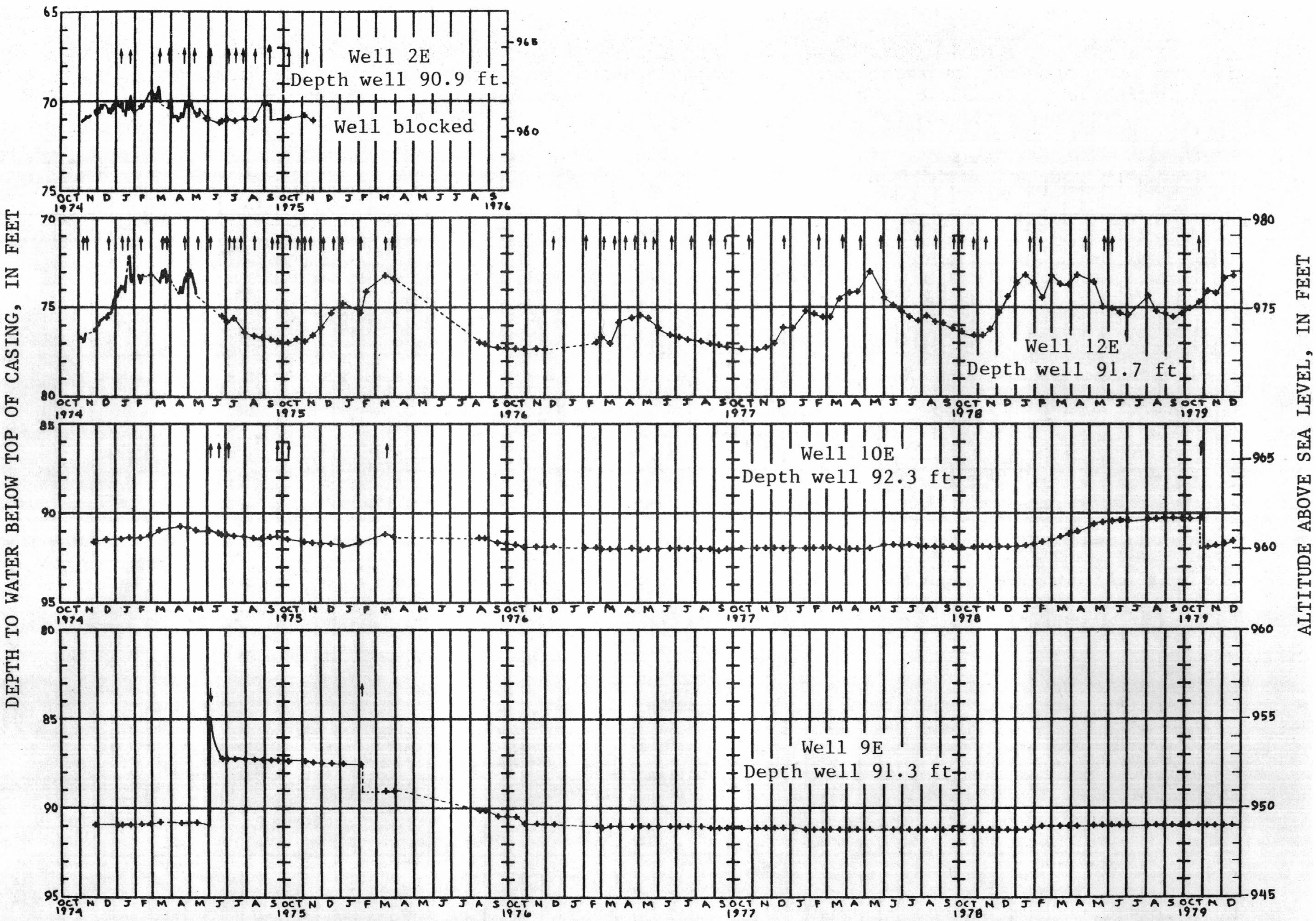
[Values in feet. Altitudes referenced to National Geodetic Vertical Datum of 1929. Dash means no measurement made.]

Pipe number[1]	Altitude of top of pipe	Altitude of ground at pipe	Altitude of bottom of pipe	Depth of pipe[2]
24	1,060.82	1,058.5	1,035.9	24.9
25-A	1,057.13	1,055.3	1,034.0	23.1
25-B	1,058.73	1,055.8	1,034.5	24.2
26	1,053.24	1,051.1	1,030.1	23.1
27	1,059.63	1,058.3	1,034.4	25.2
28-A	1,063.93	1,060.9	1,037.3	26.6
28-B	1,063.95	1,061.4	1,036.3	27.7
29-A	1,062.78	1,060.3	1,034.9	27.9
29-B	1,063.54	1,060.8	1,036.2	27.3
30	1,063.18	1,058.8	1,034.5	28.7
31-A	1,064.23	1,061.8	-	-
31-B	1,060.20	1,058.9	1,038.6	21.6
32	1,062.83	1,060.4	1,033.4	29.4
33L	1,054.62	1,052.4	1,039.8	14.8
35-A	1,059.60	1,058.0	1,034.2	25.4
35-B	1,060.32	1,057.9	1,032.7	27.6
36-A	1,061.81	1,058.9	1,040.2	21.6
36-B	1,060.47	1,059.9	1,041.1	19.4
37	1,053.25	1,051.7	1,028.0	25.3
38	1,052.96	1,052.3	1,035.5	17.5
39	1,054.55	1,053.4	1,034.0	20.6
40-A	1,051.98	1,049.9	1,019.3	32.7
40-B	1,052.52	1,050.4	1,014.5	38.0
41	1,064.28	1,060.1	1,052.7	11.6
42	1,044.36	1,042.1	1,011.2	33.2
43-A	1,035.78	1,032.8	1,004.1	31.7
43-B	1,040.93	1,038.7	1,018.5	22.4
43-C	1,046.83	1,045.0	1,009.6	37.2
44-A	1,040.75	1,037.9	-	-
44-B	1,050.65	1,048.2	1,008.7	42.0
45	1,054.32	1,051.9	1,021.4	32.9

[1]Correspond to trench numbers. If more than one pipe in trench, number followed by dash and letter.
[2]Referenced to top of pipe.



Appendix 10.-- Hydrographs of wells 1E, 4E and 8E. Depth referenced to top of casing. Upward-pointing arrows denote discharges and downward-pointing arrows denote charges. Line represents continuous water-level data, dashed where approximated. Cross represents single measurement.



Appendix 11.-- Hydrographs of wells 2E, 9E, 10E and 12E. Depth referenced to top of casing. Upward-pointing arrows denote discharges and downward-pointing arrows denote charges. Line represents continuous water-level data, dashed where approximated. Cross represents single measurement.

APPENDIX 12.--Principal-ion analyses of water from wells open from the regolith to the upper part of the Sunbury Shale

[NA means not analyzed. Analyses by U.S. Geological Survey laboratory.]

Well	Date[1]	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Bicarbonate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	Silica (mg/L)	Dissolved solids (mg/L)	pH
1E	10/75	48	33	9.6	560	110	29	350	NA	NA	8.5	1,570	NA
1E	6/79	28	62	8.5	470	1,100	26	420	NA	NA	7.9	1,740	7.3
1E	10/79	49	37	9.5	480	1,100	23	390	0.01	0.87	8.2	1,620	7.5
2E	3/75	180	120	7.0	80	540	16	660	.10	.10	16	1,440	NA
4E	10/79	70	58	15	670	150	61	1,700	NA	NA	11	2,810	6.8
8E	3/75	92	60	11	66	610	9.5	99	.00	.00	15	650	NA
8E	10/78	110	71	8.4	85	190	5.8	550	NA	NA	9.2	1,020	NA
8E	2/79	120	74	8.4	69	410	4.3	440	NA	NA	9.2	1,050	6.8
8E	6/79	110	78	8.0	74	550	5.1	370	NA	NA	9.6	976	7.1
8E	10/79	100	67	8.0	73	600	4.4	240	.01	.05	11	681	7.2
10E	10/79	240	140	14	160	220	12	570	NA	NA	19	2,750	6.8
12E	3/75	98	78	11	180	800	13	260	.00	.02	14	1,050	7.0
12E	10/78	100	80	10	230	860	7.8	300	.01	.06	15	1,160	NA
12E	6/79	100	91	9.8	200	880	6.7	330	.02	.21	13	952	7.3
12E	10/79	89	65	10	200	900	6.6	280	.01	.06	14	1,160	7.1

[1]Month/year sample collected.

APPENDIX 13.--Principal-ion analyses of water from wells 1 through 8

[Analyses by U.S. Geological Survey laboratory]

Well[1]	Cal- cium (mg/L)	Magne- sium (mg/L)	Potas- sium (mg/L)	Sod- ium (mg/L)	Iron (mg/L)	Bicar- bonate (mg/L)	Chlo- ride (mg/L)	Sul- fate (mg/L)	Ni- trite (mg/L)	Ni- trate (mg/L)	Silica (mg/L)	Dis- solved solids (mg/L)	pH
1	24	13	9.1	51	6.3	310	19	0.4	0.02	0.00	17	289	7.0
2	47	9.3	4.7	26	66	380	24	0	.00	.01	19	350	6.8
3	5.4	7.0	1.5	39	8.5	110	10	47	.00	.09	23	183	6.4
5	21	17	6.5	47	21	260	19	13	.00	.01	20	305	6.7
6	43	13	8.9	28	8.1	210	9.0	73	.00	.03	17	294	6.8
7	70	36	7.2	120	6.3	330	50	350	.00	.00	17	779	7.0
8	92	71	22	84	5.9	350	31	450	.00	.02	12	950	7.1

[1]Well number 4 not sampled. All wells open from regolith to lower part of Nancy Member and sampled in October 1979.

POCKET CONTAINS
3 ITEMS.