UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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

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Inch-pound	Multiply by	Metric
inch (in)	2.540	centimeter (cm)
foot (ft)	0.3048	meter (m)
foot squared per day (ft^2/day)	0.0929	meter squared per day (m^2/day)
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)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon (gal)	3.785	liter (L)
gallon per minute (gpm)	0.06309	liter per second (L/s)
pound (lb)	0.4536	kilogram (kg)
pound per square inch (lb/in^2)	0.07031	kilogram (force) per square centimeter (kgf/cm^2)

PRELIMINARY HYDROGEOLOGIC INVESTIGATION

OF THE MAXEY FLATS RADIOACTIVE WASTE BURIAL SITE,

FLEMING COUNTY, KENTUCKY

ABSTRACT

Maxey Flats is an isolated plateau in northeastern Kentucky, near the city of Morehead. The radioactive waste burial site is located on the plateau, about 300 to 400 feet above the surrounding valleys. Radioactive waste burial at Maxey Flats began in 1963. Completed trenches at the site are about 20 feet deep, and occupy an area of about 0.03 square miles. As of January 1972, approximately 1.2 million curies of byproduct material, plus 460 pounds of special nuclear material, plus 87 thousand pounds of source material have been buried. Byproduct material is material made radioactive by exposure to radiation. Special nuclear material is plutonium, uranium-233, and enriched uranium-235. Source material is uranium and thorium, not including special nuclear material.

Rocks in the Maxey Flats area are of Mississippian and Late Devonian age including, in descending order, the Nancy and Farmers Members of the Borden Formation, Sunbury, Bedford, and Ohio Shales, and upper part of the Crab Orchard Formation. The total thickness of these rocks is about 320 feet. All radioactive wastes are buried in shale of the Nancy Member.

Mean annual precipitation at nearby Farmers, Ky., is about 46 inches. Infiltrating rainfall is temporarily stored in weathered bedrock on hilltops, and colluvium and soil on hillsides. The water later discharges in springs at the bases of the hills. Base flow in Rock Lick Creek and its tributaries is derived mainly from alluvium in the valleys, and the mantle of regolith, colluvium, and soil on adjacent sides and tops of hills. Little is known about the ground-water hydraulics of the area. If movement of dissolved and water-suspended radioactive materials from the burial site were to occur by natural processes, surface and ground water would be the means of transport.

Well yields are low in all rocks at Maxey Flats, and most ground-water movement is in secondary openings, particularly joints. The ground-water system at Maxey Flats is probably unconfined, and recharge occurs by (a) infiltration of rainfall into the mantle, and (b) vertical, unsaturated flow from the regolith at the top of the hill to saturated zones in the Farmers Member and Ohio Shale. Discharge occurs by lateral flow from the mantle and bedrock to the sides of hills, or to alluvium in valley bottoms.

INTRODUCTION

Purpose, Scope, and Description of Study

The purpose of this report is to describe the geology and hydrology of the Maxey Flats radioactive waste burial site (hereafter referred to as the Maxey Flats site) and surrounding area. The report is entitled "preliminary" because of the short duration of the study (1 year). Although definition of the surface-water characteristics is possible with moderate time and expense, definition of the ground-water system poses difficult and complex problems.

With the possible exception of rock debris on hill-sides and stream-deposited sediments in valleys, all hydrologic units at Maxey Flats could be properly called poor aquifers (store and transmit water, but yield only small supplies to wells). Ground water moves mostly along joints (cracks) in the rocks. Flow through a jointed medium is generally much more difficult to describe than flow through a uniform porous medium. Sophisticated drilling and well-construction techniques, plus several years of data collection, would be necessary in order to attempt a quantitative description of the ground-water system.

Some site history, references available from past studies, and basic hydrologic information regarding the Maxey Flats site are presented. Basic hydrologic information is included with descriptions of the physical and structural character of the rocks, depths and water levels of wells in the area, and details of wells on the Maxey Flats site. General interpretations of ground-water flow, and quality of ground and surface water are given. This report should be an aid in interpreting monitoring data gathered by State and Federal agencies responsible for regulation of the Maxey Flats site, and protection of the environment around the site.

The period of study for this report was from July 1974, to August 1975. The scope of the study included literature review, data collection, and data analysis. Data were obtained from existing wells at Maxey Flats and surrounding area. Streamflow data were collected near the Maxey Flats site. Information on physical and structural characteristics of rocks, and ground-water discharge, was obtained by observations at outcrops, road cuts, and walls of open burial trenches.

Possible movement of radioactive materials from the burial site is of considerable interest at Maxey Flats, but emphasis of this report will be on basic hydrologic information needed to describe the ground-water system, and surface-water drainage. The construction of trenches at Maxey Flats has probably modified the ground-water flow system, but analysis of these effects is not a part of this study. Radiochemical data will be referred to in a later section of this report, but only in regard to geophysical well logs. The hydrologic significance of radiochemical data from some monitoring points operated by the responsible state regulatory agency may be deduced from the basic hydrologic information.

Reference will be made many times in this report to specific conductance of water. It is the reciprocal of the electrical resistivity of 1 cubic centimeter of water at standard temperature of 25°C (Celsius), and has units of micromhos per centimeter (μmho/cm). Multiplication of the specific conductance by the factor 0.7 gives the approximate total dissolved solids, in millgrams per liter (mg/L), for most water in rocks and streams around Maxey Flats. Specific conductance is used in this report to qualitatively estimate how ground water moves. It is assumed that water with conductance of about 500 μmho/cm or greater has been moving in the rocks for many years. It is also assumed that, the longer water has moved in the subsurface, the higher will be its specific conductance. These assumptions are believed reasonable for ground water at Maxey Flats.

Location and Site History

Maxey Flats is located in northeastern Kentucky, approximately 10 mi by road northwest of the city of Morehead (fig. 1). The area is shown on the south-central part of the Plummers Landing 7.5 minute topographic quadrangle. The Maxey Flats site is irregular in shape, but is approximately 5,000 ft long (measured along the topographic axis of the site) by about 3,000 ft wide (measured perpendicular to the topographic axis of the site).

Burial of radioactive wastes at the Maxey Flats site began in May 1963. As of January 1, 1972, approximately 25 million ft^3 of waste, containing over 1.2 million curies of byproduct material, 460 lb of special nuclear material, and 87,000 lb of source material had been buried (Clark, 1973). Briefly defined, byproduct material is material made radioactive by exposure to radiation. Special nuclear material is plutonium, uranium-233, and enriched uranium-235. Source material is uranium and thorium, not including special nuclear material. These terms are defined in more detail by the U.S. Nuclear Regulatory Commission (1975). Most waste is in solid form and is enclosed in different types of containers. Clothing, paper, glassware, shielding material, nuclear fuel rods, and animal carcasses are some of the items that make up the bulk of the waste.

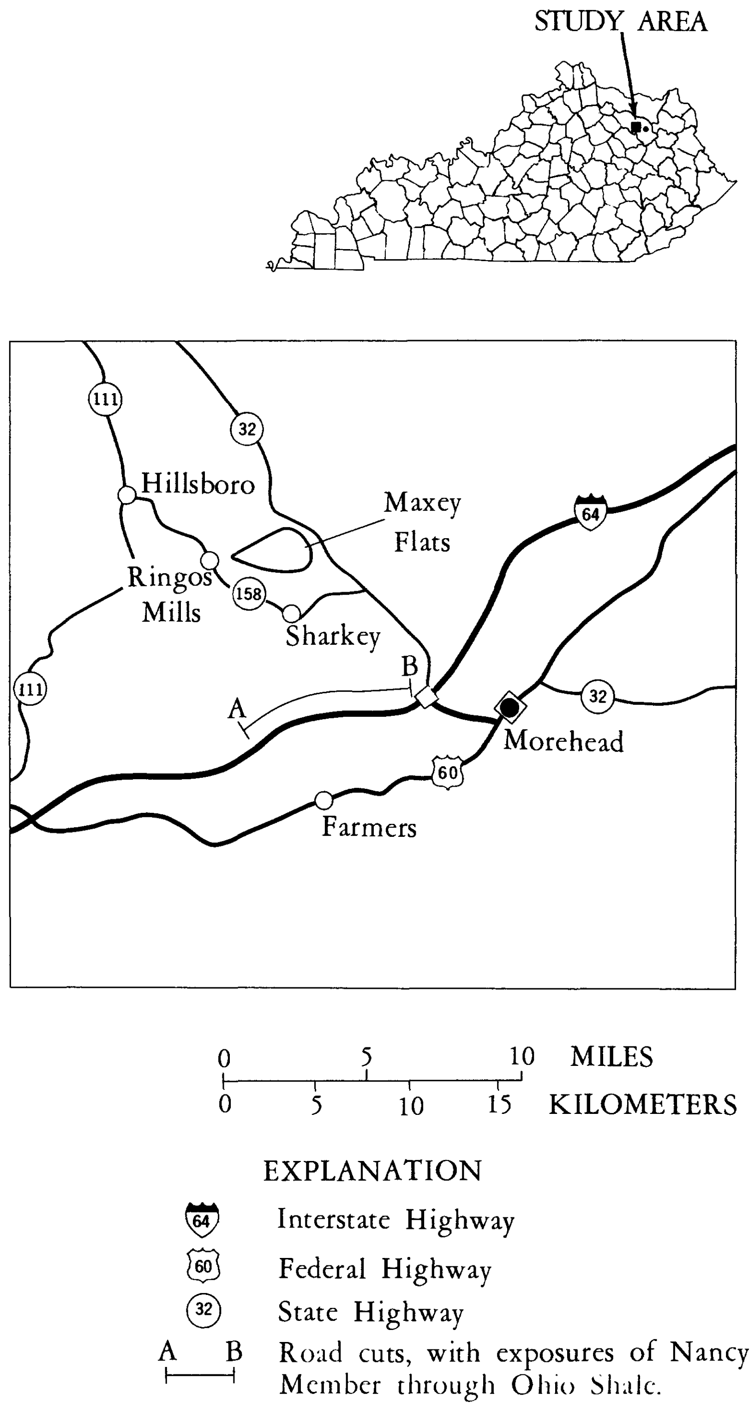


Figure 1.--Location of Maxey Flats and study area.

Most waste is buried in rectangular trenches approximately 360 ft long, 70 ft wide, and 20 ft deep (Clark, 1973), and the trenches are separated by about 5 to 10 ft of "in place" shale. When filled, they are covered with approximately 3 to 15 ft of compacted clay or crushed shale. Water from infiltrating precipitation has accumulated to different depths in the completed trenches. A program was initiated in the latter part of 1972 to remove and evaporate the accumulated water. The program is still in operation.

References are made in several parts of this report to rock exposures in road cuts. The road cuts referred to were made about 1966, and are located along Interstate 64, from the Morehead, Ky. turnoff to about 6 mi west of the turnoff (fig. 1). These road cuts are about 6 to 10 mi south of the Maxey Flats site, and will be referred to simply as the road cuts on Interstate 64. Rock strata exposed in the road cuts are essentially the same as those at Maxey Flats. Ground-water flow at road cuts is probably similar to that of Maxey Flats, and is assumed to be so when discussed in the test.

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) completed a report describing concentrations of radioactivity around the Maxey Flats site. Montgomery, and others (1977) described radionuclides in ground and surface water near the site. Meyer (1976) discussed transuranium nuclides in the environment at Maxey Flats. Problems regarding shallow-land burial of radioactive wastes were presented by the Comptroller General of the United States (1976). The geology of the Maxey Flats area has been mapped (McDowell, and others, 1971, and McDowell, 1975). Hall and Palmquist (1960) described the lithology and general water-yielding characteristics of wells in a three-county area, including Fleming County.

The following reports deal with the climate, topography, and geology, plus some hydrologic information at, or near, the Maxey Flats site:

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

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

(c) Papadopulos and Winograd (1974) reported current knowledge and future data needs to evaluate potential modes and rates of nuclide migration that could possibly occur at Maxey Flats.

(d) Emcon Associates (1975) described lithologic characteristics of 14 test borings, and drilling-water loss in some of the borings, drilled on the Maxey Flats site.

Acknowledgments

Thanks are given to the Environmental Protection Agency, particularly G. Lewis Meyer, for providing funding for the project. Gratitude is expressed to the Kentucky Department for Human Resources, Radiological Health Section; Charles Hardin provided a great deal of administrative assistance and David Clark assisted in gathering some of the field data. Discussions with Mr. Clark were vital in gaining knowledge of site history, and establishing priorities for data collection.

TOPOGRAPHY AND CLIMATE

The Knobs Region of Kentucky is the remnant of an eroded plateau, characterized by the presence of many knob-like erosional remnants of Silurian, Devonian, and Mississippian rocks (McFarlan, 1943). Maxey Flats is the top of one "knob" in this plateau (fig. 2). The Maxey Flats site is at a height of 300 to 400 ft above the valley bottoms. Valleys extend around part of the site, with an unnamed valley on the east, Rock Lick Creek to the south, and Drip Springs Hollow to the west. The valleys formed by Crane and Fox Creeks, and their tributaries farther to the north and east, complete the topographic isolation of Maxey Flats. 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.

Mean annual precipitation at Farmers, Ky., which is about 8 mi south of the Maxey Flats site (fig. 1), was 45.86 in for the period of record 1931 to 1955. The precipitation is not evenly distributed throughout the year. Months of low mean monthly precipitation occurred during September (3.04 in), October (2.20 in), and November (3.17 in), for the period of record 1931-55. Months of high mean monthly precipitation occurred during January (4.68 in), March (4.92 in), and June (4.55 in), at Farmers (U.S. Department of Commerce, 1959).

GEOLOGY

The rock units directly underlying the Maxey Flats site are, in descending order, the lower part of the Nancy Member (shale) and Farmers Member (sandstone) of the Borden Formation (Mississippian), the Henley Bed (shale) of the Farmers Member, the Sunbury, Bedford, and Ohio Shales (Mississippian and Devonian), plus the upper shale part of the Crab Orchard Formation (Silurian). The Ohio Shale, upper and lower parts of the Crab Orchard Formation, and the Brassfield Formation are exposed in the valleys around Maxey Flats. All radioactive wastes are buried in the Nancy Member.

Lithologic descriptions of the rocks are shown on figure 2. A diagrammatic, geologic section of the Maxey Flats site, to the level of Rock Lick Creek, is shown in figure 3. Figures 4 through 7 are more detailed diagrams of the rocks underlying the site, made from interpretations of geophysical logs obtained from 13 monitoring wells (see figure 8 for well locations). Core descriptions by Emcon Associates (1975) and the Kentucky Geological Survey were also used in the interpretations.

Brief descriptions are given of units from the Nancy Member to the upper part of the Crab Orchard Formation, including features relating to the hydrology of the area. In the descriptions, closely spaced minute joints are discussed. The structures are sometimes referred to as "rock cleavage," but in this report are called "hackly structure". These features are small and irregular compared to prominent joints in the Maxey Flats area. The hackly structure may be due to near-surface stress relief in the rocks, and the beginning of rock weathering. It may extend only a few feet to tens of feet below bedrock exposures.

Colluvium and Alluvium

Parts of the slopes at Maxey Flats are covered with colluvium, which is rock debris resulting from rock weathering and gravity fall. Much of this material is derived from the Farmers Member of the Borden Formation and ranges from pebble to boulder size. Sand and silt-size particles occupy voids between the larger fragments, and shallow soil is present on some of the colluvium. Material on tops of hills is regolith, which is weathered rock, resulting from in-place weathering of the shale, sandstone, and siltstone beds where they occur near the surface. The thickness of the regolith ranges from a few inches to about 25 ft. The regolith and colluvium form a cover or "mantle" of unconsolidated material over much of Maxey Flats. Bedrock is exposed in places, particularly near the tops of the hillsides, where the resistant Farmers

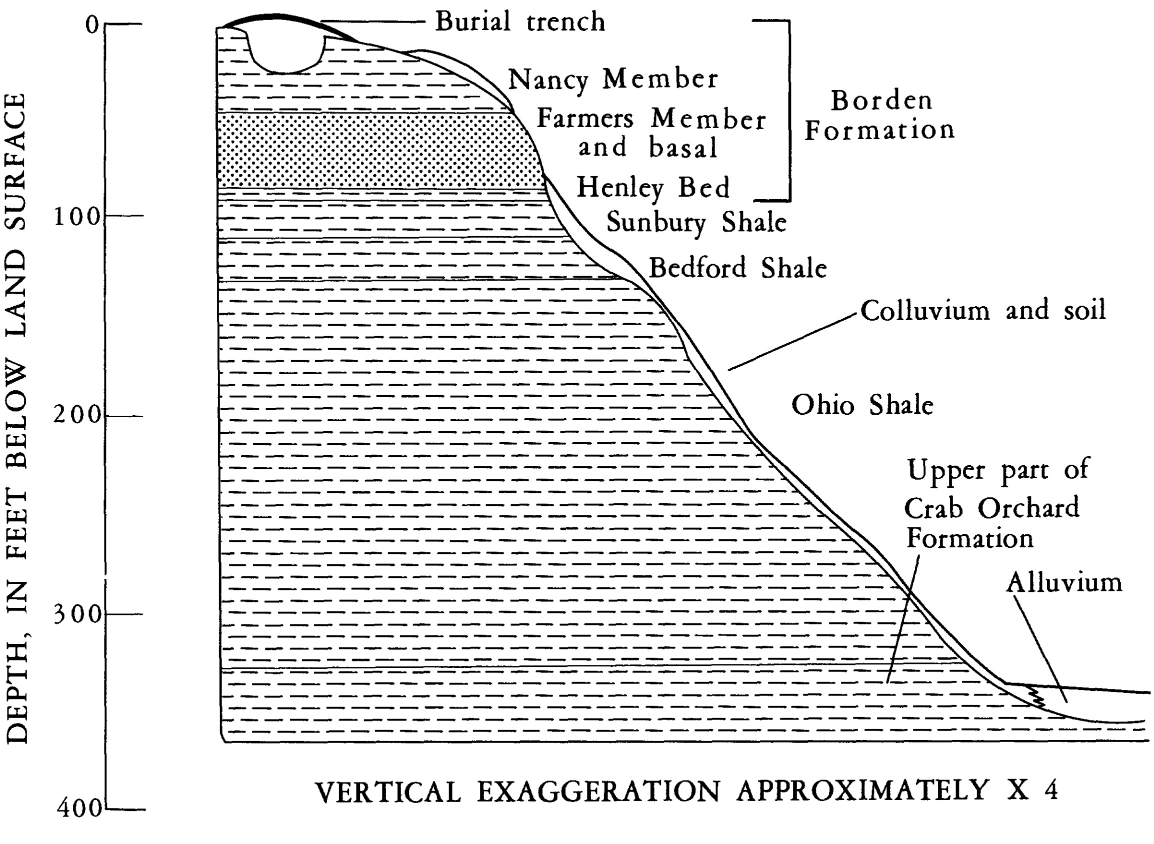


Figure 3.--Diagrammatic geologic section of the Maxey Flats site.

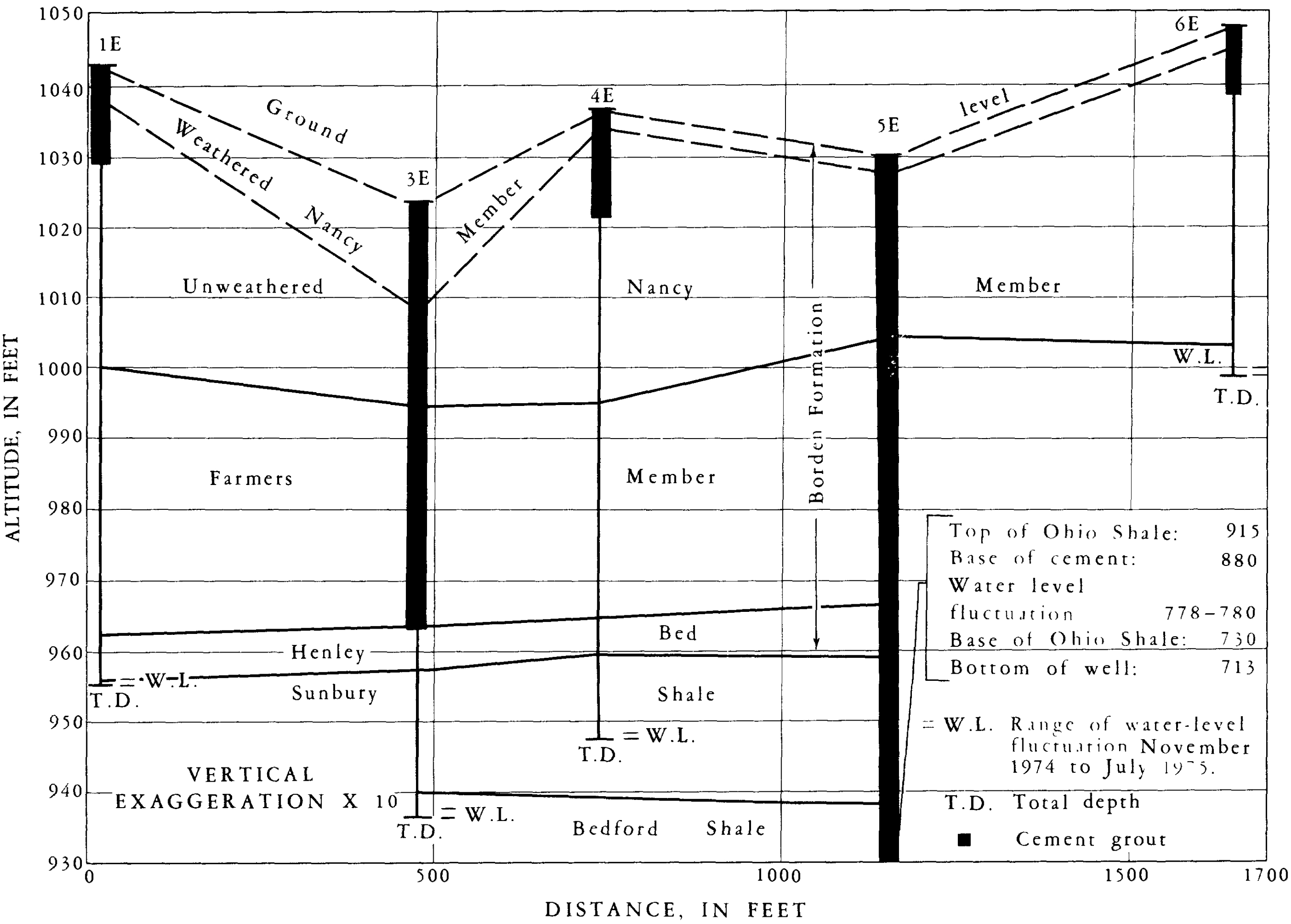


Figure 4.--Graph of wells 1E, 3E, 4E, 5E, and 6E, including water-level ranges and approximate thicknesses of rocks between wells. Thickness of weathered Nancy Member of the Borden Formation taken from EMCON Associates, 1975. Ground level approximate between wells.

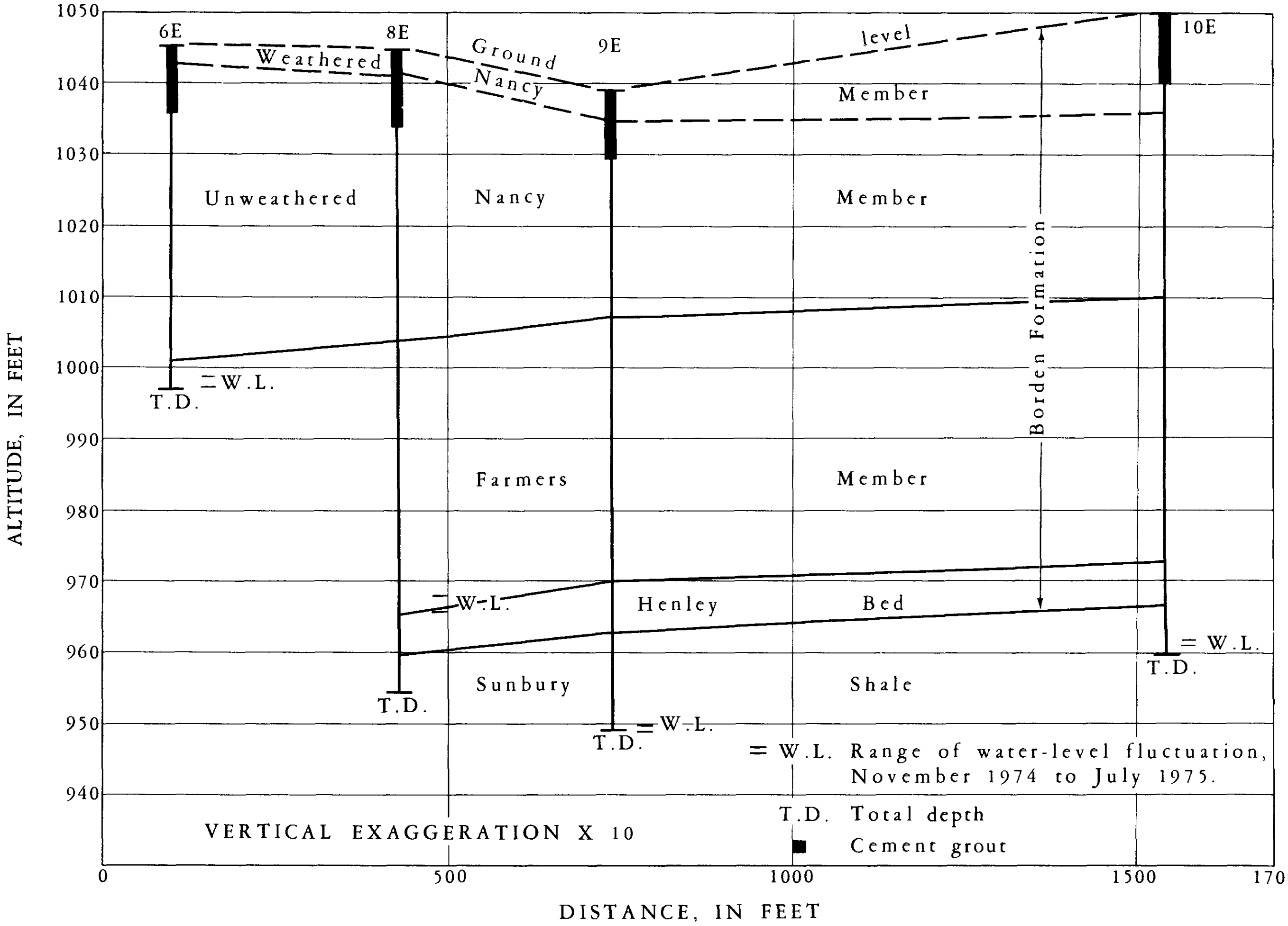


Figure 5.--Graph of wells 6E, 8E, 9E, and 10E, including water-level ranges and approximate thicknesses of rocks between wells. Thickness of weathered Nancy Member of the Borden Formation taken from EMCON Associates, 1975. Ground level approximate between wells.

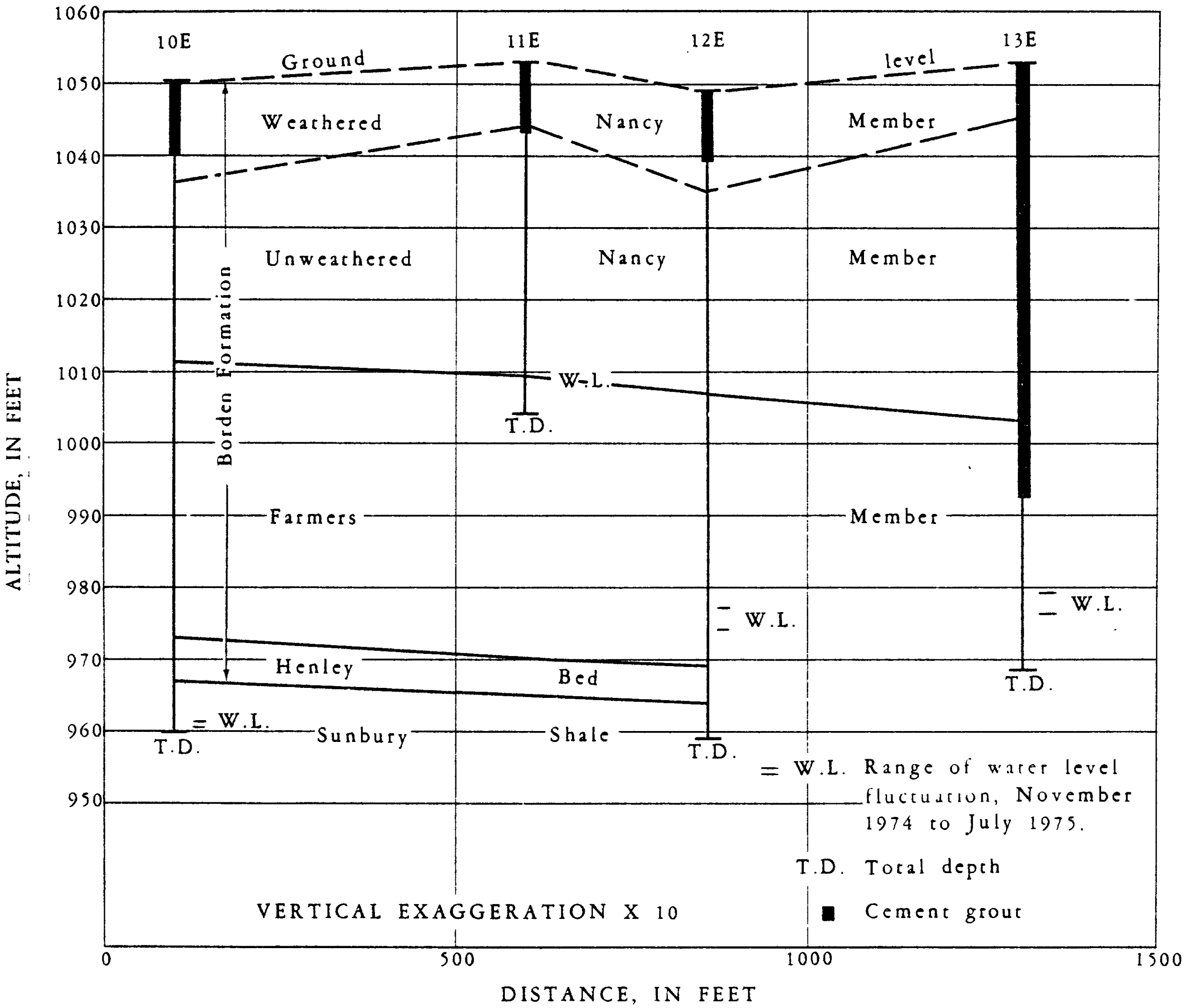


Figure 6.--Graph of wells 10E, 11E, 12E, and 13E, including water-level ranges and approximate thicknesses of rocks between wells. Thickness of weathered Nancy Member of the Borden Formation taken from EMCON Associates, 1975. Ground level approximate between wells.

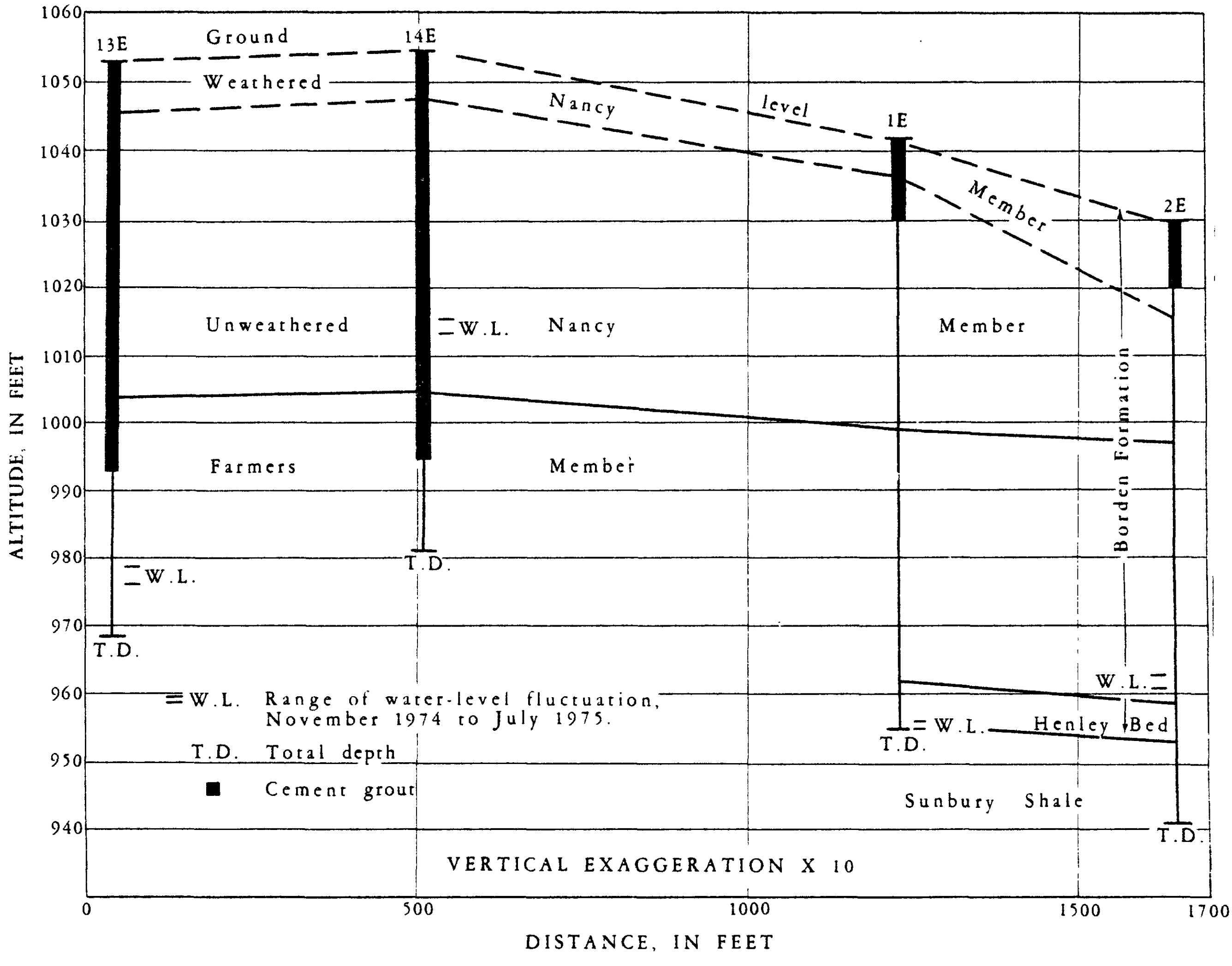


Figure 7.--Graph of wells 1E, 2E, 13E, and 14E, including water-level ranges and approximate thicknesses of rocks between wells. Thickness of weathered Nancy Member of the Borden Formation taken from EMCON Associates, 1975. Ground level approximate between wells.

Member forms steep erosional scarps. Finer grained, thicker 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.

Alluvium (sediments deposited by streams) is present in the valley bottoms and in the channels of small valleys on the slopes of Maxey Flats. The sediments are composed mainly of fragments of the Farmers Member, and siltstone fragments from interbeds in the shales. In Drip Springs Hollow, the alluvium extends from Rock Lick Creek to about 2,300 ft upstream from well W1 (fig. 8). The alluvial deposits in Drip Springs Hollow are about 400 to 600 ft wide at the road (hereafter called Rock Lick Road) located north of, and running parallel with, Rock Lick Creek. The deposits are about 200 to 300 ft wide at well W1, and about 100 to 200 ft wide at a distance of about 2,000 ft upstream from well W1. The depth of this alluvium is unknown, but at least 7 to 8 ft is exposed at places in the stream channel. The alluvial deposits at well W1 are probably at least 9.5 ft deep, which is the depth of the well.

Alluvial deposits in the unnamed valley to the east of the Maxey Flats site extend about 1,500 to 2,000 ft upstream from Rock Lick Creek. The deposits are about 300 to 400 ft wide at Rock Lick Road, and approximately 100 to 200 ft wide about 1,000 ft upstream from Rock Lick Road. They are probably at least 10 ft deep at the location of dug well W4 (fig. 8). The deposits are about 200 to 300 ft wide along Rock Lick Creek near the unnamed valley, and are about 500 to 700 ft wide near Drip Springs Hollow. The depth of the alluvium along Rock Lick Creek is unknown.

Borden Formation

Weathered Part of the Nancy Member and Sandstone Marker Bed

The upper 1 to 25 ft of the regolith at the Maxey Flats site is composed of the weathered part of the Nancy Member. It is jointed and exhibits a hackly structure. The more weathered the shale, the more pronounced the hackly structure. Blocks forming this structure are either roughly cubic, or irregular in shape. The blocks range from 1 to 6 in on each side, with most 1 to 3 in. This material is mostly orange-gray to light-brown silty clay or clayey silt, as opposed to the underlying dark-gray, indurated shale, which is not weathered.

Near the base of the weathered shale is a sandstone bed which ranges in thickness from less than 1 in to about 3 ft, and averages about 1.5 ft. In this report it is called the sandstone marker bed, and is considered part of the weathered zone of the Nancy Member. The sandstone marker bed is present over most of the Maxey Flats site. It is similar to the sandstone beds found at the base of the Nancy Member, and in the Farmers Member. The sandstone marker bed exhibits much more extensive jointing than underlying sandstones.

Where the sandstone marker bed is present, all but the upper 1 to 2 ft of underlying shale is unweathered. In local areas extending laterally a few feet to tens of feet, the sandstone marker bed thins to less than 1 in thick, or may be broken on the crests and troughs of anticlinal and synclinal structures. In these local areas, weathering of the underlying shale extends to greater depths. Deeper weathering observed along the walls of some open burial trenches extended as much as 10 ft below the level at which the sandstone bed usually occurs. The sandstone marker bed forms the bottom of many burial trenches.

Above the sandstone marker bed are a few discontinuous, thin (most less than 1 in, but some as much as 6 in thick) siltstone and sandstone beds. The weathered part of the Nancy Member extends over the edge of Maxey Flats, where it grades into the colluvium on the hillsides.

Unweathered Part of the Nancy Member

Underlying the near-surface weathered material is the unweathered part of the Nancy Member. The shale is medium-to-dark gray, silty, but with some clay. It is moderately to loosely cemented and poorly fissile (property of the rocks to split easily along closely spaced parallel planes). Within the upper part of the Nancy Member, discontinuous sandstone beds generally less than 2 to 3 in thick are present locally. At least two very fine-grained sandstone beds of greater thickness (maximum about 3 ft) are present at the base of the Nancy Member. These beds vary in thickness, and are discontinuous.

McDowell and others (1971) define the contact between the Nancy Member and underlying Farmers Member as the horizon at which the shale beds between sandstone beds are less than 3 ft thick. This definition is also used in this report. Due to the variable thickness and discontinuous character of the sandstone beds at the base of the Nancy Member, the contact with the underlying Farmers Member is an undulating surface. The thickness of the combined weathered and unweathered Nancy Member changes with topography and position of the undulating basal contact. On the upper, flat area of the Maxey Flats site, the thickness is about 45 ft on the west side and about 40 ft on the east side.

The unweathered part of the Nancy Member exhibits a hackly structure in outcrop, but the lower part of the rocks changes structure locally. In the vicinity of trench 43, located on the northeast side of the burial area (fig. 8), the hackly structure is no longer present at a depth of about 20 ft below the sandstone bed. Instead, the shale becomes more fissile. The "fissility" is not strictly in the form of sheets that break in parallel planes. Rather, the shale breaks parallel to the bedding in cylindrical slivers several inches long and about 0.5 to 1 in diameter. The importance of this structural change is that many of the major joints present in the overlying part of the Nancy Member terminate abruptly at the horizon of structural change. This produces yet another type of inhomogeneity in the rocks, in addition to the different lithologies. It is unknown if this structural change is widespread and uniform over the burial area.

Besides the very small joints comprising the hackly structure, the unweathered part of the Nancy Member contains a prominent, near-vertical joint system. The apertures of prominent joints observed in the unweathered part of the Nancy Member at trench 43 were usually less than about 0.03 in. The upper parts of the joints, at the top of the unweathered part of the Nancy Member, and in the sandstone marker bed, have apertures about 0.03 to 0.06 in wide. The wider space in the joints are partially, and in places completely, filled with particles of weathered shale. Bands of shale alteration are adjacent to almost all prominent joints. These bands usually extend 1 to 4 in to each side of the joints, and appear to be mostly iron oxide deposition, or alteration, in the shale matrix. The bands are composed of material that closely resembles the near-surface weathered shale. The iron oxide is also present in the smaller planes of separation in the hackly structure. It is not so prominent as in the major joints however, because it is essentially a film within the separations.

Although all joints observed along the walls of trench 43 terminate at the horizon of structural change, this does not mean that all joints in other parts of the Maxey Flats site terminate at this horizon. Reasons for this are that (1) the "fissile" structure may not be present in all areas, and (2) joints observed in the Nancy Member along Interstate 64 extend into the underlying Farmers Member, and similar structure is probably present at Maxey Flats.

Farmers Member

The Farmers Member is composed of very fine grained sandstone beds as much as 4 ft thick, separated by shale interbeds as much as 3 ft thick. The shale interbeds are much thinner in the lower half of this unit, ranging in thickness from a few inches to less than 1 in. The average thickness of the Farmers Member at the Maxey Flats site is 36 ft.

The sandstone beds are light brown, and composed mostly of silica grains. Silica cements the grains, and fills the original pore spaces between the grains. The interbedded shales are similar to beds in the Nancy Member. Microscopic examination of several Farmers Member samples showed the porosity (ratio of volume of pore space to total volume of rock) in the non-jointed part of the rocks to be very low. A prominent, near-vertical joint system is present in the Farmers Member, with most joints in the upper part of the member.

Henley Bed of the Farmers Member

This shale bed is poorly exposed at Maxey Flats, but can be observed in road cuts on Interstate 64. The shale is gray orange to light gray, and contains a few thin (less than about 4 in) shaly siltstone beds. The shale is poorly fissile, and is similar to the shale beds in the overlying Nancy Member. The same hackly structure present in the Nancy Member can also be observed at outcrops of this bed. Prominent vertical joints are also present in the Henley Bed. The shale averages 6 ft in thickness at the Maxey Flats site.

Sunbury Shale

The Sunbury Shale is a black, carbonaceous, very fissile shale that, in outcrop, readily breaks into brittle plates less than about 0.2 in thick. The shale is extensively jointed, the joints being mostly near vertical, with many joint planes less than 5 ft apart. Average thickness of the Sunbury Shale at the Maxey Flats site is about 20 ft.

Bedford Shale

The Bedford Shale is another medium-to-dark-gray clay shale similar to the Henley Bed and Nancy Member. It has low fissility and hackly structure in outcrop. Several thin (about 0.4 to 2 in) sandstone and siltstone beds can be observed in this formation along Interstate 64. The Bedford Shale contains a prominent, near-vertical joint system, and is about 20 ft thick at the Maxey Flats site.

Ohio Shale

The upper 170 ft of Ohio Shale is identical in appearance, and has essentially the same lithology and structure, as the Sunbury Shale. The lower 15 to 20 ft of the Ohio Shale consists of a greenish clay shale with black, carbonaceous shale interbeds that have lower fissility and less jointing than the upper part of the unit. McDowell and others (1971) report greenish clay shale beds as much as 10 ft thick are present locally within the Ohio Shale, especially 50 to 60 ft from the top of the unit. Emcon Associates (1975) report a "gray interbed" 50 ft below the top of the Ohio Shale in one of their test borings at the Maxey Flats site. The thickness of the Ohio Shale at the Maxey Flats site is about 185 ft.

Upper Part of the Crab Orchard Formation

This unit is a gray clay shale, poorly fissile, plastic when wet, and exhibits little jointing. The thickness of the upper part of the Crab Orchard Formation, as reported by McDowell and others (1971) ranges from 80 to 130 ft in the Plummers Landing quadrangle. The top of this unit and the lower part of the Ohio Shale form the valley bottoms around the Maxey Flats site.

Structure

Regional dip of the rock strata in the Maxey Flats area, as determined by structural contours drawn on the base of the Sunbury Shale by McDowell and others (1971), is about S65E at about 25 ft/mi. The contact between the Henley Bed and Sunbury Shale was picked from geophysical logs of eight wells at the Maxey Flats site to determine the local dip, which is S65E at about 40 ft/mi.

All rocks observed in road cuts on Interstate 64, and at trench walls and outcrops at the Maxey Flats site, contained major, weathered joints. The joint density is different for different rock units. No detailed measurements or statistical analyses were made of joint density below the Nancy Member. The apparent relative joint densities for different rock units, from highest to lowest, as determined by observation is: (1) Sunbury and Ohio Shales, (2) upper part of the Farmers Member, (3) interbedded siltstones and sandstones within shale units, (4) Nancy Member, Henley Bed, Bedford Shale, and lower part of the Farmers Member, and (5) upper part of the Crab Orchard Formation.

The sandstone marker bed, which is considered part of the weathered Nancy Member in this report, has greater joint density than the Sunbury and Ohio Shales. Joints in the weathered shale above the sandstone marker bed are less numerous than in the sandstone bed.

Two major directions of strike are shown by McDowell and others (1971) for joints in the Nancy Member. The directions are N63E and N47W. The joints were measured at the sandstone marker bed on the Maxey Flats site (R. C. McDowell, personal commun., 1975).

A total of 38 joints were measured in the unweathered part of the Nancy Member during the 1974-75 study for this report. The measurements were made at the long walls of trench 43. Joints measured were vertical, major joints with at least 1 to 2 in of weathering to each side of the joints. Three major directions of strike were determined for these joints, and were N70W (seven measurements), N10W (12 measurements), and N65E (10 measurements). A fourth direction of strike may be N20E, but too few measurements were obtained in this direction to be conclusive (three measurements). The distances between joints, measured along the trench wall, ranged from 2 to 37 ft, with median of 18 ft.

The difference in joint orientation measured in trench 43 and those shown by McDowell and others (1971) is probably due to different properties of the sandstone marker bed, compared to the underlying shale. Joint density is much greater in the sandstone marker bed than in the shale, and this may be partly due to stress relief.

In outcrops and road cuts, some joints in rock formations terminate at contacts with other formations. Some joints penetrate more than one rock unit without offset, whereas other joints are offset a few inches to a few feet at the contacts. Several vertical joints are continuous in trench 43, without offset, through the weathered and unweathered parts of the Nancy Member.

GENERAL HYDROGEOLOGY

Ground-water has been observed discharging from joints at outcrops, and the bottoms of major vertical joints in trench 43, demonstrating that water moves through the joint system in the Nancy Member. Bands of weathered shale adjacent to major joints are probably due to alteration, or deposition of iron oxide, from ground water. Seepage from joints in trench 43 was taking place in the summer of 1975, after a prolonged dry period (no rainfall during the previous 7 days and three rainfalls of less than 0.25 in each during the previous 14 days). Seeps occurred where joints terminated at the change in rock structure described earlier in the report.

Ground-water discharge from the joint system in the Farmers Member was observed in road cuts along Interstate 64, even during the dry part of the year of study. The water usually discharges at the bottoms of joints in the standstone beds, where the joints contact the top of underlying shale interbeds. The shale interbeds tend to "perch" the water and cause lateral ground-water movement. Some vertical, as well as lateral, movement through the shale must take place, because discharge was observed in deeper rocks. The lower part of the Farmers Member however, has much less jointing and ground-water discharge at outcrops than does the upper part of the unit. Water movement in the Farmers Member can also be inferred as taking place at the Maxey Flats site, because of water-level data from two wells finished in this unit. These data will be discussed later in the report.

The Sunbury and Ohio Shales have the greatest joint density of all the rocks at Maxey Flats. Besides ground-water movement through these joints, a multitude of bedding planes and planes of fissility in the shales may also contribute to water movement. At outcrops and road cuts, iron oxide deposits of apparent ground-water origin are present in the joints, and along the planes of fissility.

The shales of the Nancy Member, Henley Bed, and Bedford Shale look very similar, both in exposures and in microscopic inspection. Jointing, hackly structure, and thin (a few inches) interbedded siltstones or sandstones are present in all these shales. McDowell and others (1971) reported the Nancy Member as a silty shale, and described the Henley Bed and Bedford Shale as clayey shales. Dobrovolny and Morris (1965) described the Nancy Member and Henley Bed as good foundation material that will stand in steep cuts, whereas the Bedford Shale was described as a clayey shale that is unstable in steep cuts. The Bedford Shale may have less water-transmitting capability than the shales of the Nancy Member and Henley Bed because of its greater plasticity and clay content, but these three shales are probably less permeable than other rocks above the upper part of the Crab Orchard Formation. A possible exception may be the lower part of the Farmers Member, which has very low porosity, and in which few joints were observed in road cuts on Interstate 64.

Few joints were observed at exposures of the upper part of the Crab Orchard Formation, and bedding and fissility are indistinct. Dobrovolny and Morris (1965) describe this formation as expansive clay shale, with landslides and slumps common on slopes composed of these rocks. McDowell and others (1971) describe the upper part of the Crab Orchard Formation as clay shale, which is plastic when wet. Because of its clay content, plasticity, sparsity of joints, and topographic position at valley bottoms, the upper part of the Crab Orchard Formation probably forms the lower hydrologic boundary at Maxey Flats.

The hdyraulic conductivity of a medium is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow, assuming the medium is isotropic and the fluid is homogeneous. Specific hydraulic conductivities for "in place" rocks and unconsolidated materials at Maxey Flats are unknown, although Emcon Associates (1975) reported laboratory values for 11 core samples.

All cores tested were from the Nancy Member. The vertical hydraulic conductivity ranged from less than 3×10^{-12} to 3×10^{-10} ft/s for nine shale samples and was 1×10^{-9} ft/s for one sandstone sample. Only horizontal hydraulic conductivity was obtained for one shale sample, and was 3×10^{-11} ft/s. The hydraulic conductivity was obtained by: "samples were placed in triaxial equipment and were saturated under a back pressure of 90 psi. The hydraulic gradient of the tests was limited to less than 10, except in the case of sample 5E at 21.5 to 22.0 feet, where the gradient was increased due to the extremely impervious nature of the sample." (EMCON Assoc., 1975).

Because hydraulic conductivities of the jointed rocks are unknown, only relative estimates of this parameter can be made. Hydrologic units are grouped by apparent relative hydraulic conductivity in table 1. The relative hydraulic conductivities are based on physical properties of the units, and visual inspection of ground-water discharge at outcrops.

SURFACE WATER IN THE VICINITY OF THE MAXEY FLATS SITE

Drainage Routes and Characteristics

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. By observation, it is estimated that approximately 60 to 70 percent of the runoff from the trench area flows down the small valley shown as "burial site major drainageway" in figure 8. All surface-water discharge from the Maxey Flats site flows southwest down Rock Lick Creek, then west down Fox Creek, then northwest down the Licking River to the Ohio River.

Water flows in the unnamed valley, Drip Springs Hollow, and Rock Lick Creek during the wet season of the year, and during parts of the dry season. Surface flow occasionally ceases in all three of these streams. However, low areas within the stream channels always contained water during this study, so flow from the stream to the subsurface alluvium and back to the stream occurred, even when there was no continuous surface flow.

Table 1.--Hydrologic units at Maxey Flats grouped by apparent relative hydraulic conductivity. Number 1 is greatest and number 6 is least.

1	2	3	4	5	6
Alluvium (in valleys)	Colluvium and soil (on hillsides)	Regolith (on hilltops), including the sandstone marker bed	Upper part of the Farmers Member (Borden Formation) Sunbury Shale Ohio Shale	Lower part of the Farmers Member and Nancy Member (Borden Formation) Henley Bed (Farmers Member) Bedford Shale	Upper part of the Crab Orchard Formation

Continuous streamflow records for Rock Lick Creek have been obtained at the Sharkey gaging station since August 1973. This station is shown in the southwest corner of figure 8. A summary of discharge data for the water years (October through September) 1974 and 1975 is shown in table 2.

Table 2.--Summary of Rock Lick Creek discharge data for water years 1974 and 1975 at Sharkey, Kentucky gaging station.

	Discharge, 1974 water year (ft^3/s)	Discharge, 1975 water year (ft^3/s)
Maximum daily	130 (March)	193 (March)
Minimum daily	0 (October)	0 (June-July)
Mean daily	7.2	8.9

Rapid rises and falls in discharge are characteristic at the Sharkey gaging station. This is due to (a) small drainage area of 4.01 mi^2, (b) large rainfall in short time span, (c) steep topography, and (d) relatively low hydraulic conductivity of the rocks. For example, a 1.2 in rainfall on August 29, 1975, caused a change in discharge from 0.59 ft^3/s to a peak discharge of 908 ft^3/s within 24 hours; discharge then decreased to 5.2 ft^3/s within 3 days.

Low-Flow Measurements

Measurements of stream discharge were made during periods of low flow in the summer of 1974 in Drip Springs Hollow and the unnamed valley to the east of the Maxey Flats site. Due to the difficulty of measuring very small discharges in streams with rough beds, the discharge data for unnamed valley are considered extremely poor (error at most measuring points estimated to be greater than 80 percent, by observation). A portable steel weir was used to make measurements in the valley. Flow around and under the weir accounted for the large estimates of error in discharge. Only one measurement from unnamed valley is used, because of the large estimated error in others. The measurement was made on July 30, 1974, between Rock Lick Road and the stream junction with Rock Lick Creek (shown as station 5 on figure 8). The discharge was 0.1 ft^3/s.

Low flow was measured in Drip Springs Hollow by constructing cement dams across the stream channel, then embedding flow pipes in the dams, and measuring flow from the pipes volumetrically. Several of these dams were built along the stream in Drip Springs Hollow. Measurements made upstream from the bridge on Rock Lick Road are considered poor to fair, because of flow under the dams. Measurements made downstream from the bridge at station 1 (fig. 8) however, were obtained with a weir placed in a clay channel, and there was no flow under the weir. The present channel was excavated with machinery, so that flow now passes station 1. The original channel was farther to the south. Discharge measurements made in Drip Springs Hollow are shown in table 3.

Table 3.--Discharge measurements of stream in Drip Springs Hollow.

Station*	Date measured	Discharge (ft^3/s)
1	July 31, 1974	0.024
2	Aug. 1, 1974	.014
3	July 31, 1974	.014
4	Aug. 2, 1974	.0029
3	Oct. 7, 1974	.054
4	Oct. 7, 1974	.017
1	Oct. 14, 1974	.050
3	Oct. 14, 1974	.034
4	Oct. 14, 1974	.011

*Location shown on figure 8.

The discharge data from the stream in Drip Springs Hollow consistently show increasing discharge with distance downstream. It is therefore a gaining stream (water flows into stream from adjacent sediment and rocks) during the dry period of the year. The amount of flow gained by the stream is very small however, as shown by the discharge data in table 3.

The stream in unnamed valley is probably also a gaining stream during parts of the dry season, but measurements were insufficient to show this. During the months of July and October 1974, no continuous flow was observed in the stream in unnamed valley above a point about 1,000 ft upstream from the bridge on Rock Lick Road. Pools were observed at different locations in the streambed upstream from this point however, indicating flow through the alluvium. During parts of the wet season, when stream discharge is high, the streams in unnamed valley and Drip Springs Hollow are expected to become losing streams (water flows from stream into adjacent alluvium).

Although no low-flow measurements were made on Rock Lick Creek for this study, some discharge data in U.S. Geological Survey files show low flow at the Sharkey gaging station as follow: October 1973, 0.061 ft^3/s; August 1974, 0.45 ft^3/s; and October 1974, zero discharge. Flow conditions in Rock Lick Creek are probably similar to those in Drip Springs Hollow and unnamed valley, because the alluvial deposits, rock types, and small drainage area with steep topography are common to all three of these streams.

Specific Conductance Measurements

Specific conductance of water from the stream in Drip Springs Hollow was 162 µmho/cm during low flow on July 29, 1975, when discharge was estimated to be less than 0.5 ft^3/s. The sample was obtained at the bridge on Rock Lick Road. Water samples were taken from Rock Lick Creek at the Sharkey gaging station during low flow in the summer of 1974. The discharges at time of sampling were 0.45 ft^3/s and 0.53 ft^3/s. Specific conductances of both samples were 230 µmho/cm. The highest conductance on record (1973-75) for streamwater at the Sharkey gaging station is 600 µmho/cm, measured during a flow of 0.06 ft^3/s.

The specific conductances of the surface-water samples are lower than conductance of water from wells on the Maxey Flats site, which are mostly greater than 1,000 µmho/cm. If most stream discharge around the Maxey Flats site during periods of low flow originated from bedrock, it would be expected that the conductance of the streamwater would be similar to that of water from wells on the site. However, it is not.

It is therefore concluded that water flowing down Drip Springs Hollow, unnamed valley, and Rock Lick Creek during periods of low flow consists mostly of flow from the alluvium, which is derived from (a) direct infiltration of rainfall, (b) infiltration of surface runoff, and (c) flow from colluvium and soil on the slopes of adjacent hills. It is reasonable to also conclude that some contribution to streamflow must be derived from flow out of bedrock, assuming all ground-water discharge is not evaporated or transpired. This is because water infiltrating the rocks at altitudes above the valley bottoms flows laterally through the rocks to the mantle and alluvium, or to the ground surface. The conductance data indicate that the portion of water from the bedrock is smaller, probably much smaller, than that derived from the alluvium. It is realized that this flow system is a gradually changing continuum, so that the ratio of water from bedrock to water from alluvium will gradually change. When little flow is present in the streambed, and most flow is ground-water flow, the contribution of flow from bedrock will gradually become proportionately greater, perhaps even exceeding that of flow solely from the alluvium. However, this was not observed.

WELL AND SPRING RECONNAISSANCE

Although all formations in the Maxey Flats area can be considered poor aquifers, domestic water supplies are obtained from any one, or combination, of these formations. Drilled wells are discussed separately from dug wells, because they are deeper than dug wells, and are completed in bedrock. Dug wells were constructed with hand tools, and are completed in shallow material overlying bedrock. Specific details of monitoring wells drilled on the Maxey Flats site are described in a later section.

Description of Data Collected, Method of Collection, and Water Use

During the summer and fall of 1974, a well and spring reconnaissance was conducted within a 5 mi radius of the Maxey Flats site. A total of 52 drilled wells, 65 dug wells, and 27 springs were inventoried (fig. 2). Drilled wells inventoried are estimated to be 65 to 75 percent of the total number of drilled wells present in the area of survey. Dug wells were too numerous to inventory in an equivalent percentage. On Maxey Flats, a total of 13 wells were inventoried. This is estimated to be about 60 to 80 percent of all dug wells and 100 percent of all drilled wells on the hill.

Depth to water and depth of well were measured where possible. When these measurements could not be made, the depth of the well as reported by the owner was used. Where possible, water samples were taken from wells for measurement of specific conductance. Where no pumps were present in wells, the water samples were obtained from within a few feet of the bottoms of the wells to reduce the chances of sampling runoff or shallow soil water that had seeped down the outsides of the well casings. Where operable pumps were in wells, the samples were obtained from taps after running the water 2 to 5 minutes.

Some people report that their water supply is from "cisterns". This word has different meaning to different people. In some cases, the cisterns are concrete structures in which the sole water supply is from sources other than ground water. In most cases, people term cisterns holes dug in the ground and shored by close-fitting rocks. These latter "cisterns" are essentially dug wells containing ground water, but additional water is supplied continually or periodically by downspouts from roofs or water hauled by vehicle. In this report, the term "cistern" is applied both to concrete structures, and to dug wells from which supplies in addition to ground water are used. No water samples were taken from cisterns.

Some wells and springs are utilized for drinking and household use, some are used for purposes other than drinking (where water is highly mineralized), and some are abandoned. Ponds are used by many people who find ground-water supplies inadequate for their needs.

The dug well nearest to the Maxey Flats site that is presently in use is located about 1,000 ft west of the site (W1 on fig. 8). The drilled well nearest to the Maxey Flats site that is presently in use is about 2.5 mi east of the site, at the intersection of Route 32 and the road crossing Maxey Flats (fig. 2). The dug well might receive some recharge by flow from the site. It is very unlikely that the drilled well receives recharge from the site, because of its distance and topographic position relative to the site.

Drilled Wells

Most drilled wells have steel casing set from ground surface to a few feet or tens of feet below ground surface, and are open-hole below the casing. Some of the wells have cement pads at the surface, but none of the owners reported any wells as having cement in the casing-borehole annulus. Surface water and near-surface ground water can therefore percolate down the space between the casing and the borehole.

Most of the wells inventoried are located in the valley bottoms (about 85 percent), rather than on hilltops (fig. 2). This is because most of the population is located in the valleys. The majority of wells therefore penetrate the lower part of the Ohio Shale and rocks below the Ohio Shale. Wells drilled into rocks above the base of the Ohio Shale are usually open to more than one rock member or formation. It is not possible to draw meaningful water-level contours from these data, because drilled wells are too few and too widely spaced to provide suitable water-level control, particularly in rocks above the base of the Ohio Shale.

Specific conductances of water from drilled wells vary widely, even for water from groups of rock units adjacent to one another (figs. 9 through 11). The conductances are evidently dependent, not only on the type of rocks supplying the water, but also on (a) the distance water has moved through the rocks, (b) the contact time between the water and the rocks, and (c) seepage from near-surface soil or overland runoff down the space between casing and borehole.

The median conductance of water from wells shown in figure 9 closely corresponds to conductances of water from wells finished above the Ohio Shale at the Maxey Flats site. Most specific conductances shown in figure 10 are probably much less than that for water coming from rocks

Number above bar denotes measured depth of well, in feet, from which water sample was obtained. Letter R after number denotes depth of well is a reported value.

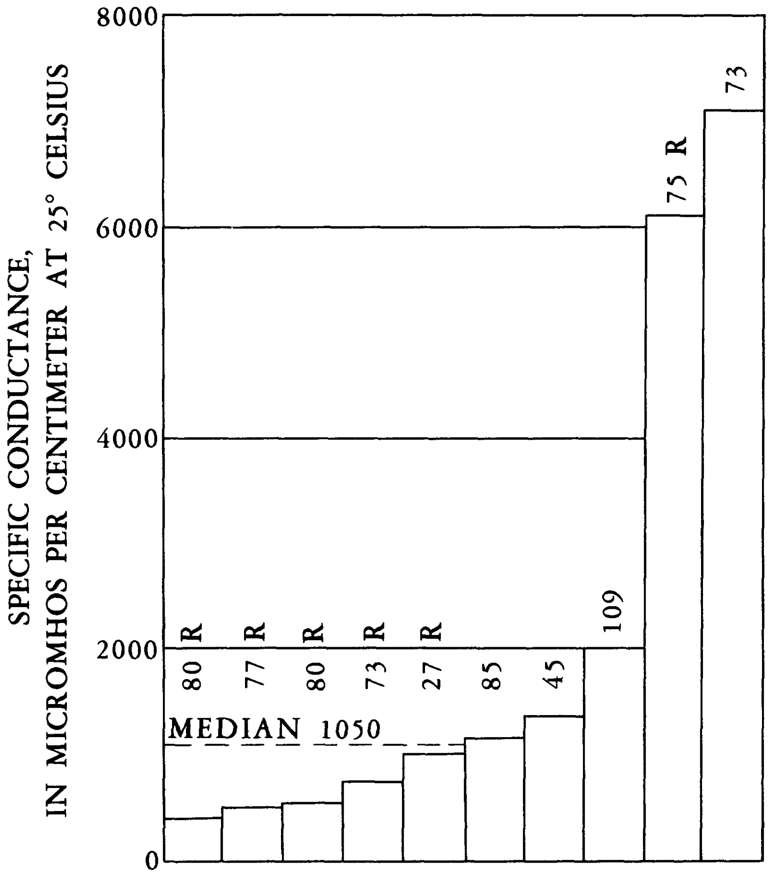


Figure 9.--Specific conductance of water from drilled wells completed in rock units from the Nancy Member of the Borden Formation through the Bedford Shale.

Number above bar denotes measured depth of well, in feet, from which water sample was obtained. Letter R after number denotes depth of well is a reported value.

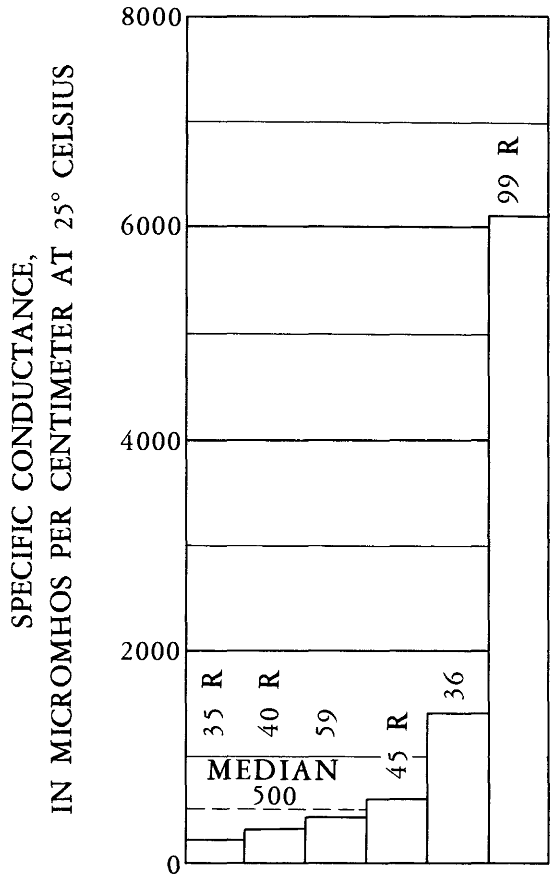


Figure 10.--Specific conductance of water from drilled wells completed in the Ohio Shale and upper part of the Crab Orchard Formation.

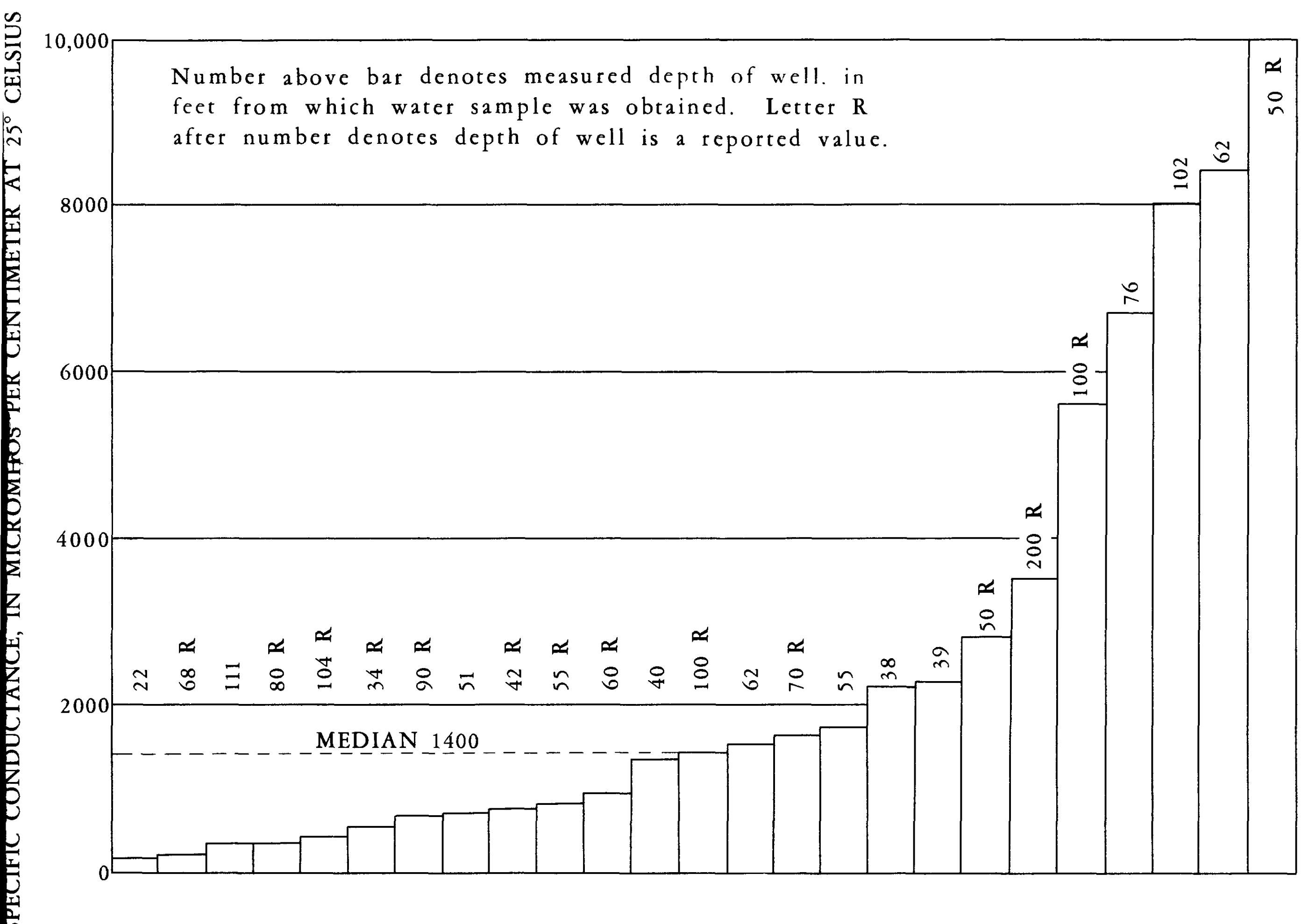


Figure 11.--Specific conductance of water from drilled wells completed in rock units below the Ohio Shale.

at depths of 100 ft or more in the Ohio Shale and upper part of the Crab Orchard Formation. One well located on the Maxey Flats site is open to 185 ft of Ohio Shale. This well is discussed in a later section of the report, but it is appropriate to state here the conductance of the water from this well ranges from 6,000 to 8,000 μmho/cm.

Dug Wells

Most dug wells are located on the valley bottoms, and are completed in colluvium and alluvium. All dug wells on Maxey Flats are completed in the Nancy Member and most, if not all, of the member is weathered to the depth at which these wells are dug. Of the 65 dug wells inventoried, 22 are located in the Nancy Member. The 22/65 ratio is not representative of the area of study however, because approximately 60 to 80 percent of all dug wells on Maxey Flats were inventoried (10 wells), and probably less than 50 percent were inventoried in other areas.

Most of the dug wells on Maxey Flats are about 2 to 4 ft diameter, 10 to 25 ft deep, and had water levels at depths of less than 10 ft from ground level in the summer of 1974 (fig. 2). In addition to the dug wells, there are 10 cisterns.

Two dug wells on Maxey Flats, located near Daulton School (fig. 2), were reported by the owner to never run dry. In order to have an adequate supply however, some owners must supplement well-water supplies by sources other than ground water. The yield of the dug wells on Maxey Flats may be described as yield sufficient for limited household use. Need for additional water supply depends, not only on ground-water yield from the wells, but also on the volume demands by each well owner.

Dug wells located in weathered bedrock, colluvium, or soil in the area around Maxey Flats are similar in construction, depth, and yield to those located on Maxey Flats. Many cisterns are also present in these areas (fig. 2). Owners of most dug wells located in alluvium however, reported the wells as having sufficient yield for household use. There are few cisterns in the alluvium.

Figure 12 shows specific conductance of all dug wells sampled. The specific conductances are much lower for dug wells than those for drilled wells (figures 9 through 11). This is expected, because (a) length of flowpath and contact time of water with the shallow, unconsolidated materials are shorter than in the deeper rock, (b) many of the soluble minerals have been leached from the unconsolidated materials, and (c) much of the alluvium in stream valleys consists of sandstone and siltstone fragments composed mostly of silica, which does not contribute significantly to water conductance.

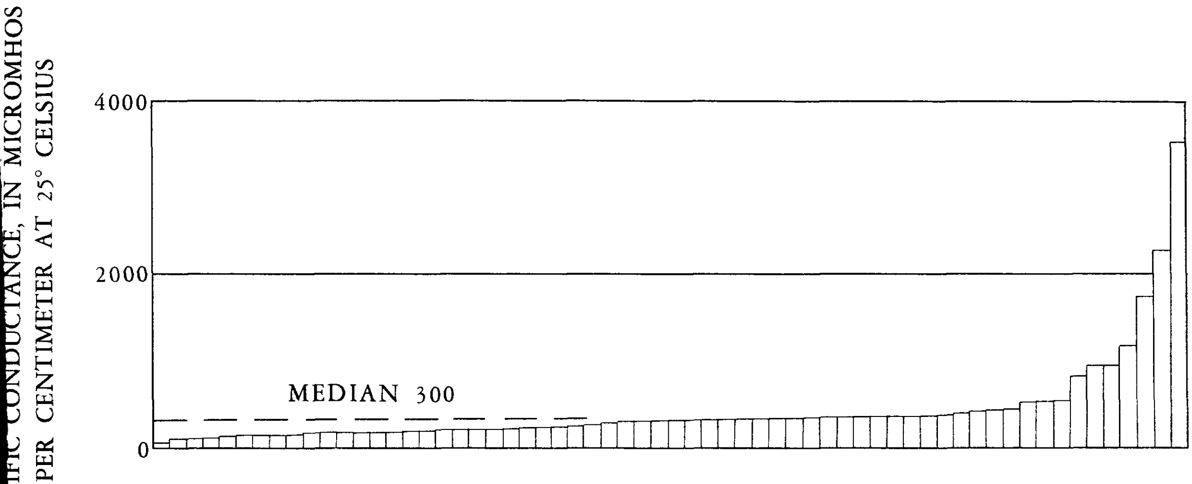


Figure 12.--Bar graph of specific conductances of water from dug wells completed in materials overlying bedrock.

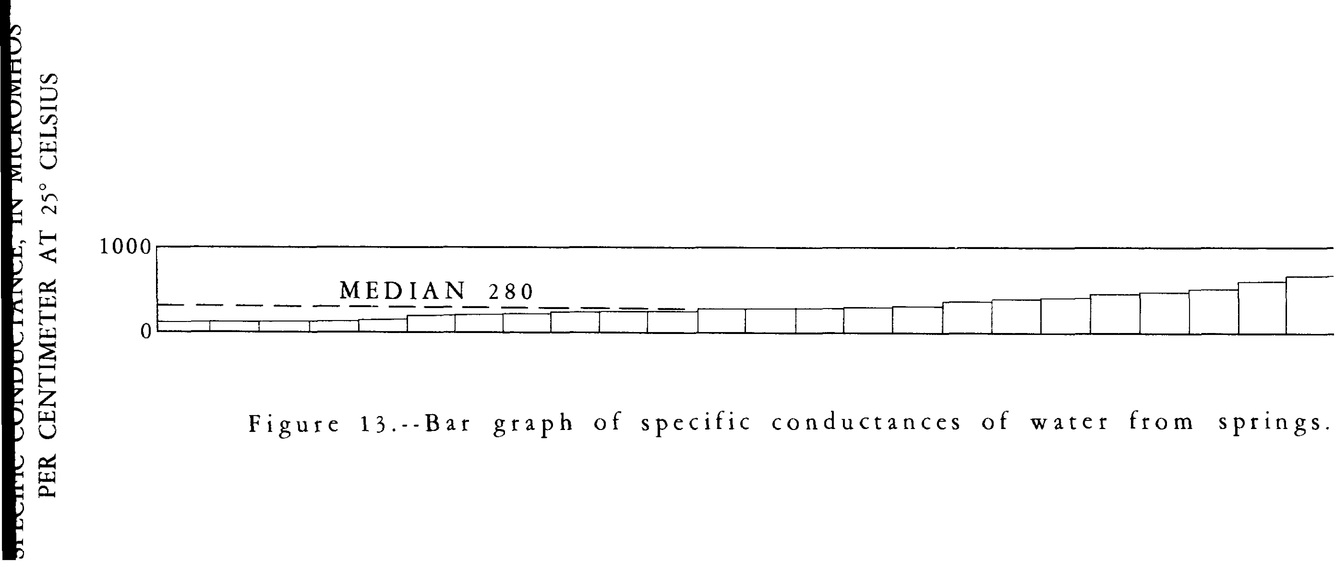


Figure 13.--Bar graph of specific conductances of water from springs.

Five dug wells are located at the base of the hill below the Maxey Flats site (wells W1 through W5, shown on figure 8). These wells are discussed in detail, because they are (a) the closest wells to the Maxey Flats site, and four of these wells provide water for human consumption, and (b) part of the radiochemical monitoring network operated by the State of Kentucky. Wells W1, W2, W4, and W5 are reported by owners to yield sufficient water for household use, and supplementary supplies are not needed. Well W3 is not in use at present.

Water samples were obtained from wells W1 and W2 in April 1975, and well W4 in March 1975, for chemical analysis. The samples were filtered through 0.45 micrometer filters and an alloquot acidified in the field within 2 hours after collection. A summary of the analyses is given in table 4.

Well W1 is completed in Drip Springs Hollow alluvium, about 50 to 100 ft west of the stream. Relative elevations of the water level in well W1 and the water level in the stream directly adjacent to the well were measured at low flow in the summer of 1975. The stream channel is rather flat at this location, with less than 1 ft difference in elevation in a 30 ft length of stream channel. The water in most parts of the stream was less than 1 in deep, and was 0.9 ft lower than the water level in the well. Assuming hydraulic connection between the well and the stream, flow from the alluvium to the stream was occurring. During periods of higher streamflow, the direction of flow probably reverses, so that the alluvium is partly recharged by runoff from the Maxey Flats site.

Specific conductances of water from well W1, and from the stream adjacent to the well, were measured on site once in July 1975, and once in August 1975. Conductances were 210 μmho/cm for both samples of the well water. The values were 205 and 208 μmho/cm, respectively, for the samples from the stream. The similar conductances indicate a common source, and probable hydraulic connection between the well and the stream.

The specific conductances of water from well W1 are much lower than those obtained from (a) bedrock wells in the Maxey Flats vicinity (figures 9 through 11), and (b) most wells on the Maxey Flats site, which are greater than 1,000 μmho/cm. Based on the conductance data and the chemical analyses, it is concluded that most water supplying well W1 originates from direct infiltration of rainfall into the alluvium, plus infiltration of overland runoff originating from the hills upstream from the well. Some water may be from regolith and colluvium. Relatively small contribution may be from bedrock.

Well W2 is located in a wedge of sediments that have accumulated at the base of the small valley at the south end of the Maxey Flats site. This sediment saturates to near ground level. The water level in the

Table 4.--Chemical analyses and specific conductances of water from wells W1, W2, and W4, March and April, 1975. Analyses by U.S. Geological Survey.

Well	Specific conductance μmho/cm	Dissolved solids (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Bicarbonate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)
W1	202	141	13	8.6	3.7	6.0	7.0	2.3	77
W2	308	249	13	7.0	3.8	3.8	0	1.4	130
W4	100	62	10	2.9	4.0	6.9	22	4.5	23

well was measured in July 1974, and was 5 ft below ground level. Numerous seeps were observed on the front and sides of the sediment wedge during the year of study. Specific conductance of water taken from well W2 in July 1974 was 280 micromhos per centimeter. Based on the specific conductance, it is concluded that most of the water in the sediment wedge is of near-surface origin, as described for well W1. Surface flow from the southern part of the Maxey Flats site therefore apparently provides most recharge to this area.

Well W4 is located in unnamed valley, about 75 ft from the nearest point in the stream channel, and is completed in alluvium. Relative elevations were measured of the water level in well W4 and water levels at three points in the streambed near the well. The measurements were made during low flow, when water depth was less than 2 in. At a point 30 ft upstream from the well, the water level in the stream was 0.6 ft below the water level in the well. The water level in the stream was 2.5 ft and 4.5 ft below the water level in the well at points about 50 ft and 70 ft downstream from the well, respectively. Assuming hydraulic connection between the well and the stream, the stream was gaining water from the alluvium at the time of measurement. Flow probably reverses during periods of large discharge, so that overland flow originating from the hills upstream from the well, including the Maxey Flats site, supplies recharge to the alluvium.

Specific conductance of a water sample taken from well W4 in July 1974 was 90 μmho/cm. Because of the relatively low conductance, it is concluded that the origin of most of the water in well W4 is from near-surface flow, as described for well W1. Similar conditions and origins of flow described for wells W1 and W4 are likely for wells W5 (conductance 175 μmho/cm) and W3 (conductance 360 μmho/cm). Unlike the other wells, well W5 is isolated from surface and ground-water flow from the Maxey Flats site. Flood-frequency data for Fox Creek show that floods with frequency as large as 500 years (probability of occurring once in 500 years, on the average) could not cause sufficient reversal of gradient on Rock Lick Creek so that flow from the Maxey Flats site would reach well W5.

Springs

Twenty-seven springs were inventoried. This is estimated to be less than one-half, possibly less than one-quarter, of all springs present in the 5-mi radius of study area. It was not possible to determine, by observation, where the water from these springs originated. Most springs are located in colluvium and soil. All springs on bedrock are located on hillsides, or at the bases of hillsides. The slopes just above the springs are usually covered by colluvium and soil, from which ground water discharges. Observations of springs were therefore not useful in determining positions of saturated zones in bedrock.

Information regarding spring locations was obtained by questioning local residents, many of whom use springs for water supply. Most residents live in valley bottoms, and know the locations of springs near their homes. Virtually no one lives on the hillsides, which are steep and covered with dense forest. Therefore, fewer springs were inventoried on hillsides, as compared to valley bottoms.

The contact of the Ohio Shale and upper part of the Crab Orchard Formation occurs near the break in topographic slope from the hillsides to the valley bottoms in most (central part) of the study area (fig. 2). This results in a large percentage of springs inventoried being located near the lower contact of the Ohio Shale. The break in slope at the perimeter of the study area occurs near the contact of the upper and lower parts of the Crab Orchard Formation, or near the top of the Ohio Shale. Springs are also present in these areas, but relatively fewer were inventoried than in the central part of the study area.

Water samples were obtained from most springs for measurements of specific conductance. Values are shown in figure 13. Specific conductances are low compared to those for water from bedrock wells (figs. 9 through 11). Because of the low specific conductance, it is concluded that the water in most springs originates from (a) infiltration of rainfall or surface runoff into colluvium and soil, then movement through this material until it discharges at the surface, or (b) shallow (a few feet) infiltration into the bedrock, then discharge at the surface.

Conclusions regarding near-surface origin of spring water should not be construed to mean no water flows from bedrock to the surface. Water flows through the rocks, as described earlier in the report. Discharge of water from bedrock to the surface, or beneath soil and colluvium, will occur because different hydraulic conductivities in the rocks will cause lateral flow. The water from bedrock is evidently diluted considerably by water from near ground surface.

Some springs around Maxey Flats could be due to ground-water discharge that is mostly from saturated zones in bedrock, but it is not certain if this is true. On the north-central side of Maxey Flats is a small valley called Sulfur Springs Hollow. Local residents in that area did not describe any spring locations in the valley, and none were inventoried. If springs with large concentrations of dissolved solids and gasses are present in the valley, the water could be discharging directly from bedrock. In Drip Springs Hollow, there are numerous seeps, both on the alluvial-valley bottom and in the colluvium at the bases of hillsides. Small areas around these seeps contain deposits which appear to be iron oxide. No samples could be obtained from the seeps for measurement of specific conductance, because insufficient water was available.

Spring 1 is located in the major drainageway for the Maxey Flats site (fig. 8), and is a sampling point in the radiation monitoring network operated by the State of Kentucky. The sampling point is a pool formed at the base of a wet, steep outcrop of Ohio Shale. To each side of the rock face are steep hills covered with colluvium and soil. Water was observed dripping over the rock face, even during dry summer months when there was no surface flow in the small valley above the face, and the surfaces of the colluvium and soil on the adjacent hillsides were dry. Specific conductance of a water sample obtained from the pool during a dry period in July 1975 was 425 μmho/cm.

Spring 1 is located about 75 ft above the base of the Ohio Shale. Altitude of the top of the spring was obtained by a leveling traverse made from a U.S. Geological Survey reference mark located near Drip Springs Hollow. Closure of the traverse was 0.2 ft from beginning altitude. The altitude of the top of the seepage face was 808 ft. This was 30 ft above the low water levels measured in well 5E, located on the Maxey Flats site about 1,000 ft northwest of the spring (fig. 8). Well 5E is open to the entire thickness of the Ohio Shale.

If the location of spring 1 is the position of the water table in the Ohio Shale, the altitude difference between the spring and the water level in well 5E could possibly be due to composited potentials in the well (described in a later section, Hydrologic Information from E-wells). However, specific conductances of water in well 5E range from 6,000 to 8,000 μmho/cm, which are much greater than the 425 μmho/cm measured at the spring. Based on specific conductance, it is concluded that most of the water at spring 1 originates from near-surface sources. Continuous water yield during the dry season is probably due to continuous flow from the mantle, and near-surface (a few feet depth) bedrock. Small amounts of water may enter the spring from saturated zones in bedrock.

Spring 2 is located near the top of the Ohio Shale on the west side of the Maxey Flats site (fig. 8), and is occasionally dry in summer and fall. The specific conductance of water obtained from the spring in October 1974 was 580 μmho/cm. Origin of the water is probably similar to that for Spring 1.

HYDROLOGIC INFORMATION FROM WELLS DRILLED

ON THE MAXEY FLATS SITE IN 1962

Walker (1962) described the lithology and injected-water acceptance in eight wells drilled in 1962. Depths of these borings range from 39 to 49 ft, and locations are shown on figure 8. All the wells are completed in the Nancy Member, except wells 2 and 3, which may have been drilled into the upper few feet of the Farmers Member. The wells were reported dry when drilled, but a "moist zone" was described in well 5 below 19 ft (Walker, 1962). Walker attributed moisture in this zone as probably due to secondary openings in the Nancy Member below depth 19 ft. The length of time the wells were measured for possible water-level recovery is unknown.

Water-injection tests were conducted in selected intervals of seven of the eight test holes. Pressures used in wells 1, 3, 4, 5, and 6 were 25 lb/in^2. Water-acceptance rates for eight tests in these five wells ranged from 0.008 gal/min to 0.603 gal/min, with median at 0.031 gal/min. Well 2 was not tested, and acceptance rates for well 7 were not measured. Water-acceptance rates in well 8 were greatest, and were 0.437 gal/min at 25 lb/in^2 for the interval 20 to 36 ft, and 0.728 gal/min at 10 lb/in^2 for the interval 0 to 36 ft (Walker, 1962).

The injection tests show small water-acceptance rates for most wells, but the larger acceptance rates in well 8 illustrate the jointed character of the rocks. Well 8 may have encountered one or more joints in the Nancy Member, and the acceptance rate of 0.728 gal/min at 10 lb/in^2 injection pressure indicates a more permeable zone above depth 20 ft. This permeable zone is probably the sandstone marker bed.

Open-end, steel casing was set from near ground level to the bottoms of the drill holes. The casing was not cemented, so that near-surface infiltration can percolate down the outsides of the well casings. Only occassional measurements were made of depths to water in the wells for the present study. Water levels in most wells ranged from ground level to about 15 ft below ground level. Most of the wells are of little value in determining positions of saturated zones, because surface water has infiltrated the casing-borehole annuli. However, water levels in wells 3, 6, and 8 were at depths of about 19 ft below ground level, and may indicate a saturated zone in the sandstone marker bed. No specific conductance measurements were made of water from wells 1 through 8.

Altitudes are given in table 5 for all wells on the Maxey Flats site. Beginning altitude was 1,060 ft, taken at the intersection of the road crossing Maxey Flats and the road leading to the Maxey Flats site. This altitude is estimated to have accuracy of plus or minus 3 ft relative to mean sea level. Altitudes of all wells have accuracy of plus or minus 0.03 ft, relative to each other.

Table 5.--Altitudes of wells on the Maxey Flats site.

Well	Altitude, top of casing (feet)	Altitude, ground level (feet)
1	1050.65	1048.2
2	1050.09	1049.7
3	1055.07	1054.2
4	1064.32	1060.8
5	1051.85	1051.6
6	1054.55	1052.1
7	1058.65	1054.9
8	1053.70	1052.3
1E	1042.37	1040.75
2E	1031.70	1029.79
3E	1021.67	1021.56
4E	1034.80	1034.46
5E	1028.55	1027.74
6E	1046.68	1045.58
8E	1045.58	1044.39
9E	1040.06	1038.67
10E	1052.03	1050.15
11E	1055.19	1053.34
12E	1050.07	1048.74
13E	1053.34	1052.93
14E	1054.59	1054.44

Reference mark for top of casing is blue paint spot on casing. Reference mark for ground level is blue paint spot at junction of casing and cement surface seal on E-wells, and unmarked ground at base of casing for other wells.

HYDROLOGIC INFORMATION FROM E-WELLS

Fourteen wells were drilled on the Maxey Flats site in 1973 and described by Emcon Associates (1975). One of the wells (7E) collapsed during drilling, and is no longer in existence. Data were collected from the remaining 13 wells, which are referred to as "E-wells" in this report, to avoid confusion with the eight wells drilled during a study by Walker (1962).

Well Construction

Few specific details regarding construction of the E-wells are available. Figures 14 and 15 are modifications of diagrams for proposed E-well construction. The original diagrams were drafted before the E-wells were drilled (J. McCollough, Emcon Assoc., personal commun., 1975). Most wells have cement in the casing-borehole annulus to a depth of about 10 ft, and are open to the rocks from 10 ft to about 90 ft. Four wells are cemented to greater depth, and all but one of these four wells (3E) are open only to one rock unit.

Casing diameter and total depths of the wells were measured, and are approximately as shown in figures 14 and 15. The 3 in borehole diameters in the lower parts of the holes were verified, but the diameters of the upper parts of the wells could not be verified. Data from gamma and gamma-gamma geophysical logs indicate the depth of cement below ground surface is about 150 ft in well 5E, and about 10 ft in wells 1E, 2E, 6E, 10E, and 11E. Cement depth could not be verified for other wells, and is assumed to be as shown in figure 14.

Water Quality

Water samples were obtained from some wells in March 1975 for chemical analysis. Table 6 shows results of the analyses and specific conductance of water from most wells (wells 4E and 9E were not sampled). Water quality is somewhat similar in wells 2E, 8E, 12E, 13E, and 14E, but is considerably different in wells 5E and 11E. Water from well 5E has greater total dissolved solids, sodium, and chloride, but less sulfate than water from other E-wells. The differences in water quality from well 5E are probably due to the water coming only from the Ohio Shale, whereas other wells obtain water from overlying rocks.

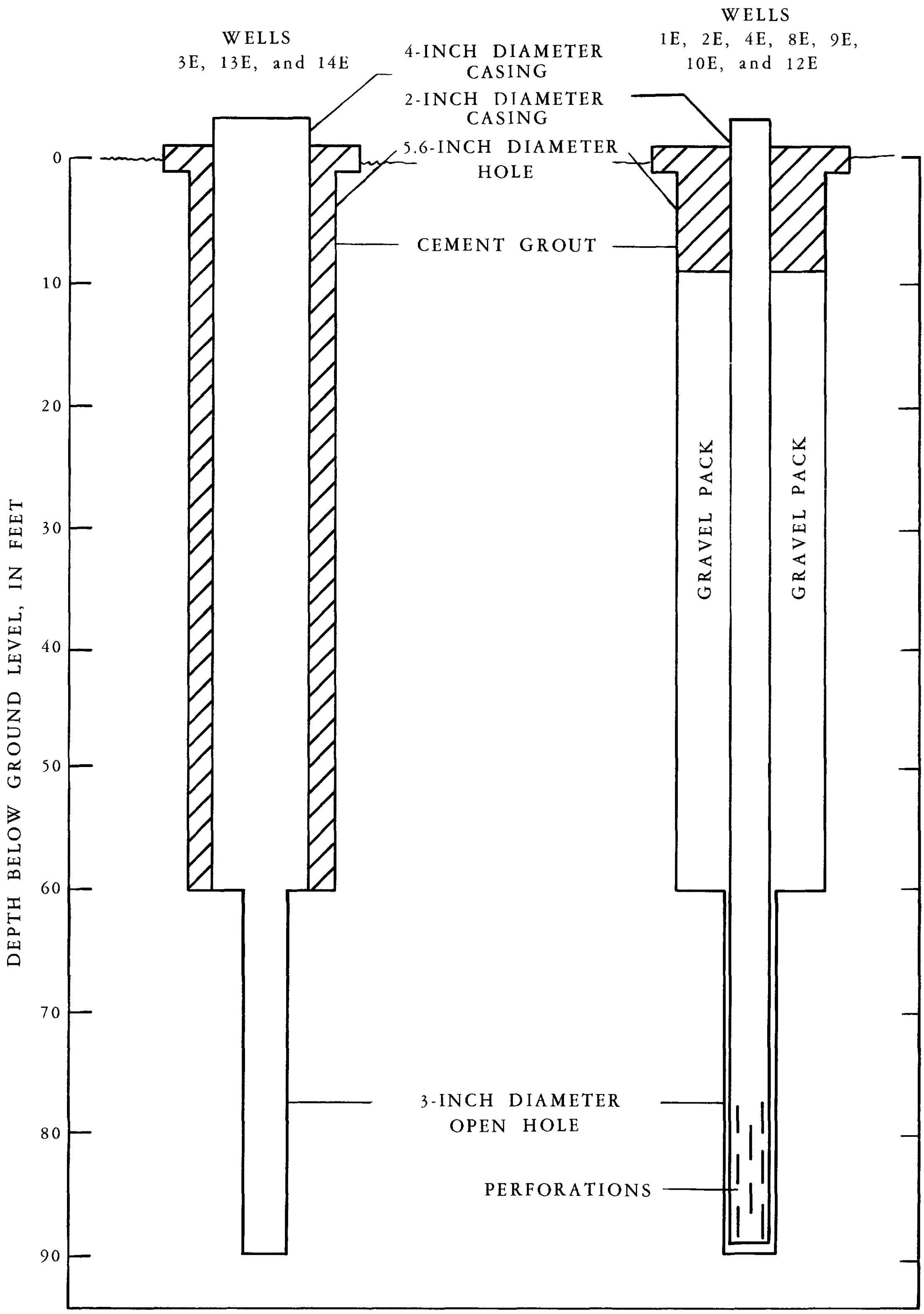


Figure 14.--Diagram of proposed construction for most E wells (modified from McCollough, personal communication, 1975).

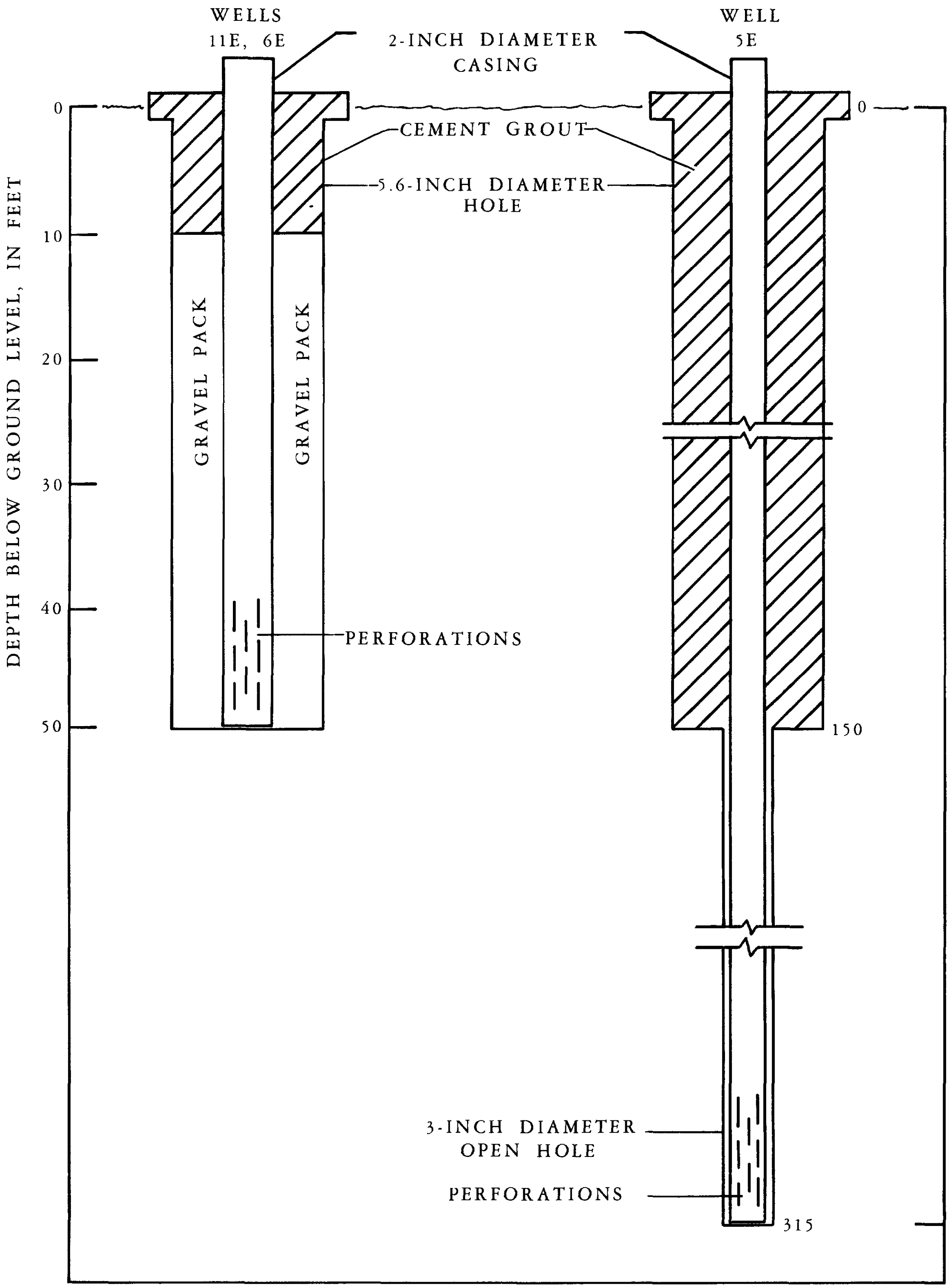


Figure 15.--Diagram of proposed construction for wells 5E, 6E, and 11E (modified from McCollough, personal communication, 1975).

Table 6.--Chemical analyses and specific conductances of water from E-wells, March 1975. Analyses by U.S. Geological Survey.

Well	Well open to rock units*	Specific conductance µmho/cm	Dissolved solids (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Bicarbonate (mg/L)	Chloride (mg/L)	Sulfate (mg/L)
1E	N-F-H-S	1800	-	-	-	-	-	-	-	-
2E	N-F-H-S	1520	1440	180	120	7.0	80	538	16	660
3E	H-S-B	5500	-	-	-	-	-	-	-	-
5E	O-UCO	8000	4450	64	18	18	1800	734	2400	9.6
6E	N-F	2500	-	-	-	-	-	-	-	-
8E	N-F-H-S	960	647	92	60	11	66	612	9.5	99
10E	N-F-H-S	2500	-	-	-	-	-	-	-	-
11E	N-F	2500	2500	150	270	14	150	363	87	1300
12E	N-F-H-S	1380	1050	98	78	11	180	795	13	260
13E	F	1790	1200	67	39	8.0	260	364	110	470
14E	F	1670	1070	82	59	7.5	220	818	51	210

*N-Nancy Member of the Borden Formation, F-Farmers Member of the Borden Formation, H-Henley Bed of the Farmers Member of the Borden Formation, S-Sunbury Shale, B-Bedford Shale, O-Ohio Shale, UCO-upper part of the Crab Orchard Formation.

Water from well 11E has total dissolved solids about twice as large, and magnesium and sulfate concentration at least twice as large as water from wells 2E, 8E, 12E, 13E, and 14E. Well 11E is open to the Nancy Member and the upper 2 to 5 ft of the Farmers Member. It would be expected that ionic concentrations in water from well 11E would not exceed those in water from wells open to deeper rocks, as are the wells described above. The greater concentrations in well 11E may mean this well is not open to major joints. Water entering the well may be from minor joints in which water movement is very slow, thus allowing more time for rock minerals to be dissolved.

Well 6E contains water with specific conductance the same as water from well 11E (2,500 μmho/cm), and is open to the same rock interval. As described for well 11E, this relatively large specific conductance may mean that the well is not connected to major joints. The same reasoning may be used to explain the high conductances of 5,500 μmho/cm in well 3E and 2,500 μmho/cm in well 10E, even though these wells are open to deeper rocks.

Water Levels and Zones of Saturation

Water levels were measured in all E-wells at about 2-week intervals. Continuous water-level measurements were made for some wells, and these data showed most wells respond to rainfall or barometric pressure changes, and possibly both. Water levels in most wells also respond to seasonal changes.

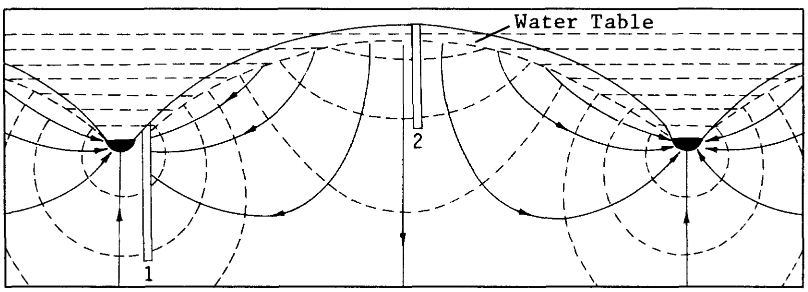
Some definitions and explanations are appropriate before further discussion of water levels in the wells at Maxey Flats. A material is homogeneous if its hydrologic properties are identical everywhere. A material is isotropic if all its significant properties are independent of direction. Head, as used in this report, is the height above a standard datum of the surface of a column of water that can be supported by the static pressure at that point, and is the sum of the elevation head and the pressure head. A water table is that surface in an unconfined water body at which pressure is atmospheric. It is defined by the levels at which water will stand in wells that penetrate the water body just far enough to hold standing water. A potentiometric surface is a surface that represents the static head above a reference datum. As related to an aquifer, the potentiometric surface is represented by the levels to which water will rise in tightly cased wells. The water table is a particular potentiometric surface. Where the head changes appreciably with depth in an aquifer, a potentiometric surface is meaningful only if it describes the static head along a particular stratum in that aquifer (Lohman and others, 1972).

Equipotential lines are lines of equal potential energy. Flow lines are lines showing direction of flow, and intersect equipotential lines at right angles in isotropic media. Although rocks at Maxey Flats are not isotropic, individual rock units might be assumed so on a large scale. Such an assumption would imply that all hydrologic properties are averaged throughout a rock stratum.

Because rock units such as the Henley Bed and Bedford Shale apparently have less hydraulic conductivity than rocks overlying them, flow lines in saturated parts of the overlying strata should have a horizontal component. However, a vertical-flow component must also exist, because water is present in the underlying Ohio Shale. The flow lines are analogeous to resultant vectors with components in both horizontal and vertical directions. The flow lines are thus at angles other than horizontal, and are perpendicular (or nearly so) to equipotential lines, which are at angles to the vertical. The water levels in wells drilled on Maxey Flats therefore do not represent the true position of the water tables, nor any one potentiometric surface, because the water levels represent a composite of all potentials present in the entire open-hole interval in each well. This composite can be anywhere within the range of highest to lowest heads originally present in the open-hole interval.

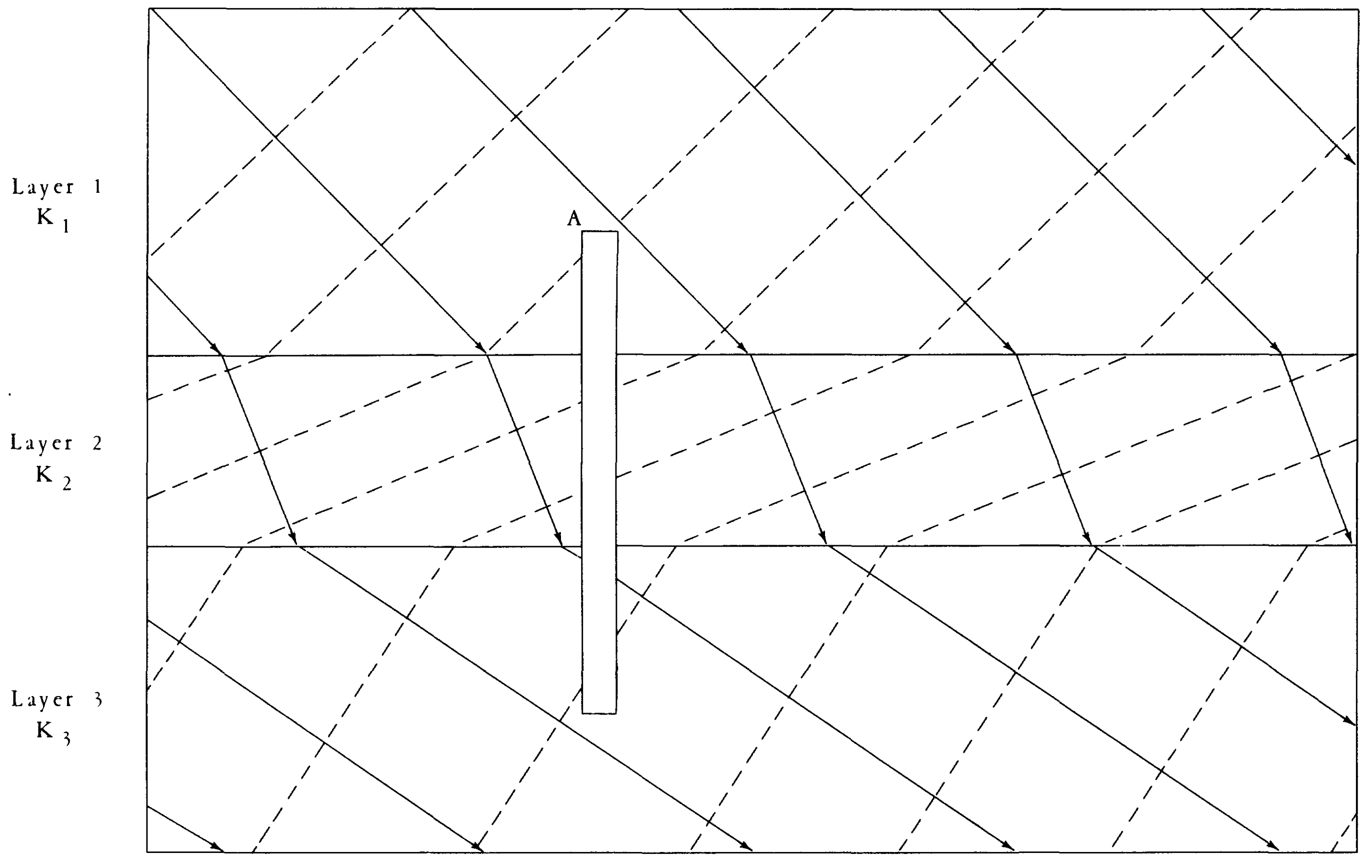
Composited potentials are discussed in detail here, because understanding this principal is vital in interpretation of water-level data and description of the complexity of the ground-water system at Maxey Flats. Figure 16 shows a rather simple case of a single-aquifer system with uniform recharge to the upland area and discharge to adjacent streams. This diagram would represent the hydrologic system at Maxey Flats if the area were underlain by one isotropic stratum instead of many strata with different hydrologic properties. Well 1 encounters increasing potentials with depth, and would flow when completed at the depth shown. Well 2 encounters decreasing potentials with depth, and the water level in the well would be below the water table when the well was completed at the depth shown. The water tables at Maxey Flats intersect ground surface at the adjacent streams, as shown in figure 16, and also intersect ground surface higher up on the hill, so that the hillside is a seepage face.

If the hill in figure 16 were a multiple-aquifer system, as is Maxey Flats, a detailed section of one part of the hill might be as shown in figure 17. This figure shows a saturated, nonjointed, three-aquifer system which is homogeneous and isotropic within each aquifer (layer). The system contains a set of equipotential lines at different angles in each layer, with both vertical and horizontal components. Potentials decrease with depth, but the decrease per unit depth is different for each layer, depending on the hydraulic conductivity. Layers with lower hydraulic conductivity require a greater vertical gradient to transmit the same flow rate.



Solid lines are flow lines, with arrowheads denoting direction of flow.
Dashed lines are lines of equal potential.
Intervals shown at 1 and 2 denote open-hole intervals of wells.

Figure 16.--Flow net of homogeneous, isotropic, single-aquifer system with uniform recharge to upland area. From Hubbert (1940, p. 930, fig. 45).



K is hydraulic conductivity and $K_3 > K_1 > K_2$

Solid lines are flow lines, with arrowheads denoting direction of flow.

Dashed lines are lines of equal potential.

Interval shown at A is open-hole interval of well.

Figure 17.--Flow net of non-jointed, multiple-aquifer system.

As shown in the two-dimensional flow system (fig. 17), a potentiometric surface would be meaningful only if it were described along a particular level in each layer. Definition of at least two potentiometric surfaces in each layer would be necessary to describe the distribution of head (and direction of flow) in the three-layer system. Maxey Flats has at least eight layers. For a three-dimensional problem (head changes differently in the direction perpendicular to the diagram), head data would also be needed in the third dimension.

If a well were placed as indicated in figure 17, open to the entire interval shown, its equillibrium water level would result from the composite of all potentials encountered in the open section of the well. If a joint were present in the three layers, the system could be further complicated in that the hydraulic conductivity of the joint could be different than those in the three layers, and the flow net would be more complex than that shown in figure 17.

In the few wells at the Maxey Flats site that are open to one rock unit, the water levels will be somewhat below the first potentiometric surface (the water table), because all wells are located in simlar position to the recharge, or upland, area of the hill in figure 16. Most wells are open to several rock units, and water levels in these wells represent composite potentials that may be far below the actual water table.

The composite potentials can have two effects pertinent to interpretation of water-level data from Maxey Flats, as follow. (1) Water levels in wells open to all of one rock unit, particularly one with a thick zone of saturation, will show smaller horizontal and greater vertical gradients than those finished only in the upper part of that zone of saturation, and (2) water levels in wells that are open to several rock units may not indicate zones of saturation in the upper rocks. The water contributed by the upper zones may actually flow out of lower zones at such a rate that the water level in the well would never rise to the upper zone. This may be particularly true where unsaturated intervals are present between saturated zones.

Assuming wells have good hydraulic connection to the rocks (no obstructions on borehole walls or well casings), water-level differences among wells would result, not only from (a) such variables as lithology, bedding, fissility, jointing, and spatial relationships regarding recharge and discharge areas, but also from (b) the possibility that some wells may be open to major joint systems and other wells may be open only to minor joint systems, even in the same rock strata. The two joint systems could have different flow rates, head losses, and water quality.

The definitions and explanations described in the previous paragraphs must be kept in mind when attempting to interpret water-level data from the E-wells. It is assumed that the ground-water system is unconfined (nonartesian). The assumption is believed reasonable because (a) most flow occurs in joints, (b) rocks above the base of the Ohio Shale at the Maxey Flats site cover relatively small areal extent and have shallow dip (25 to 40 ft/mi), and (c) Maxey Flats is an isolated plateau, and it is logical that recharge is from vertical infiltration of rainfall into the top of the hill.

All E-wells except 1E, 4E, and 9E are sampled about twice-monthly for radiochemical analysis. Well 1E is sampled only when sufficient water has accumulated for a sample (about once per year), and wells 4E and 9E do not contain sufficient water for sampling. Withdrawals from well 13E were temporarily ceased until static water levels could be measured and hydraulic testing performed.

Water levels in some wells recover from the 1 to 2 gal sample withdrawals in less than 1 day. In other wells, water levels do not recover to pre-sampling level between bi-monthly sampling periods. Characteristics of water-level recoveries are shown in table 7. Included in this table are measured well depths, ranges of water levels, and open intervals in the wells. The differences between measured well depths and those depths shown in figures 14 and 15 may be due to sediment accumulations in the bottoms of the wells, or changes from "as planned" depths as the wells were drilled.

Well data and indications of saturated zones are discussed in some detail, because of variable well-by-well response to seasonal change and to water withdrawals, and because wells with similar construction in the same strata have very different water levels. Reference to table 7, particularly the rock intervals to which the wells are open, may be useful in the discussion.

Water depths in the bottoms of wells 6E and 11E are 1 to 2 ft during most of the year. In December 1974, the water level in well 11E rose about 7 ft, which is about 3 ft above the base of the Nancy Member. The water level remained at that level until March 1975, then declined to the former level. No such changes were observed in well 6E. The data from the two wells indicate a saturated zone in the shale-sandstone sequence at the top of the Farmers Member. The data from well 11E indicate a saturated zone in the bottom of the Nancy Member during late winter or early spring, but this is inconclusive because the water level in well 6E did not rise during this period.

Wells 2E, 8E, and 12E have static water levels in the lower part of the Farmers Member, but flow from upper to lower zones may occur in the wells. The data indicate a saturated zone in the Farmers Member, and

Table 7.--Water levels in E-wells.

Well	Open to rock units	Approximate recovery time after one-gallon withdrawals (days)	Depth of well (feet)	Range of depth to water level (feet)	Range of water level altitude (feet)	Seasonal variation in water level?
1E	N-F-H-S	Tens*	86.8	85.0- 86.4	955.8- 954.4	Not determined.
2E	N-F-H-S	0.5	89.0	67.6- 69.3	962.2- 960.5	Yes.
3E	H-S-B	Tens*	85.5	83.5- 84.8	938.1- 936.8	Not determined.
4E	N-F-H-S	**	87.3	86.6- 86.8	947.9- 947.7	No.
5E	O-UCO	0.5-1	311	247.4-250.1	780.3- 777.6	Not determined.
6E	N-F	Tens*	49.0	47.2- 48.7	998.4 996.9	Not determined.
8E	N-F-H-S	5	89.7	76.8- 78.8	967.6- 965.6	Yes.
9E	N-F-H-S	**	89.9	89.4- 89.6	949.3- 949.1	Yes.
10E	N-F-H-S	Tens*	90.4	89.6- 89.8	961.4- 960.6	Yes.
11E	N-F	Tens*	49.3	41.0- 49.1	1012.3- 1004.2	Yes.
12E	N-F-H-S	0.5	90.4	71.5- 74.6	977.2- 974.1	Yes.
13E	F	Tens	85.0	75.1- 78.4	979.3- 976.0	Not determined.
14E	F	3	75.0	39.6- 41.1	1014.8 1013.3	Yes.

N-Nancy Member of the Borden Formation, F-Farmers Member of the Borden Formation, H-Henley Bed of the Farmers Member of the Borden Formation, B-Bedford Shale, O-Ohio Shale, UCO-Upper part of Crab Orchard Formation.
All depths referenced to ground level.
*Static water level may not have been measured, because complete recovery may not have occurred between sampling periods.
**Not sampled.

possibly the Henley Bed and Sunbury Shale. A saturated zone in the lower part of the Farmers Member is also indicated by data from well 13E, because a static water level is located in the lower part of the well.

There are considerable differences in the rates of water-level recoveries when comparing wells 2E and 12E with wells such as 8E and 13E. Drawdown of only a few tenths of a foot was measured within minutes after water withdrawals of 2 gal in wells 2E and 12E. Complete recovery took less than 12 hours in both wells. Withdrawals of 2 gal from wells 8E and 13E produced about 6 ft of drawdown in each well, and recovery took about 10 days for well 8E and 20 days for well 13E. Other wells have even slower recovery rates. The differences in rates of water-level recoveries illustrate apparent differences of hydraulic conductivity from place to place at Maxey Flats, even in the same rock strata. Assuming good hydraulic connection of the wells to the rocks, these are likely due to most water movement occurring in joints, and to the number of joints intercepted by the wells.

Well 10E has extremely slow recovery rates, and complete recovery after water withdrawals may not have occurred during the period of study. Although the water levels measured in well 10E are in the Sunbury Shale, no conclusion can be drawn regarding the positions of saturated zones at this location. This is because no static water levels were measured, and water can enter the well from rocks above the Sunbury Shale.

Wells 1E, 4E, and 9E have very shallow depths of water in the bottoms of the wells (usually less than 2 ft), and the water levels are located in the Sunbury Shale. "Slug tests" were performed by adding 1 to 2 gal of water to each of the three wells, raising the levels 3 to 6 ft. The levels slowly declined over a period of several months, and had not reached the original position by the end of the period of study. Assuming that no obstructions were present in the annuli between casings and boreholes, the very slow declines of the raised water levels indicate that (a) hydraulic conductivities in the upper part of the Sunbury Shale and lower part of the Henley Bed are extremely small in the vicinity of the wells, and (b) very little water is contributed to these wells from rocks above the Sunbury Shale.

Data from wells 1E, 4E, and 9E indicate a saturated zone in the Sunbury Shale, because raised water levels declined in the wells, and because static water levels had been measured in the wells prior to the slug test. The data are inconclusive however, because a slow acceptance of ground water under less than the 2 ft of head originally present in the wells could equal a small contribution of water into the borehole from higher rocks.

Water depths of 1 to 2 ft in the bottom of well 3E indicate a saturated zone, or zones, in the Henley Bed, Sunbury Shale, or Bedford Shale. Static water levels in well 5E are about 50 ft above the base of the Ohio Shale, and show presence of a saturated zone in this formation.

The water level in well 14E is stable in the lower part of the Nancy Member. The water level in well 14E is unusually high compared to other E-wells of similar depth and altitude, particularly well 13E, which is also open only to the Farmers Member. The high water level in well 14E may represent a water table in the Nancy Member because (1) its altitude is about 1,014 ft, and is near the range of water-level altitudes in the Nancy Member at well 11E, which is about 1,004 to 1,012 ft, and (2) it is the only E-well located near the center of the Maxey Flats site, and the water level may represent a mounding of the water table in the Nancy Member along the topographic axis of the site. Also, the specific conductance of 1,500 μmho/cm for water from well 14E is comparable to conductances of water in other wells, so very rapid, local infiltration of surface water into the well is not likely.

A summary of interpretation of water-level data follows.

Saturated zones are present in:

(1) Upper, weathered part of the Nancy Member - because domestic water supplies are obtained from dug wells finished in this unit.

(2) Farmers Member - because of water-level data from wells 2E, 6E, 8E, 11E, 12E, 13E, and 14E.

(3) Ohio Shale - because of water-level data from well 5E. If it is assumed that the upper part of the Crab Orchard Formation is the lower hydrologic boundary at Maxey Flats, most flow in the Ohio Shale would be horizontal, and equipotential lines would be vertical. A 135 ft head loss in well 5E for the 185 ft thickness of Ohio Shale would therefore be unlikely, so that the upper part of the Ohio Shale is possibly unsaturated.

Saturated zones may be present in:

(1) Unweathered part of the Nancy Member - because of water-level data from wells 11E and 14E.

(2) Henley Bed, or Sunbury Shale, or Bedford Shale - because of water-level data from well 3E, and possibly wells 1E, 4E, 9E, and 10E. It is unknown if unsaturated zones are present in these units, or if the entire interval from the base of the Sunbury Shale to the top of the Henley Bed is saturated.

The water-level data indicate, generally, that hydraulic head declines with depth, as would be expected for a system with vertical flow.

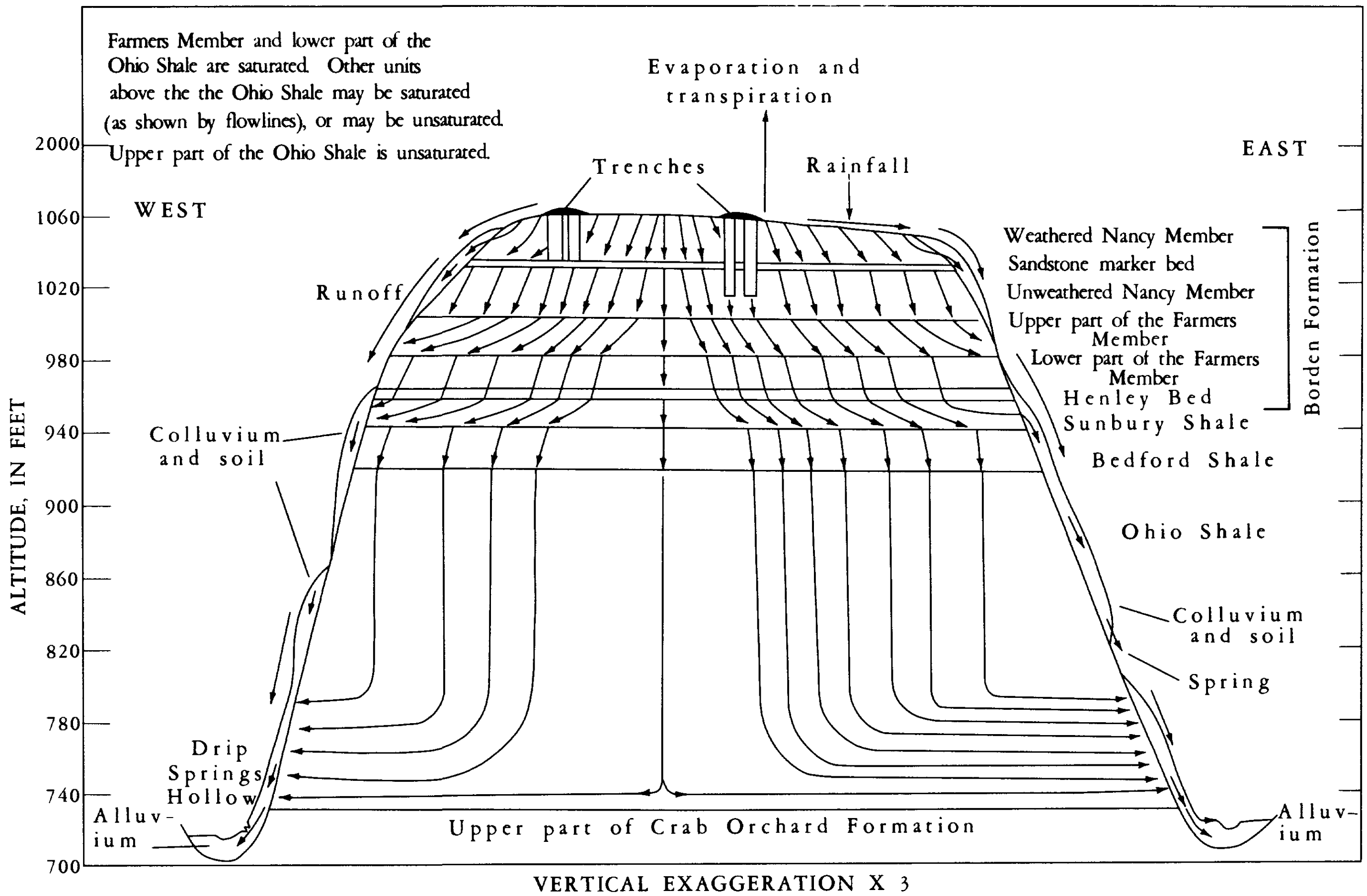
The gradient of the composite potentiometric surface is estimated, using composited potentials in wells 2E, 8E, and 12E. These wells are all open to the same rocks (Nancy Member to the upper part of the Sunbury Shale), recover from 1 gal withdrawals in 5 days or less, respond to rainfall or barometric pressure changes, and have similar water quality. The estimated gradient is S57E at about 0.008 ft/ft, based on water levels measured in June 1975.

It is emphasized that the gradient of the composite potentiometric surface is influenced by all factors described earlier in this section of the report regarding composite heads, and leakage from upper zones to lower zones. The actual shape of the water table is not defined by the water levels in the three wells. The gradient of the water table may be steeper than that given above, because composited potentials indicate shallower gradients than are really present in the rocks. The water table may be influenced by topography, in which case the saturated zone would have the form of an elongated mound, with the axis of the mound oriented in a NE-SW direction.

The system at Maxey Flats is too complex for accurate, quantitative description with the few data available and, perhaps, with much additional data. Only reasonable simplification of the problem can be used to obtain estimates of how ground water moves through the rocks. A simplified, conceptual section of the flow system at Maxey Flats is shown in figure 18, for which it is assumed that the position of the water table is influenced by topography. Also included in figure 18 are relationships of surface-water runoff, infiltration, evapotranspiration, and flow through materials overlying bedrock.

Most aspects of the flow system are shown in figure 18. Recharge occurs by infiltration into the top of the hill. Some recharge to shallow bedrock occurs on the hillsides. Flow in the upper (perhaps unsaturated) part of the Ohio Shale is presumably vertical, and is nearly horizontal in the lower, saturated part of the formation. Rocks above the Ohio Shale have both vertical and lateral components, with greater lateral components in the more permeable rocks. Some, perhaps most, water entering bedrock discharges to ground surface above the Ohio Shale.

Recharge to colluvium is by infiltration of rainfall, and by discharge of water from bedrock. Water in springs is due to discharge from colluvium, overland runoff, and discharge from bedrock. Recharge to alluvium is from overland runoff and flow from colluvium.



VERTICAL EXAGGERATION X 3

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

Figure 18.--Diagrammatic, geologic section of the Maxey Flats site, showing relationship of rainfall, runoff, evaporation, transpiration, and ground-water flow.

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 storage coefficient (S) is the volume of water an aquifer releases or takes into storage per unit surface area per unit change in head (Lohman and others, 1972).

The parameters T and S are needed to quantitatively describe rate and volume of flow through hydrologic units. The saturated thickness of an aquifer, perpendicular to the direction of flow, divided into T gives the hydraulic conductivity of the aquifer. If the hydraulic conductivities, volumetric flow rates, and boundary conditions are known, the head distribution (and direction of flow) can be calculated for a system such as that shown in figure 17. Ideally, for a homogeneous and isotropic medium, only one well in each layer of the system could be sufficient for verification of head calculations. However, the Maxey Flats system is more complicated because of jointing, as described below.

Water-withdrawal tests were made on three wells (8E, 13E, and 14E) to determine T and S values for rocks at Maxey Flats. The water level in well 8E was located in the lower part of the Farmers Member at the time of testing, but the well was also open to the basal Henley Bed and upper part of the Sunbury Shale. Only the Farmers Member was tested in wells 13E and 14E.

Water-level recoveries are shown in figures 19 through 21. Well 14E recovered 30 ft in 6 days, which is a greater recovery rate than occurred in the other two wells. Also, well 14E is 3 in diameter in the lower part of the borehole, but 5 in diameter where recovery was 15 to 21 ft, and 4 in diameter above recovery of 21 ft (fig. 21). Borehole diameters in the recovery sections of the other two wells are 3 in. The greater recovery rate in well 14E is interpreted to reflect the jointed character of the rocks, with greater recovery rates occurring where wells intersect major joints.

The method of analysis used in attempting to determine T and S 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. An example of the aquifer-test analysis is shown in figure 22. Although of similar general shape, the recovery data do not match the type curves in this test, nor do the recovery data from the tests of wells 13E and 14E. For the type of analysis used, the medium tested is assumed to be confined, homogeneous, isotropic; 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

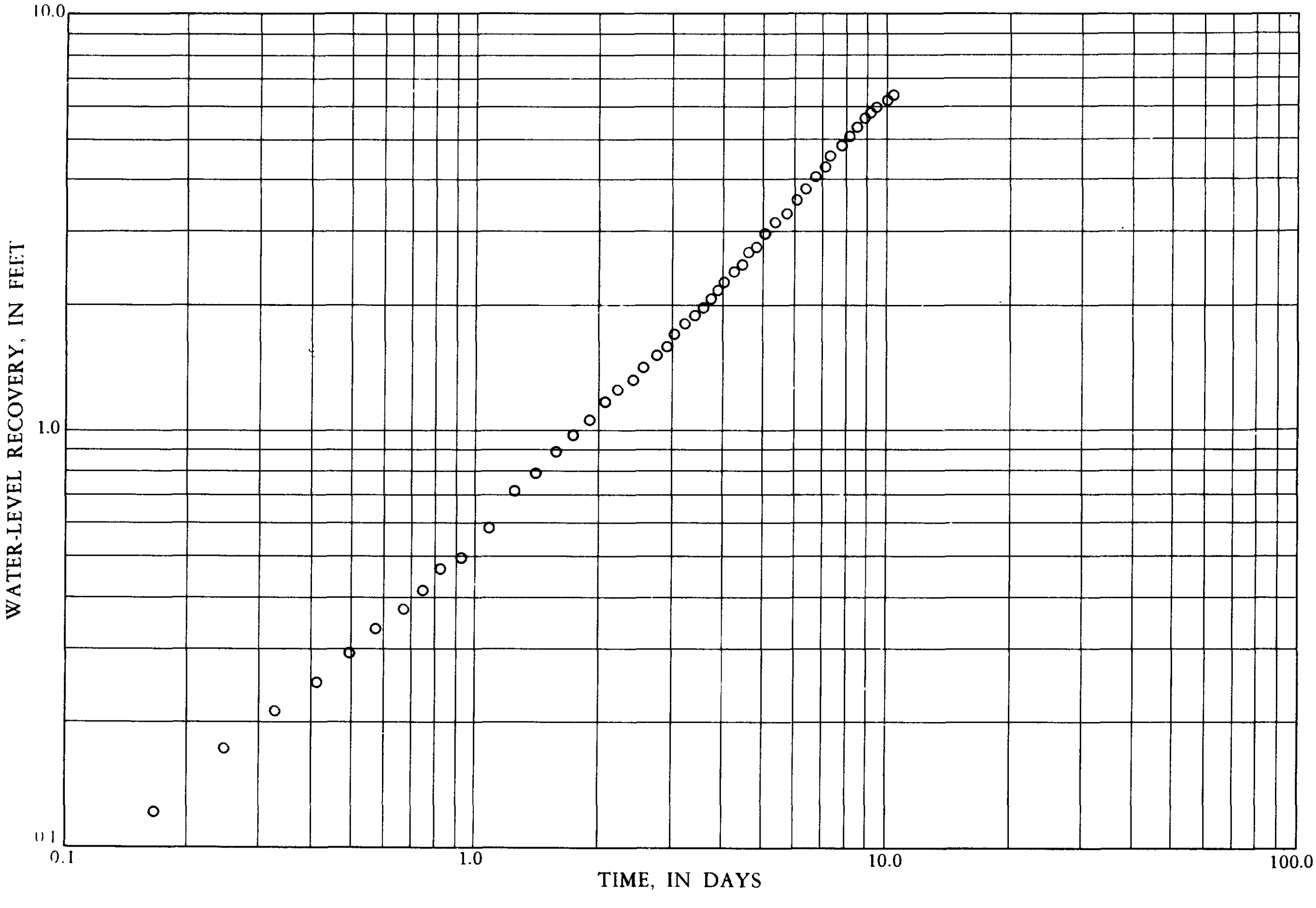


Figure 19.--Log-log hydrograph of water-level recovery from aquifer test of well 8E. Volume withdrawn was 2.1 gal and drawdown was 6.34 ft.

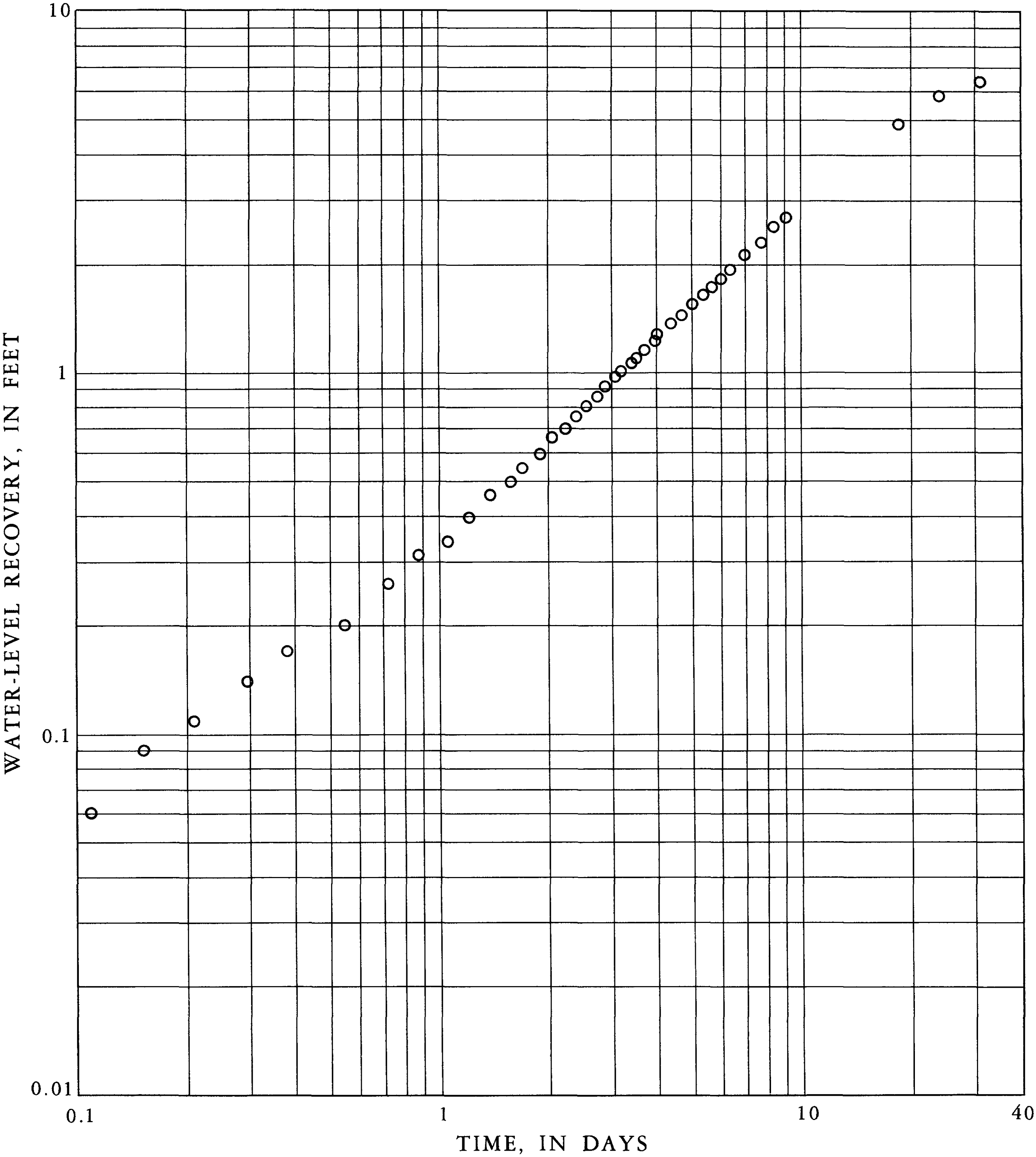


Figure 20.--Log-log hydrograph of water-level recovery from aquifer test of well 13E. Volume withdrawn was 3.0 gal and drawdown was 6.48 ft.

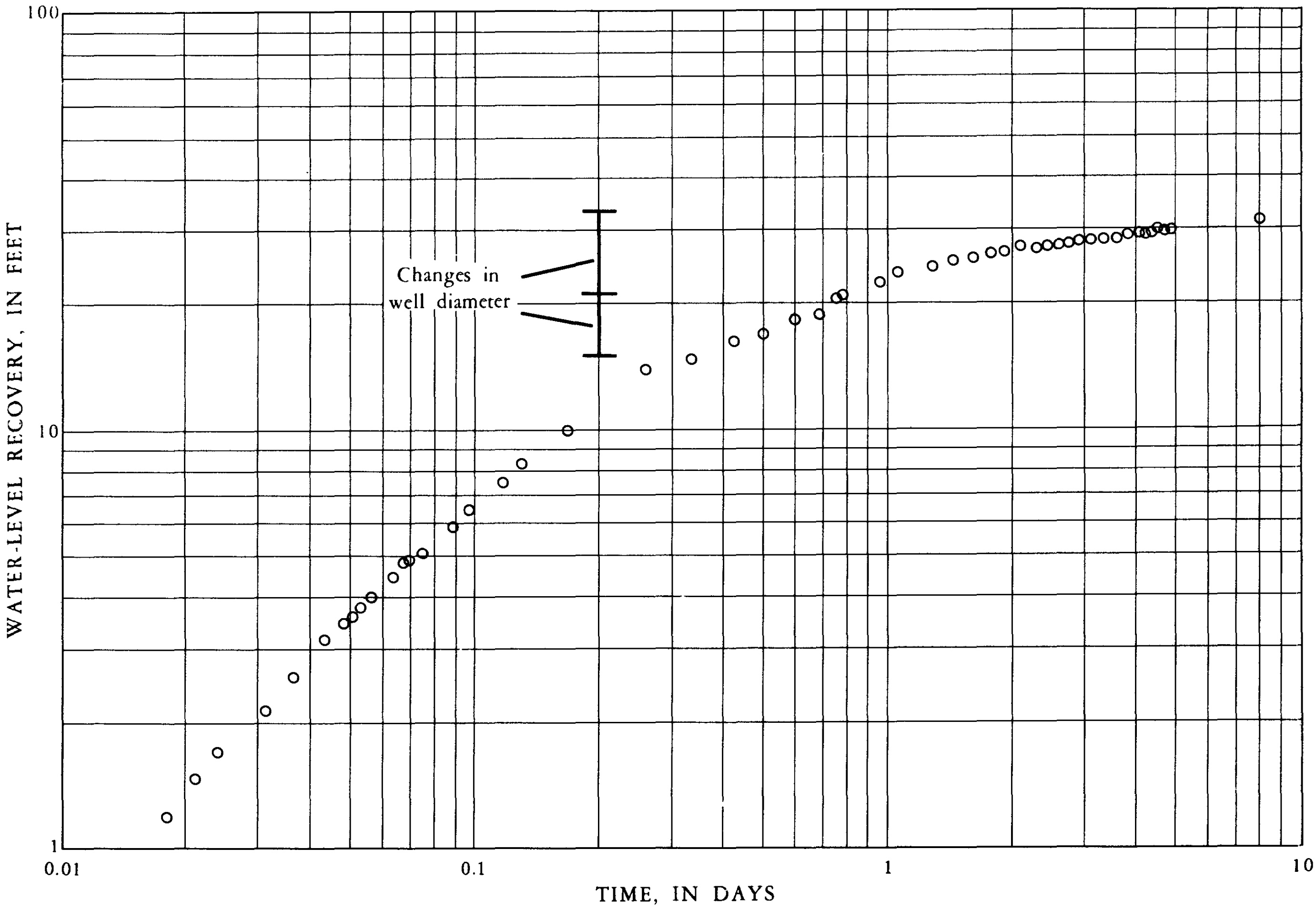
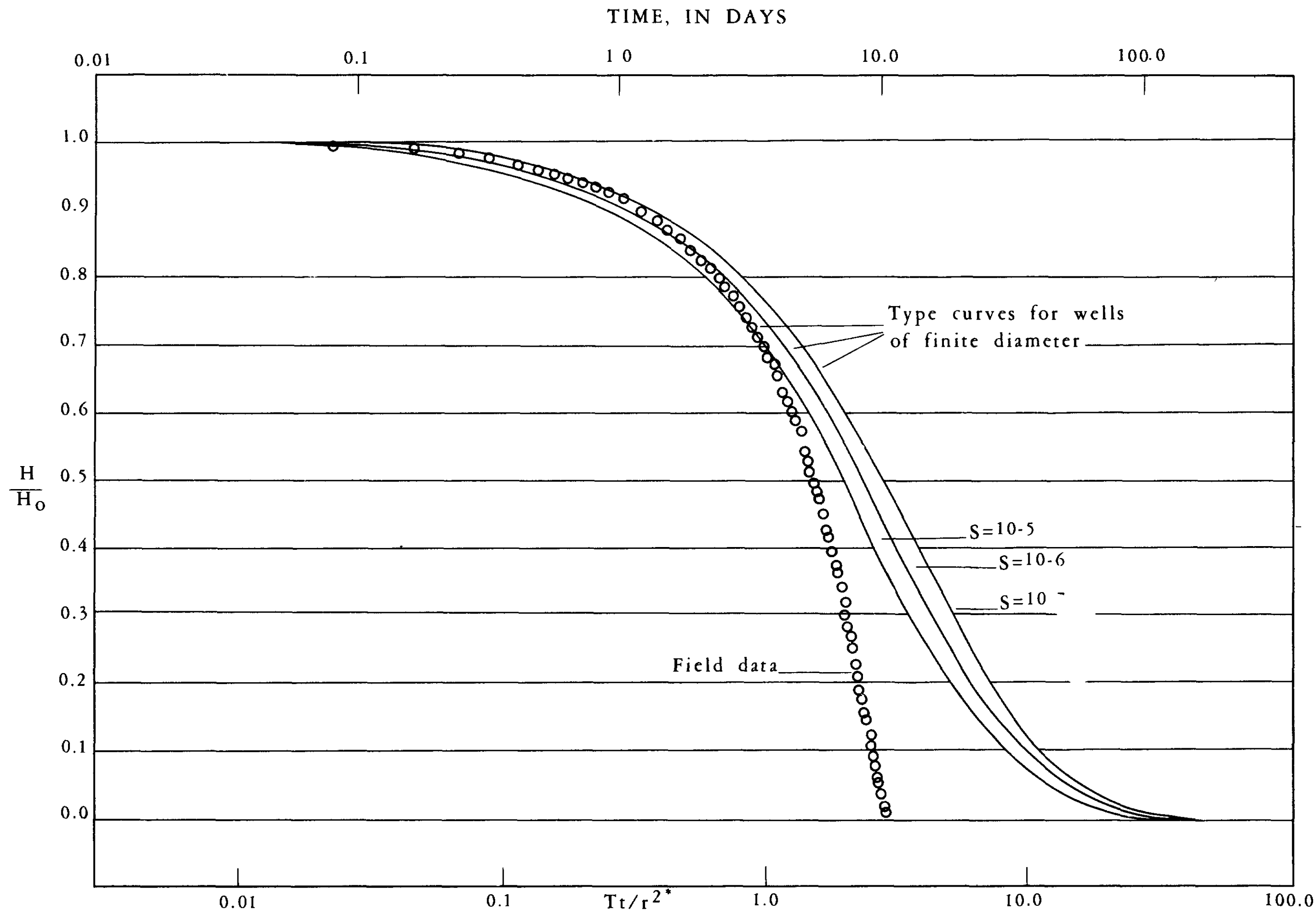


Figure 21.--Log-log hydrograph of water-level recovery from aquifer test of well 14E. Volume withdrawn was 26 gal and drawdown was 33.8 ft.



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

Figure 22.--Semi-logarithmic hydrograph of water-level recovery from aquifer test of well 8E, compared to type curves for aquifer test of finite-diameter wells.

nonsteady, radial flow of confined ground water. Ground water in rocks at Maxey Flats is probably unconfined, and jointed rocks generally do not constitute an isotropic medium. Also, if the water levels in the wells tested were drawn below joints supplying water to the wells, the water-level recoveries would not follow that due only to radial flow. It was therefore not possible to obtain T and S values from the tests.

Because of the apparent small hydraulic conductivity of the rocks and large spacing between wells, only single-well tests are feasible at Maxey Flats. No other suitable type of analysis is available for single-well testing at this time, with the well data available.

Geophysical Logs

Geophysical logs were first made in October 1973, of all wells at the Maxey Flats site except number 2, which had casing too badly bent for insertion of the logging tool. The gamma log of well 12E showed unusually high count-rates through the Nancy Member. Count-rates obtained in the Nancy Member in other wells ranged from about 65 to 80 cps (counts per second) on the logging unit used. Count-rates in well 12E averaged about 100 cps through the depth interval 15 to 25 ft, and about 200 cps between 25 to 45 ft (all depths given for well 12E are referenced to the top of the casing, which is 1.3 ft above ground level). Within these intervals of relatively large count-rates, there were three zones which had greater count-rates than those at adjacent depths. Peak count-rates and depths of these zones were 300 cps at 30 ft, 200 cps at 37 ft, and 700 cps at 45 ft. The contact of the Nancy and Farmers Members in well 12E is at depth 45 ft, plus or minus 5 ft. No unusually large count-rates were obtained below 45 ft.

Additional gamma logs were made of all wells (except number 2) in February, May, and October of 1974, and June, 1975. Count-rates obtained during these investigations were about the same as those obtained in October 1973.

In August 1974, a U.S. Geological Survey logging unit with gamma-spectral capability was used to investigate the zones of relatively large count-rates in well 12E. Counting periods of 10 minutes each were made with the spectral tool at depths 20, 29.8, 36, 44, 45, and 55.5 ft. No activation or fission products could be observed from the spectrum taken at 55.5 ft. Activation and fission products identified as cesium-134, cobalt-60, and cesium-137 were present at all other depths stated above, except depth 20 ft. At depth 20 ft cobalt-60 was present, but cesium-134 and cesium-137 were not detected. The gamma-spectral probe was held about 6 in above ground at well 12E, and near ground surface approximately 30 ft northeast and 30 ft southwest of the well. Counting periods of several minutes were made at each of these points, and cobalt-60 was detected at all of them (W. S. Keys, written commun., 1974). Cesium-134 and cesium-137 were not identified on these spectra, but this may have been the result of poor definition due to short counting periods.

Several possibilities are given regarding the origin of the waste isotopes in well 12E: (1) the isotopes were introduced when the well was drilled, (2) lateral movement of contaminated ground water into the well at a depth immediately below the cemented part of the well, then vertical movement down the well to the zones at which the isotopes were detected, (3) ineffective cement seal in the well, so that isotopes from the contaminated ground moved with overland flow, or shallow soil-water flow, past the cement and into the well, (4) lateral flow of contaminated ground water from the trench area along joints, bedding planes, or interbedded sandstones and siltstones in the unweathered part of the Nancy Member. Further discussion of each of these possibilities follows.

(1) Portions of cores from depths 24 to 58 ft were analyzed for isotopic content. No cesium or cobalt isotopes were detected on the cores (W. S. Keys, written commun., 1975). The isotopes were therefore not introduced during coring, but may have been introduced during reaming, or setting of casing and gravel pack.

(2,3) If comtaminated water infiltrated the well at shallow depth, the three discrete zones of higher count-rate would have to be explained by (a) preferential sorption of the isotopes, or (b) some means of physical entrapment (such as washouts or ledges in the borehole). Most of the Nancy Member is shale, particularly in the upper two-thirds of the unit. The preferential sorption would then be assumed to take place on the interbedded sandstones. This would be unusual, because sandstone generally has less capacity for sorption than shale. The presence of cobalt-60 and absence of cesium-134 and cesium-137 at shallow depth raises more doubt about preferential sorption, because cesium is readily sorbed by shale from Maxey Flats (T. Tamura, Oak Ridge National Laboratory, written commun., 1962).

The possibility of physical entrapment could not be investigated in the cased and gravel-packed well.

(4) Water accumulated in burial trenches in the past. This water could have moved laterally through the rocks adjacent to the trenches. The discrete zones of larger count-rates may therefore represent zones of contaminated water source, with smaller count-rates occurring where water is flowing over the borehole wall. The absence of cesium-134 and cesium-137 at shallow depth is not explained by this possibility. Another possibility is that contamination originated from a combination

of a near-surface source containing only cobalt-60 moving down the well, and deeper, lateral migration from the trenches containing cobalt-60, cesium-134, and cesium-137.

In summary of the above discussion, no absolute explanation can be given for the mode of movement of contaminants into well 12E. A carefully drilled corehole nearby the well, penetrating similar rocks and structure, would be needed to determine which of the possibilities actually caused the presence of the contaminants.

Gamma spectra were also obtained from selected depths in wells 1, 5E, and 13E. The spectra showed the presence of potassium-40 and uranium, but no cesium or cobalt isotopes (W. S. Keys, written commun., 1974). Potassium-40 and uranium occur naturally in the shales underlying Maxey Flats.

Several gamma logs were made of the hillside adjacent to well 12E in September 1974. The purpose of this investigation was to see if a zone of anomalously high gamma radiation could be detected on the hillside, thus indicating discharge of contaminated water from a saturated zone. The logging was accomplished by pulling the gamma-detecting probe and cable down the hillside to the lower part of the Ohio Shale, placing the probe on the ground, and logging count-rate with distance as the probe was dragged essentially straight up the hill. Five lines of logging were made in this manner, with the lines at about equal distances in the interval from well 11E to approximately halfway between wells 12E and 13E.

Nothing unusual was observed on most gamma logs of the hillside. Where soil cover was present, a constant count-rate was obtained. Where outcrops were present, the count-rate would increase slightly, as expected. The exception to this was count-rates obtained over the soil at well 12E, to a distance of about 50 to 75 ft from the well. In this area, the count-rate was about 300 percent greater than soil areas farther down the hillside. As stated previously, gamma spectra taken near ground level at well 12E showed the presence of cobalt-60. Spills of radioactive material have evidently occurred in this area.

No conclusions can be made regarding the gamma logs of the hillside adjacent to well 12E. The lack of anomalously large count-rates could mean that no contaminated water from a saturated zone is present in the rocks logged. Conversely, such contaminated water could be present, and the lack of anomalously large count-rates could mean that (a) contaminated water is flowing out of the rock, then beneath the soil cover, which shields the logging tool from gamma radiation originating from waste isotopes, or (b) near-surface flow sufficiently dilutes the contaminated ground water so that definition by the logging equipment is not possible.

SUMMARY AND CONCLUSIONS

Burial of radioactive wastes at the Maxey Flats site began in 1963. The site is located atop an isolated plateau in hilly terrain. The climate is humid, with mean annual precipitation of about 46 in. Streams draining the site flow into Fox Creek, Licking River, and eventually to the Ohio River. Discharges in the streams are very small to absent during the dry season. Based on specific-conductance data, most low flow in the streams is derived from near-surface sources, and relatively small contribution is made from bedrock.

A mantle, composed of regolith on the hilltop and colluvium on the hillsides, covers most of Maxey Flats. The regolith and colluvium grade together laterally, and this mantle also grades laterally into the alluvium in the adjacent valleys. Water is stored in, and transmitted through, the mantle and alluvium. This conclusion is based on data from dug wells and observations of springs in the area.

Springs obtain most of their flow from the mantle. Water in alluvium originates from surface and near-surface sources. These conclusions are based on specific conductance of the water. Some water from bedrock must be supplied to the mantle and alluvium, however, because there is evidence of lateral flow in the bedrock.

Alluvium in stream valleys probably has the greatest hydraulic conductivity of any hydrologic unit at Maxey Flats. The mantle probably has hydraulic conductivity less than the alluvium, but greater than any of the bedrock strata. These conclusions are based on (a) measurement of low flow in streams, (b) specific conductance of water samples, and (c) information from dug wells in the area.

All rocks exposed at Maxey Flats are poor aquifers, and most water in the rocks is transmitted through joints. Topography may be the controlling feature for regional direction and gradient of ground-water flow. Jointing is probably the principal control on local directions, gradients, and rates of ground-water flow. Bedding, fissility, and hackly structure are less important, and flow in the unaltered part of the rocks is least important. Based on observations at outcrops, joint density in rocks, grouped from highest to lowest, is (1) Sunbury and Ohio Shales, (2) upper part of the Farmers Member, (3) lower part of the Farmers Member, Nancy Member, Henley Bed, and Bedford Shale, and (4) upper part of the Crab Orchard Formation.

Based on observation of ground-water discharge at outcrops and recovery rates after water withdrawals from wells, the order of relative hydraulic conductivity for rocks is the same as that given above for joint density. Neither transmissivity nor storage coefficient could be obtained from aquifer testing, because field data did not match type curves. The assumptions used in the method of analysis are not met, probably because ground-water flow to the wells is primarily through joints.

Water-level data obtained from wells on the Maxey Flats site and surrounding area indicate saturated zones in the weathered part of the Nancy Member, the Farmers Member, and the Ohio Shale. Data are insufficient to determine whether or not saturated zones are present in other rocks above the Ohio Shale. It is unknown if unsaturated zones are present between saturated zones.

Domestic water supplies are obtained from any one, or combination, of rock units from the Nancy Member to rocks below the upper part of the Crab Orchard Formation. Ground-water supplies are also obtained from the mantle, and from alluvium. Many well owners do not obtain sufficient ground water to meet their requirements, and obtain additional supplies by means other than wells.

The median for total dissolved solids in ground water below depths of about 100 ft is about 700 mg/L for rocks above the Ohio Shale, and thousands of milligrams per liter in the Ohio Shale. The quality of water in all rocks changes considerably from place to place, and is probably dependent, not only on rock type, but also on distance and rate of water movement through the rocks.

Most existing wells on the Maxey Flats site are of marginal value for determining the water-transmitting and water-quality characteristics of the rocks. Many wells open only to small intervals in the rocks would be needed to attempt to analyze and describe the distribution of heads from water-level data, and enable meaningful interpretations of water-quality data. There is little probability that such drilling would be successful, mostly because chances of encountering widely spaced joints are small.

The ground-water system at Maxey Flats, including the pathways of water movement, cannot be described quantitatively or accurately at the present time, mostly because (1) jointing in the rocks is responsible for nearly all their hydraulic conductivity, (2) positions of water-bearing zones are difficult to locate in jointed rocks which have very low hydraulic conductivity between joints, (3) methods of analysis for single-well aquifer testing are not available for jointed rocks with the data available, so water-transmitting properties of the rocks cannot be quantified, and (4) most wells at Maxey Flats are open to more than one rock stratum, and the strata have different hydraulic properties.

Only a generalized description of the flow system at Maxey Flats is possible at the present time. In general, most precipitation flows from the hill as surface runoff, or is evaporated and transpired. Some precipitation infiltrates regolith, and much of this water flows laterally to colluvium on hillsides, then to alluvium in valleys. Some water infiltrates trenches and bedrock on the Maxey Flats site. Water movement in bedrock is probably near-vertical in the upper part of the Ohio Shale, more lateral in the lower part of the Ohio Shale, and has both vertical and lateral components in the five bedrock units above the Ohio Shale. Assuming the upper part of the Crab Orchard Formation is the lower hydrologic boundary of the ground-water system, virtually all ground water in the hill eventually moves into the valleys adjacent to Maxey Flats.

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