

STATE OF ARKANSAS

Arkansas Geological Commission

Norman F. Williams, State Geologist

INFORMATION CIRCULAR 20-N

**WATER QUALITY AND QUANTITY IN ABANDONED UNDERGROUND COAL MINES
OF
WEST-CENTRAL ARKANSAS AND USE OF SURFACE ELECTRICAL RESISTIVITY
IN
ATTEMPTING QUALITY DETERMINATIONS**

By

Ronald R. Potts

Arkansas Mining and Mineral Resources Research Institute



**Little Rock, Arkansas
1987**

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CONVERSION FACTORS

For use of readers who prefer to use International System (SI) units, rather than the inch-pound terms used in this report, the following conversion factors may be used:

<u>Multiply</u>	<u>By</u>	<u>To obtain</u>
foot (ft)	0.3048	meter (m)
square foot (ft ²)	0.09294	square meter (m 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 per minute (gal/min)	0.0631	liter per second (L/s)
inch (in.)	25.40	millimeter (mm)
mile (mi)	1.609	kilometer (km)
square mile (mi)	2.590	square kilometer (km)
acre	0.4047	hectare
acre-foot (acre-ft)	1,233	cubic meter (m)
short ton	0.9072	megagram (Mg)
pound (lb)	453.6	gram (g)

Temperature in degrees Fahrenheit (°F) as follows:

$$F = 1.8 \times ^\circ C + 32$$

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

WATER QUALITY AND QUANTITY IN ABANDONED UNDERGROUND COAL MINES
OF WEST-CENTRAL ARKANSAS AND USE OF SURFACE ELECTRICAL
RESISTIVITY IN ATTEMPTING QUALITY DETERMINATIONS

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ABSTRACT

A study was made of the water in abandoned underground coal mines in the Arkansas Valley region of west-central Arkansas. Objectives of the study were to assess the quality of water contained in the old workings, to estimate its quantity, and to test the use of surface electrical resistivity as a tool for estimating water quality in the mines in this area. The quality of water in most mines was highly variable with sulfate, calcium, sodium, and magnesium being the major constituents. Dissolved solids were less than 1,000 milligrams per liter at all but one site. pH ranged from 3.2 to 7.9 with a median of 6.5; most values ranged between 6.0 and 7.0. The total amount of water in the mines has been estimated to be between 1.7 and 2.0 x 10⁹ cubic feet (39,000 to 46,000 acre-feet). Resistivity surveys were not effective in differentiating water quality between the mined and unmined areas, probably because of a low resistivity shale overlying the coal seams in the area and the presence of waters which do not have large differences in specific conductance.

INTRODUCTION

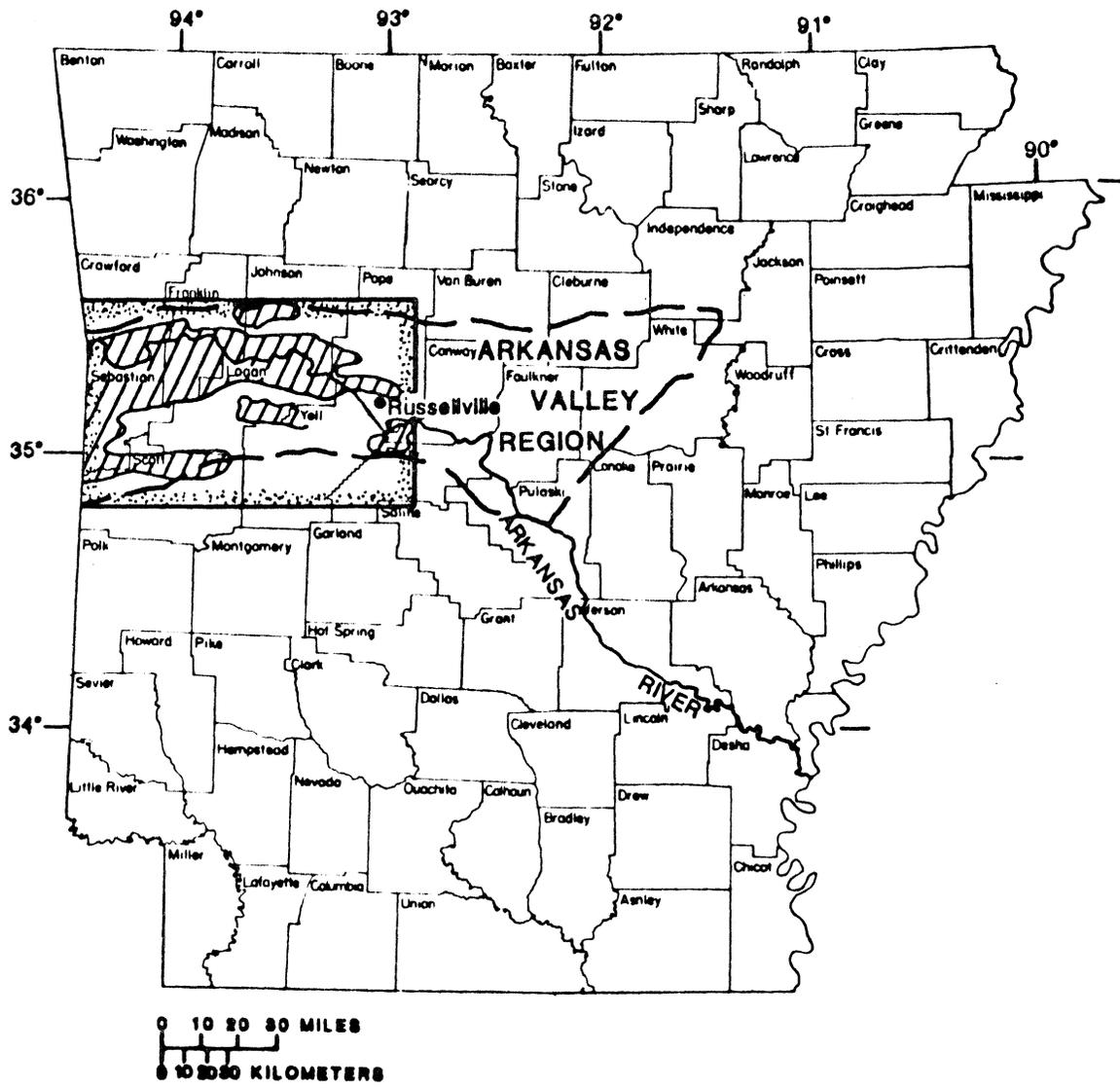
Coal has been mined in west-central Arkansas for about 100 years. Many of these mines, either individually or in conjunction with adjacent mines, extend under tens or hundreds of surface acres. All of these mines have been abandoned and all are partially or completely filled with ground water. A few (less than ten) of the old underground workings now are being strip mined in areas of shallow overburden to recover pillars of coal left by previous operations. Some of the mines are acting as artesian aquifers, with the water flowing out of what used to be airshafts or some other opening to the underground workings.

The purpose of this report is to describe the results of a study to determine the general quality of water in underground mines, to estimate the total amount of water contained in the old underground mine workings, and to examine the use of surface electrical resistivity to determine its effectiveness in assessing the water quality in underground mines. This last objective was established with the expectation that general water quality might be determined with instruments at the land surface in areas where the mine workings are no longer accessible and where no point source of water is available for taking samples.

It should be noted that many of these mining areas are a combination of surface and underground mining activities. Most of the coal seams crop out at the surface and were mined at the surface until economic or physical constraints dictated going underground. The old surface pits are directly connected to the old underground workings. This makes it difficult to distinguish the quality and quantity of water in the surface pits from that in the underground workings. However, the areal extent of underground mine workings is, in general, much greater than that of the surface mines. For this study, the surface mines associated with underground mines were not considered in the analysis.

Description of Study Area

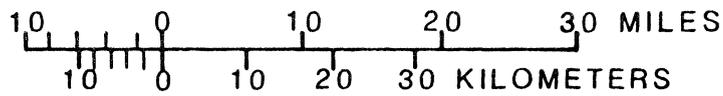
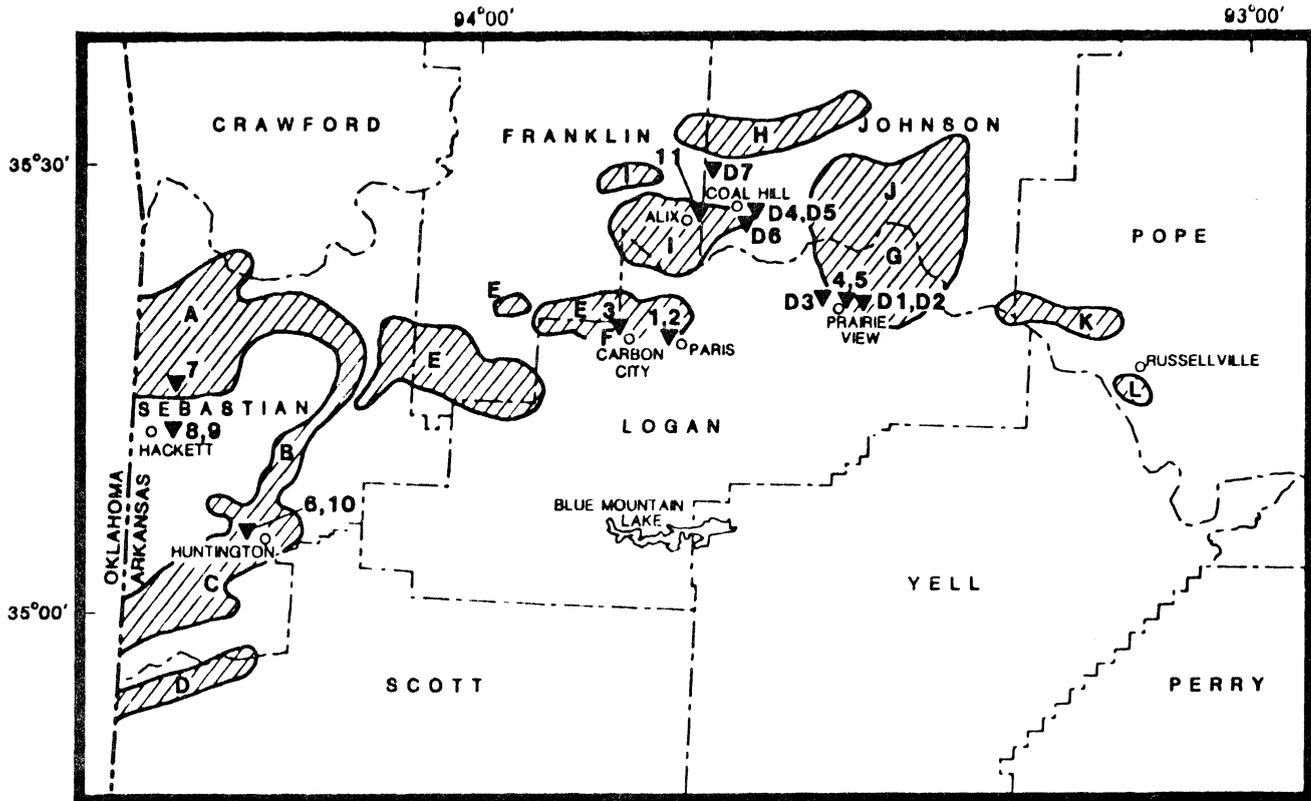
The study area is located in west-central Arkansas and lies within the boundaries of the western portion of the Arkansas Valley physiographic province, and extends from near Russellville, Arkansas, in the east to the Oklahoma State line on the west (fig. 1). Within this area there are located 12 separate coal fields which comprise the Arkansas Valley Coal District and which were the focus of this investigation. The locations and names of the individual coal fields are shown in figure 2. The coal seams in this district occupy the extreme eastern tip of the southern part of the Western Interior Coal Region. The U.S. Geological Survey has subdivided the coal regions of the United States into separate hydrologic areas. The majority of this study area lies within Area 42 (Bryant and others, 1983) and the remainder, along the Oklahoma State line, lies within Area 41 (Marcher and others, 1987).



EXPLANATION

-  **STUDY AREA**
-  **ARKANSAS VALLEY COAL FIELD**

Figure 1.—Study area and physiographic provinces of Arkansas (modified from Bush and Gilbreath, 1978).



EXPLANATION

-  COAL FIELD
- A. BONANZA - JENNY LIND
- B. EXCELSIOR - GREENWOOD
- C. HARTFORD - HUNTINGTON
- D. BATES
- E. CHARLESTON
- F. PARIS
- G. SCRANTON
- H. PHILPOTT
- L. DENNING - COAL HILL
- J. SPADRA
- K. QUITA
- L. SHINN
-  7 WATER-QUALITY SAMPLING SITE AND NUMBER

Figure 2.--Fields in the Arkansas Valley coal district and location of water-quality sampling sites (modified from Bush and Gilbreath, 1978).

The area is characterized by the flat to gently rolling river valley, which is punctuated by numerous large hills. Altitudes in the lower regions of the valley generally are from 310 to 500 ft above sea level with the higher hills exceeding 1,000 ft. The overall setting of the river valley is that of a trough which separates the Ozark Plateaus to the north from the Ouachita Mountains to the south. The hills in this region are capped by a resistant sandstone and generally trend east-west. Average annual precipitation in the area ranges from about 42 to 46 in. and is fairly evenly distributed throughout the year, with spring being slightly wetter and winter slightly drier. Average annual runoff varies from about 14 in. in the west to 16 in. in the east (Freiwald, 1985).

Acknowledgements

The author would like to gratefully acknowledge the assistance given in this project by the staff of the U.S. Geological Survey, Water Resources Division, Arkansas District. They provided insights and encouragement as well as funding for the resistivity equipment. Mention should also be made of the Arkansas Water Resources Research Center, located on the campus of the University of Arkansas at Fayetteville, for their part in administering the Federal funding of the project.

I would especially like to thank the student technicians/laborers used on this project, all of whom were geology students at Arkansas Tech University. Several have developed an interest in hydrology due primarily to their involvement in this project.

Finally, thanks must go to Carla Terry, our administrative assistant at the Arkansas Mining and Mineral Resources Research Institute, for the many hours of typing of this report.

COAL GEOLOGY AND MINING

Coal is known to occur in three separate geologic formations in this area, all of which are Pennsylvanian in age. These formations, from oldest to youngest are the Atoka, McAlester, and Savanna Formations. Between the McAlester and Atoka, there is another formation named the Hartshorne Sandstone, which contains no known coal. A total of 19 different coal beds have been described in the literature (Bush and Gilbreath, 1978) but only 4--the Lower Hartshorne, Upper Hartshorne, Charleston, and Paris coal beds--have been mined on a significant scale. These coal beds are discontinuous over the study area, having been folded, faulted, and eroded to their present configurations (Haley, 1960). Most of the individual mining areas consist of a coal seam in a syncline or around the perimeter of an anticline. In either case, the coal crops out at the surface and dips downward several degrees, in some cases approaching the vertical. Both the Lower and Upper Hartshorne coal beds are within the McAlester Formation, and the Paris and Charleston coal beds are within the Savanna Formation.

Although these coal seams overlie one another stratigraphically, not all are present in the same area because of erosion. Where present together, they have not been mined under the same areas because of the depth and (or) thinness. Of all the seams, the Lower Hartshorne covers the largest area (about 1,300 mi²) and has provided most of the coal production (Haley, 1960). Figure 3 shows a generalized stratigraphic column of the coal-bearing formations in this area.

Although coal may have been mined earlier in small isolated quantities, the first significant coal mining started about 1870 (Haley, 1960). Most coal mined prior to the end of World War II came from underground operations. Few of these were active by the 1960's and the last underground mine closed in 1977, leaving only surface mines to produce all the State's coal. Peak production occurred from 1901 through 1920, when the average annual rate of coal mined was about 2 million tons per year (Haley, 1960). It was not possible to determine precise dates of mining activity at all mines, but mines at the sampling locations were closed nearly 40 years ago or more, and all have long since filled with water.

GEOHYDROLOGY

There are two distinct environments in which the ground water occurs in the study area. One is the alluvial aquifer which borders (generally extending 1 to 5 mi) the Arkansas River and its major tributaries and is composed of unconsolidated sediments. The other includes all of the various zones within the Pennsylvanian System of rocks, which are very well consolidated, and composed primarily of shales, siltstones, and sandstones (Cordova, 1963). It is not known to what extent, if any, these two environments may be hydraulically interconnected.

Yields of wells in the alluvium are much greater than those in the Pennsylvanian rocks, varying between 300 and 700 gal/min, whereas wells in the Pennsylvanian rocks usually yield less than 50 gal/min, and usually need to be drilled deeper than a well in the alluvium (Bryant and others, 1983). Water flows through this rock by way of interconnected fractures, and well yield is highly dependent on the size, concentration, and degree of interconnection of these fractures. Therefore, water yield in this rock can be, and is, highly variable from well to well.

The presence of the old mine workings in the Pennsylvanian rocks probably has at least a local influence on ground-water quality and quantity. In terms of quality, the water is exposed to much more surface area in the coal, inducing chemical reactions and dissolving various constituents. In terms of quantity, the many openings to the surface permit almost immediate access of the rain and associated runoff and flooding to the subsurface environment. The space that was once occupied by coal that has been removed by mining is now able to hold a large amount of water. These voids are now forming large underground reservoirs of potentially usable water which could be tapped by wells yielding a much greater rate than those completed in the surrounding rock formations.

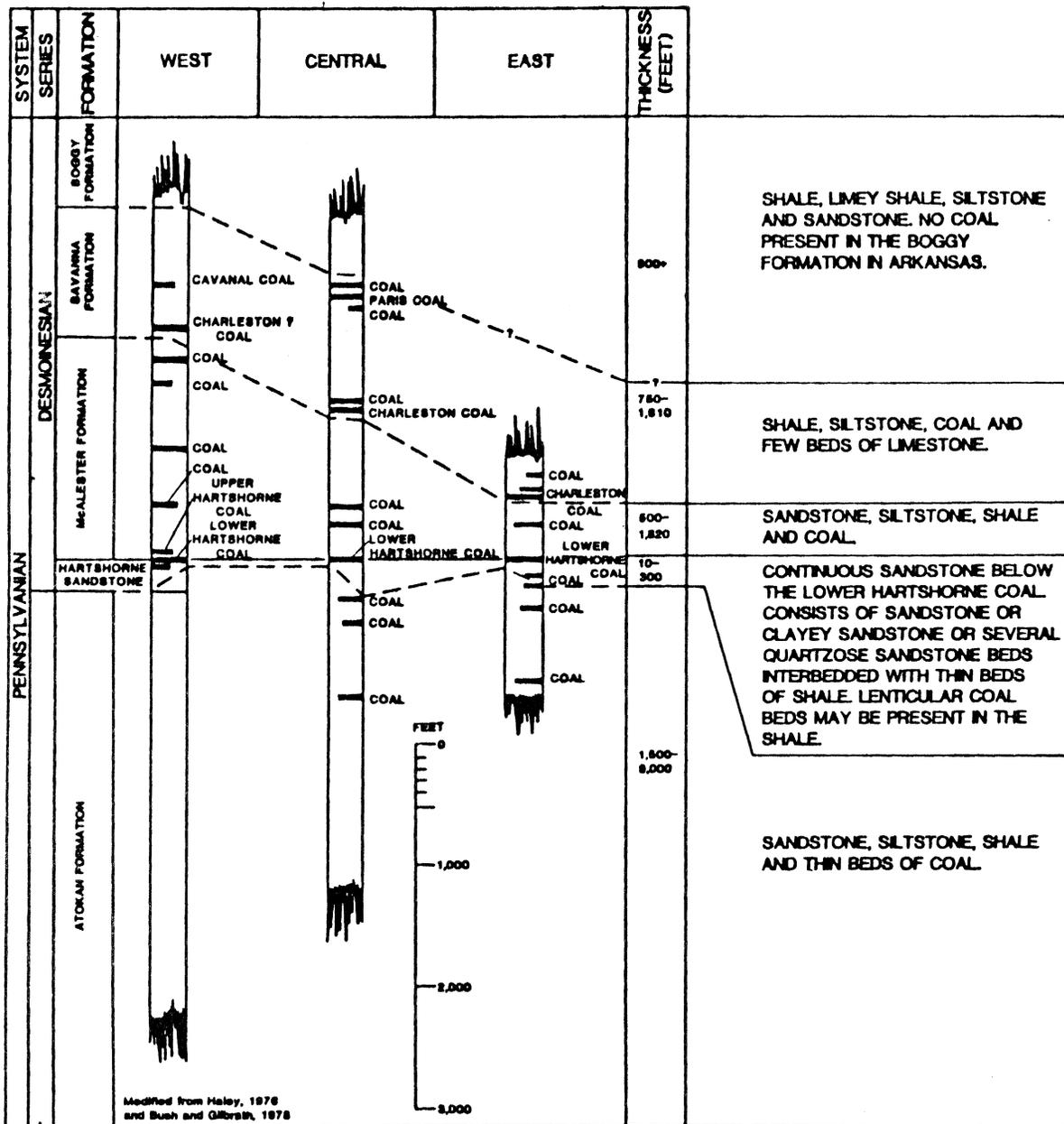


Figure 3.—Generalized stratigraphic section of the formations and coal beds in the Arkansas Valley region (from Bryant and others, 1983).

WATER QUALITY

Sampling Site Selection and Description

Prior to this study, no investigations had systematically examined the quality of the water contained in and issuing from the old underground coal mines of the Arkansas Valley. Some water-quality information on ground water from wells contained in the Arkansas River alluvium (Bedinger and others, 1963; Bryant and others, 1983) and on the ground water from wells contained in the Pennsylvanian rocks of this region (Bryant and others, 1983) is available. Because the coal is located within the Pennsylvanian rocks, water-quality data from domestic wells completed in Pennsylvanian rocks are shown in table 1 for comparison with water quality in coal mines.

In looking for suitable sites to accomplish this study, two conditions needed to be satisfied. One was that the area be undermined and the other was that water be either flowing out of the mine or accessible through an old shaft or pipe. The first of these conditions was the easiest to satisfy in that over 26,000 acres of land are known to have been undermined in the past, and fairly complete maps of these areas showing where the mines are located were readily available. The second condition was not so easily satisfied. Most of the old mines have been long abandoned and are no longer accessible from the surface, whether through being plugged by the mining company or some later owner, or by caving in on itself over the years. Commonly, open shafts have literally been filled with trash over the years by local residents who use them as convenient dump sites. Much field work was done searching areas of known mining for shafts with remaining openings. Local residents were of great help in locating most of these sites because of their knowledge of the area and its history.

Of the 12 coal fields in the study area, only the Charleston field had no underground mining. Of the remaining 11, 6 were found to have suitable sampling conditions: Bonanza-Jenny Lind; Excelsior-Greenwood; Hartford-Huntington; Paris; Scranton; and Denning-Coal Hill. Eight locations within these 6 fields containing a total of 11 sample sites were finally chosen. The site numbers and their locations are shown on figure 2 and have been tabulated and are presented in table 2. Three of these locations have multiple sampling sites, all of which are presumed to be accessing water from the same old underground mine, based on maps of the old workings. One place apparently not accessing a mine is sample site 5. This consists of a 6-in. pipe extending a few inches above the surface alongside a gravel county road. At first it was presumed that this old drill hole penetrated the flooded mine workings even though it was located too far east according to the placement of the mine workings from the maps. This was presumed because many of the old workings were inadequately located on the original maps and could be mislocated by a large enough amount to have this point over the mine. In addition, the type and size of the pipe is similar to that used in the old mines for drilling into the workings from the surface and it was overflowing water in a similar fashion to the nearby pipes and shaft which were known to be into the mine workings. Subsequent sampling and analysis of water has indicated, however, that this pipe is not connected to the old mine based on sulfate, calcium, sodium, and specific conductivity values of less than 25 percent of those recorded in water from the nearby mine. Local residents indicate it was drilled after mining ceased.

Table 1.--Average values of selected physical properties and dissolved constituents in ground water from Pennsylvanian rocks, west-central Arkansas (Bryant and others, 1983)

[Concentrations in milligrams per liter unless otherwise specified]

Constituent	Range	Median	Number of wells
Silica	0.3-23	9.8	22
Iron (micrograms per liter)	0-150	0	15
Calcium	1.2-78	12	30
Magnesium	0.2-53	8.6	30
Sodium	3.1-211	23	31
Potassium	0.5-24	2.1	31
Bicarbonate	8.0-508	100	31
Sulfate	0.2-535	11	32
Chloride	2.5-288	22	35
Fluoride	0.1-0.7	0.2	28
Nitrate as N	0-34	1.4	32
Dissolved solids (residue at 180 degrees Celsius)	24-870	176	23
Specific conductance (microsiemens per centimeter at 25 degrees Celsius)	59-1,200	288	36
pH units	5.7-8.3	7.2	36
Temperature (degrees Celsius)	16.5-23.0	19.0	28

Table 2. Mine water sampling site locations

Site number	Quadrangle	Latitude	Longitude	Legal description	U.S. Geological Survey site number
1	Paris	35°18'20"	93°44'04"	SW $\frac{1}{2}$ SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 3, T. 7 N., R. 26 W.	351749093442500
2	Paris	35°18'36"	93°44'07"	SW $\frac{1}{2}$ SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 3, T. 7 N., R. 26 W.	---
3	Caulksville	35°18'34"	93°48'55"	SW $\frac{1}{2}$ NW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 6, T. 7 N., R. 26 W.	351811093483500
4	Scranton	35°13'19"	93°31'50"	SE $\frac{1}{2}$ NW $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 23, T. 8 N., R. 24 W.	352047093305100
5	Scranton	35°19'12"	93°15'34"	SE $\frac{1}{2}$ NW $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 23, T. 8 N., R. 24 W.	---
6	Huntington	35°04'36"	94°18'13"	NW $\frac{1}{2}$ NE $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 33, T. 5 N., R. 31 W.	350425094190100
7	Greenwood	35°14'27"	94°21'21"	SE $\frac{1}{2}$ SE $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 36, T. 7 N., R. 32 W.	---
8	Hackett	35°11'24"	94°23'19"	SE $\frac{1}{2}$ NW $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 23, T. 6 N., R. 32 W.	---
9	Hackett	35°10'36"	94°23'19"	SW $\frac{1}{2}$ NE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 26, T. 6 N., R. 32 W.	351036094231900
10	Huntington	35°04'38"	94°18'14"	NW $\frac{1}{2}$ NW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 27, T. 5 N., R. 31 W.	---
11	Coal Hill	35°25'39"	93°42'31"	SW $\frac{1}{2}$ NE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 24, T. 9 N., R. 26 W.	---

Sample site 1, located in the Paris coal field at the edge of the city of Paris, is an old mine air shaft and consists of a concrete structure about 3 ft above ground level. In the center is a 12-in. pipe extending down to the old workings. It is presently partially blocked only a few feet down, but has had artesian flow during most of this project. The owner stated that it only stops flowing during extremely dry periods. A short distance to the north (about 1,000 ft) is sample site 2, consisting of a 6-in. steel pipe extending about 6 ft above the ground surface. Flow occurs at the base of this pipe where a crack or hole has formed. This pipe extends into the same mine as sample site 1.

Sample site 3 is also located in the Paris coal field in Logan County, but near its western end, north of Carbon City. This point consists of a well which was drilled into old workings about 90 ft deep in order to obtain water for a chicken house. The water is not flowing artesian and must be pumped into the chicken house. The water sample was taken at the point where the water enters the chicken house. Before sampling, the water was allowed to run all morning (about 4 hours) to clear the line of stagnant water.

Sample sites 4 and 5 are located about 1 mi northeast of the town of Prairie View, in the Scranton coal field in eastern Logan County. These both consist of steel pipes 6 to 12 in. in diameter, but only the pipe at site 4 extends vertically into the old workings. Both are nearly flush with the ground surface. Sample site 5 is located alongside a gravel road about 0.25 mi to the east of site 4. Both have artesian flow.

Sample site 6 is the old Number Six mine shaft located about 3 mi west of Huntington, in the Hartford-Huntington coal field, in southern Sebastian County. This shaft has filled with water and usually has artesian flow out the eastern edge. The shaft is vertical, and has an opening about 10 ft square.

Sample site 7, located about 50 ft to the south of the Bonanza road in central Sebastian County is in the Bonanza-Jenny Lind coal field, and consists of a 6-in. diameter steel pipe encased in a concrete block which extends about 6-in. above the ground surface. This was probably an air supply pipe extending into the old workings. This was flowing artesian during much of the year.

Sample sites 8 and 9 are in west-central Sebastian County about 1 mi east of Hackett and are in the Excelsior-Greenwood coal field. Sample site 8 is a vertical shaft with an opening about 8 ft square, in which water was standing about 30 ft below the surface. Water had been pumped out of this shaft for several months preceding this study for a coal washing operation that was reclaiming old gob piles. About 1 mi south is sample site 9, which is a 12-in. diameter vertical pipe extending into the same workings as the above mentioned shaft. This sample point is flowing artesian, and has cut an approximately 5-ft deep channel into the land surface.

Sample site 10 is the old Number Three mine shaft and is located in southern Sebastian County about 2 mi west of Huntington, in the Hartford-Huntington coal field. This shaft has been actively pumped off and on for the last several years to help dewater the workings which are located updip and are being strip mined. Depending upon the extent of pumping, the water in this shaft stands from about 10 ft to over 50 ft below the land surface.

Sample site 11 is in eastern Franklin County, about midway between Alix and Coal Hill and located within the Denning-Coal Hill coal field. This sample site consists of a 6-in. diameter steel pipe extending from the mine workings to about 1 ft above the ground surface. It flows artesian, even in periods of drought, according to the landowners.

In addition to the numbered sampling sites, which indicate mine water, samples of ground water from domestic wells off the site of mining activities were taken at Prairie View and Coal Hill. This was done to get a comparison of the effects of the mine openings on the local water quality. These sample sites are designated D1 through D7 and are given in table 3, along with their location coordinates. Sites D1 through D3 are near Prairie View, and sites D4 through D7 are near Coal Hill. Two of the Coal Hill sites are actually on the same property, but one well, D5, was in a field and used exclusively for livestock watering; D4 was the source of household water. It was not known previously how deep any of these wells were, although the owners all said they went down into rock.

Table 3.--Locations of sampled domestic wells near
Prairie View and Coal Hill, Arkansas

Site number	Quadrangle	Latitude	Longitude	Legal description
D1	New Blaine	35°20'18"	93°29'40"	NE $\frac{1}{4}$ SW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 24, T. 8 N., R. 24 W.
D2	Scranton	35°20'08"	93°31'16"	NE $\frac{1}{4}$ SE $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 23, T. 8 N., R. 24 W.
D3	Scranton	35°20'13"	93°31'01"	SE $\frac{1}{4}$ NW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 23, T. 8 N., R. 24 W.
D4	Coal Hill	35°27'05"	93°38'56"	SE $\frac{1}{4}$ SE $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 15, T. 9 N., R. 25 W.
D5	Coal Hill	35°27'02"	93°38'51"	SE $\frac{1}{4}$ SE $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 15, T. 9 N., R. 25 W.
D6	Coal Hill	35°26'22"	93°39'43"	SW $\frac{1}{4}$ SW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 15, T. 9 N., R. 25 W.
D7	Coal Hill	35°27'41"	93°43'00"	SW $\frac{1}{4}$ NW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 7, T. 9 N., R. 25 W.

Water Sampling

Most of the sites from which samples were taken had water flowing under artesian conditions from the old mine workings. This greatly simplified the sampling, as a sample bottle had only to be immersed in the water to be filled. The flowing artesian sampling sites were 1, 2, 4, 5, 6, 9, and 11. The other sampling sites were either shafts or pipes through which water could be withdrawn by a bucket or small diameter sampler. Although under artesian conditions, these sites did not overflow. Because of the depth and surface area of the pipes and shafts, there was too great a volume of water to totally evacuate the system prior to taking a sample. Each site was visited at least once and most of the sites visited several times during the course of this study.

During each visit, two samples of water were taken. One sample was filtered through a 0.45 micron filter, and placed in a 1-liter (L) plastic bottle, along with about 3 milliliters (mL) of redistilled nitric acid to help preserve the metal ions. A 1-L unfiltered sample was also taken and placed in a plastic bottle. This bottle was then placed in an ice chest for the trip back to the lab, where it was kept in the refrigerator until testing the next day.

In addition to the two samples which were returned to the lab, a few tests were run in the field on the water as it came from the source. These were: temperature, pH, specific conductance, and alkalinity.

At three of the locations, site numbers 1, 4, and 11, an attempt was made to measure the amount of flow coming out of the old shaft or pipe. This was done by the use of a simple portable plywood weir, cut so that it would fit into the channel which had developed at these places, and roughly calibrated in the office using equations for a sharp crested rectangular notched weir (doubly contracted) so that the flow could be easily measured. This method met with good success at sites 4 and 11 and only moderate success at site 1 which had a less well defined channel. The results of these measurements are shown in table 4 and are an indication of how much flow may be occurring through the old underground workings. It is assumed, however, that water would also be flowing out through other openings which were not located.

Table 4.--Estimated outflow rates from selected sample points

Site number	Date	Estimated flow rate	
		(cubic feet per second)	(gallons per minute)
1	2-06-86	0.167	75
4	2-06-86	.076	34
11	2-25-86	1.02	460

Methodology

As mentioned previously, four measurements were taken on each sample while still in the field: pH, temperature of the water as it came out of the ground, specific conductivity, and alkalinity. The pH and specific conductivity measurements were taken using battery-powered instruments; the alkalinity was measured using a Hach¹ field test kit. Two 1-L bottles were taken back to the laboratory for more detailed testing. One of these bottles was not filtered but kept refrigerated and was used for testing anions. Dissolved solids (evaporated at 105 °C) were also determined using a filtered 100 mL water sample taken from the unfiltered bottle. The other bottle was filtered and treated with nitric acid for preservation and digestion of the cations, or metals. All sampling and laboratory analyses were done following the standard guidelines for water and wastewater sampling and analyses (American Public Health Association and others, 1985).

A total of 13 tests were run on each sample brought into the laboratory, 7 for metal ions, 5 for non-metal ions and anionic radicals, and 1 for dissolved solids. Six of the metals (sodium, potassium, calcium, magnesium, manganese, and iron) were analyzed using atomic absorption/emission spectroscopy. Because of equipment limitations, aluminum was not tested with atomic absorption, but by spectrophotometric methods. Iron and manganese were also tested using spectrophotometry as a check on the results from the atomic absorption methods. Both methods gave nearly identical results.

In addition to the periodic sampling done by the Arkansas Mining and Mineral Resources Research Institute (AMI), a duplicate set of samples was collected by U.S. Geological Survey personnel during the collection trip of February 27, 1986. These samples were analyzed by the U.S. Geological Survey laboratory facilities and served as a check on the results from the laboratory at the Institute. Most of these Geological Survey analyses agreed fairly well with those done by the AMI, with 62 percent agreeing within 25 percent of the AMI value and 84 percent agreeing within 50 percent. The one major exception was the test for iron, in which the AMI results were consistently lower by two or three times. This seems to indicate either an incomplete digestion of the iron in the sample, or that some of the iron may have precipitated prior to testing.

Results

There are several similarities in water chemistry among the various mine sites sampled. The results of the analyses from both the field and laboratory are given in table 5. All are relatively high in concentrations of sodium, calcium, and magnesium cations, and sulfate anions. The high sulfate was expected since most coal has an abundance of pyrite (FeS) associated with it which is readily oxidized when exposed to air and water. One

¹Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Table 5.--Quality of water in abandoned underground coal mines and in adjacent domestic wells

[°C = degrees Celsius; $\mu\text{S}/\text{cm}$ = microsiemens per centimeter at 25 degrees Celsius; mg/L = milligrams per liter; $\mu\text{g}/\text{L}$ = micrograms per liter; AMI = Arkansas Mining and Mineral Resources Research Institute; USGS = U.S. Geological Survey; -- = no data.]

Site number	Sampling date	Collecting and analyzing agency	pH	Temperature (°C)	Specific conductivity ($\mu\text{S}/\text{cm}$)	Alkalinity as CaCO_3 (mg/L)
1	11-18-85	AMI	6.9	17.5	620	--
	2-06-86	AMI	6.5	16.0	520	393
	2-27-86	AMI	6.5	17.5	1,100	383
	2-27-86	USGS	6.5	--	1,040	362
	4-08-86	AMI	6.8	18.0	1,200	428
2	11-18-85	AMI	6.8	17.5	--	--
3	11-18-85	AMI	6.9	18.0	--	--
	2-27-86	AMI	6.4	14.5	330	128
	2-27-86	USGS	6.8	--	400	117
4	11-01-85	AMI	6.6	18.0	1,700	205
	12-06-85	AMI	6.4	17.0	1,800	--
	1-17-86	AMI	5.8	18.0	1,650	205
	2-06-86	AMI	6.3	16.0	1,600	171
	2-14-86	AMI	6.7	17.0	1,750	171
	2-27-86	AMI	6.6	17.0	1,600	170
	2-27-86	USGS	6.2	--	1,750	148
5	2-14-86	AMI	7.0	--	170	120
6	2-18-86	AMI	5.9	17.0	750	15
	2-27-86	AMI	3.4	17.0	600	0
	2-27-86	USGS	3.2	--	700	0
7	1-21-86	AMI	6.7	14.5	960	394
	5-08-86	AMI	7.2	17.0	1,300	479
	6-10-86	AMI	7.4	17.0	1,200	462
8	1-21-86	AMI	6.3	17.0	520	120
9	1-21-86	AMI	6.4	19.0	1,300	668
	2-27-86	AMI	6.5	19.0	1,180	594
	2-27-86	USGS	6.9	--	1,400	624
10	2-18-86	AMI	7.9	10.0	220	62
11	11-18-85	AMI	6.1	16.0	680	--
	11-27-85	AMI	6.9	--	--	--
	1-17-86	AMI	5.9	15.5	510	--
	2-25-86	AMI	7.2	15.0	650	85
	4-08-86	AMI	6.5	16.0	700	120
D1	4-08-86	AMI	6.5	22.0	900	257
D2	4-08-86	AMI	5.9	18.0	175	69
D3	4-08-86	AMI	6.2	18.0	150	17
D4	4-08-86	AMI	6.3	14.0	80	51
D5	4-08-86	AMI	6.3	15.0	100	51
D6	4-08-86	AMI	6.5	20.0	300	120
D7	4-08-86	AMI	6.7	18.0	100	103

Table 5.--Quality of water in abandoned underground coal mines and in adjacent domestic wells--Continued

Site number	Collecting and analyzing agency	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Calcium, dissolved (mg/L as Ca)	Silica, dissolved (mg/L as SiO ₂)
1	AMI	130	3.5	39	10
	AMI	140	3.6	48	11
	AMI	130	3.3	49	11
	USGS	160	1.7	43	13
	AMI	210	2.3	28	11
2	AMI	130	3.5	36	11
3	AMI	41	2.7	2.9	11
	AMI	39	3.0	31	10
	USGS	36	1.3	22	12
4	AMI	110	3.6	140	--
	AMI	100	5.3	120	12
	AMI	100	5.1	120	9.7
	AMI	63	4.3	140	12
	AMI	80	4.1	93	10
	AMI	86	4.1	110	10
	USGS	79	2.0	140	13
5	AMI	21	5.2	20	27
6	AMI	17	3.1	42	17
	AMI	19	3.1	42	20
	USGS	13	1.8	37	24
7	AMI	220	3.7	12	10
	AMI	160	2.4	4.8	12
	AMI	320	2.3	5.2	11
8	AMI	31	2.8	54	13
9	AMI	190	4.0	38.8	--
	AMI	160	2.7	42	9.7
	USGS	240	4.6	28	11
10	AMI	13	2.9	25	5.4
11	AMI	50	3.4	46	--
	AMI	48	3.3	44	--
	AMI	40	3.0	42	--
	AMI	40	3.1	45	10
	AMI	50	2.6	32	12
D1	AMI	55	.9	17	18
D2	AMI	13	.2	1.3	27
D3	AMI	11	.1	1.5	24
D4	AMI	10	.3	1.7	22
D5	AMI	14	.6	1.8	18
D6	AMI	48	.5	1.7	30
D7	AMI	27	.1	1.5	27

Table 5.--Quality of water in abandoned underground coal mines and in adjacent domestic wells--Continued

Site number	Collecting and analyzing agency	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Nitrate, dissolved (mg/L as No ₃)	Sulfate, dissolved (mg/L as SO ₄)
1	AMI	7.5	--	--	220
	AMI	7.5	0.75	0.12	180
	AMI	18	.74	.40	270
	USGS	23	.6	<.50	170
	AMI	23	.48	1.3	220
2	AMI	20	--	--	210
3	AMI	7.0	--	--	22
	AMI	6.0	.32	.07	130
	USGS	7.3	.2	<.50	59
4	AMI	6.0	--	.16	640
	AMI	--	--	--	--
	AMI	5.0	.96	.10	780
	AMI	20	.65	.14	540
	AMI	5.8	.54	1.9	570
	AMI	6.3	.80	.50	400
	USGS	6.5	.2	<.50	790
	AMI	4.5	.13	.72	7
6	AMI	2.3	.25	--	350
	AMI	4.0	.80	.04	380
7	USGS	2.1	.1	<.50	300
	AMI	8.5	.83	1.1	94
	AMI	12	.86	1.8	190
8	AMI	20	.50	--	180
	AMI	5.0	.29	.56	170
	AMI	3.3	.93	.48	27
9	AMI	7.0	.66	.64	48
	USGS	29	.7	<.50	44
	AMI	5.5	.15	.93	79
11	AMI	15	--	--	27
	AMI	16	--	--	200
	AMI	12	.69	.30	200
	AMI	25	.42	.70	200
	AMI	18	.42	.19	250
D1	AMI	13	.25	.79	0
D2	AMI	6.0	.09	2.0	26
D3	AMI	3.0	.15	.47	54
D4	AMI	7.5	.13	2.2	0
D5	AMI	6.0	.09	2.3	9
D6	AMI	17	.09	1.1	0
D7	AMI	7.0	.09	.28	0

Table 5.--Quality of water in abandoned underground coal mines and in adjacent domestic wells---Continued

Site number	Collecting and analyzing agency	Dissolved solids, (mg/L residue at 105 °C)	Magnesium, dissolved (mg/L as Mg)	Manganese, dissolved (µg/L as Mn)
1	AMI	650	17	550
	AMI	670	13	700
	AMI	620	16	630
	USGS	^a 647	17	560
	AMI	600	20	900
2	AMI	640	22	420
3	AMI	370	10	260
	AMI	160	11	320
4	USGS	^a 209	10	260
	AMI	1,550	86	6,400
	AMI	--	20	8,200
	AMI	1,410	25	8,000
	AMI	1,320	33	12,900
	AMI	1,350	97	9,500
	AMI	1,290	66	10,000
5	USGS	^a 1,290	92	6,800
	AMI	70	6.0	810
6	AMI	360	21	2,800
	AMI	410	23	2,800
	USGS	^a 420	28	2,600
7	AMI	690	7.2	70
	AMI	690	4.5	180
	AMI	750	6.5	170
8	AMI	450	18	1,170
9	AMI	730	14	200
	AMI	710	11	360
	USGS	^a 736	11	320
10	AMI	160	12	60
11	AMI	540	23	1,900
	AMI	480	21	1,800
	AMI	400	16	1,500
	AMI	260	16	1,100
	AMI	420	19	1,800
D1	AMI	180	15	210
D2	AMI	62	8.4	960
D3	AMI	66	7.5	520
D4	AMI	76	6.0	370
D5	AMI	99	.9	100
D6	AMI	130	6.6	540
D7	AMI	98	4.2	510

^a mg/L residue at 180 °C

Table 5.--Quality of water in abandoned underground coal mines and in adjacent domestic wells--Continued

Site number	Collecting and analyzing agency	Iron, dissolved ($\mu\text{g/L}$ as Fe)	Aluminum, dissolved ($\mu\text{g/L}$ as Al)
1	AMI	1,600	--
	AMI	720	--
	AMI	690	--
	USGS	1,600	<100
	AMI	2,000	4
2	AMI	1,300	--
3	AMI	1,200	--
	AMI	400	28
	USGS	980	<100
4	AMI	11,500	--
	AMI	10,800	--
	AMI	10,400	--
	AMI	10,700	--
	AMI	9,800	81
	AMI	7,500	24
	USGS	8,600	<100
5	AMI	8,400	76
6	AMI	10,800	--
	AMI	9,700	1,800
	USGS	32,000	1,300
7	AMI	2,200	--
	AMI	190	81
	AMI	470	62
8	AMI	1,100	--
9	AMI	70	--
	AMI	80	40
	USGS	120	<100
10	AMI	170	200
11	AMI	11,500	--
	AMI	11,400	--
	AMI	1,500	--
	AMI	1,700	71
	AMI	6,900	240
D1	AMI	700	36
D2	AMI	7,600	95
D3	AMI	1,900	150
D4	AMI	430	45
D5	AMI	270	53
D6	AMI	8,500	600
D7	AMI	5,500	8

Table 5.--Quality of water in abandoned underground coal mines and in adjacent domestic wells--Continued

Site number	Collecting and analyzing agency	Carbon dioxide, dissolved (mg/L as CO ₂)	Bicarbonate, dissolved (mg/L as HCO ₃)	Total organic carbon, dissolved (mg/L as C)
1	USGS	222	440	3.4
3	USGS	36	140	3.2
4	USGS	180	180	.5
6	USGS	0	0	.3
9	USGS	152	760	2.6

Site number	Collecting and analyzing agency	Boron, dissolved (µg/L as B)	Copper, dissolved (µg/L as Cu)	Lead, dissolved (µg/L as Pb)	Zinc, dissolved (µg/L as Zn)
1	USGS	160	<10	<10	14
3	USGS	50	<10	<10	15
4	USGS	100	<10	<10	15
6	USGS	50	<10	<10	150
9	USGS	280	<10	<10	12

finding that was somewhat surprising is the degree of variability in concentrations of the various ions, not just between different mines or areas, but also between time periods at the same sample point. This may indicate the ongoing decomposition of the coal still left in the mines, which is releasing varying amounts of material as time goes by possibly due to the heterogeneous distribution of these ions within the coal seam, or the varying amount of time the water may reside in the old workings. Some reactions may be taking place where the water table in the workings fluctuates slightly, exposing the coal to the atmosphere and an oxidizing condition for brief time periods during droughty situations. For the most part, however, it is thought that the mine workings stay completely flooded year round.

Another surprising finding was that the pH of almost all the mine water is above 6.0 units. The median value from all samples taken is 6.5 units. This is only slightly less than the pH of natural waters in the surface streams in this area which averages around 7.0.

In comparing the results of the chemical analysis for the mine water with that of the domestic water wells located nearby but not over the mine sites, substantial differences were observed. As expected, the mine waters were found to have higher amounts of most constituents. The exceptions were found to be iron, manganese, and chlorides, which seem to be about the same in both types of water, and nitrates and silica, which were consistently higher in the domestic water supplies. It is theorized that this is due to the water being used by these domestic wells having a longer contact time with the sandstone through which it passes, thereby leaching out the silica. There appears to be little or no relation between the quality of the water contained in the mine workings and that of the surrounding water-supply wells, indicating little or no contamination coming from these old workings into the surrounding ground-water environment.

Comparison to Water Quality Standards and Criteria

Depending upon the desired use, standards and criteria have been adopted or proposed for water quality by various government agencies and industry groups. The most stringent of these standards are those for drinking water that have been adopted by the U.S. Environmental Protection Agency (1986a and 1986b). These standards limit the amount of various dissolved constituents as well as defining other limiting parameters such as those for odor and color. Some of these limits are imposed due to the health risk associated with the constituent, such as for heavy metals, while others are primarily for esthetics rather than health, such as odors caused by sulfates or stains from iron or manganese.

Although the water that was tested during this study would not be considered toxic, most of it would not be esthetically acceptable for domestic use as it comes out of the mine opening. Almost without exception, there were substantial amounts of iron and manganese staining, as well as the rather foul odor caused by hydrogen sulfide gas. Esthetics aside however, most of this water is suitable for drinking purposes, although concentration of iron and manganese in the majority of analyses exceeded U.S. Environmental Protection Agency standards. Other limits, such as for sulfate, were nearly

exceeded and in some instances were. None of the above noted constituents are particularly harmful, at least for a short-term supply, and may be removed or reduced with limited treatment. In some places, the probable presence of sulfur reducing bacteria was indicated by an off-white color deposited around the shaft or pipe from which the water was flowing. Two notable exceptions occurred at sample sites 3 and 10. At sample site 3 the quality of water was suitable without treatment for supplying a 12,000 unit chicken house with drinking and cooling water.

Other standards for water uses, such as those for irrigation or for use as boiler water are not as restrictive as those for drinking water. For irrigation purposes and livestock watering, all of the water tested could be considered as suitable. If used for low pressure boiler water, the calcium, sodium, and magnesium levels may be too high in some instances. Table 6 lists water quality criteria for various uses.

Table 6.--Water-quality standards and criteria

Constituent, mg/L, dissolved	Drinking	General household ^c
Chloride	^a 250	--
Fluoride	^b 4.0	--
Iron	^a .3	0.5
Magnesium	^a 125	100
Manganese	^a .05	.3
Nitrate	^b 44	--
Sulfate	^a 250	300
Total dissolved solids	^a 500	2,000
pH (units)	^a 6.5-8.5	--

^aSecondary drinking water standards, U.S. Environmental Protection Agency, 1986b.

^bPrimary drinking water standards, U.S. Environmental Protection Agency, 1986a.

^cDavis and DeWeist, 1966, p. 121.

ESTIMATE OF WATER QUANTITY IN UNDERGROUND WORKINGS

Because the coal beds are folded and cropping out on or near the valley floors instead of along hillsides, water has always been a problem during mining operations. Often, mining ceased at least partly because of an inability of dewatering operations to contend with the rate of flow into the workings. As a result, most of these workings filled completely with water shortly after operations ceased. Most openings observed during the course of this study were overflowing or at least had the water surface within sight from the surface of the ground. At least during some parts of the year, all the underground openings are probably filled with water.

The total volume of underground workings available for holding this water has been calculated in two ways to check the gross accuracy of the number. First, it was determined from historical documents (Bush and Gilbreath, 1978) that 90,612,124 short tons of coal had been mined by underground methods in Arkansas since about 1890. For all practical purposes, this can be considered the total amount mined because little coal was mined by all methods prior to 1890. Also, all but an insignificant amount of coal mined in Arkansas has been from the Arkansas Valley Coal District. From measurements done in the laboratory at the AMI it was determined that the average density of coal from Arkansas is close to 90 lb/ft³ or 0.045 ton/ft³, therefore:

$$90,612,124 \text{ tons} \div 0.045 \text{ ton/ft}^3 = 2.0 \times 10^9 \text{ ft}^3$$

of void space or contained water.

A second method which was used to check this number was to find the total surface area of the underground workings, which had been determined in a previous study (Bush and Gilbreath, 1978) to be 26,545 acres (convert to square feet by multiplying by 43,560), multiply that by the average thickness of the coal mined (2.9 ft), and then by 50 percent, which should be a typical rate of recovery in the old workings. This method is subject to more error, because two averages (thickness and recovery) are used, and also because surface area would be slightly smaller than sloped (actual underground) area. The result is as follows:

$$(26,545 \text{ acres}) (43,560 \text{ ft}^2/\text{acre}) (2.9 \text{ ft}) (0.5) = 1.7 \times 10^9 \text{ ft}^3$$

of void space or contained water.

Converted to acre-feet, these two numbers would be 45,900 using the tonnage mined and 39,000 using surface area mined, for a difference of almost 15 percent. These values constitute the equivalent storage capacity of a moderately large lake. For comparison, Blue Mountain Lake, located just to the south of the study area, has a volume of about 24,600 acre-ft at its conservation pool level (Arkansas Soil and Water Conservation Commission, 1981).

The void space contained in some of the largest individual mines has been calculated, as well as the void space in each of the mines underlying the various sample sites, and is shown in table 7 along with the name or names of the companies owning the mine at the time of operation and the coal field in which the mine is located.

Table 7.--Coal field, company name and estimated void space in selected large mines and in mines at sample sites

Coal field	Company at time of operation	Estimated void space in mine, acre-feet	Site number
Bonanza-Jenny Lind	Young & Son Coal Company	7,120	7
Hartford-Huntington	Bull Moose Coal Company/ Bates Coal Company	5,370	-
Spadra-Clarksville	E.H. Johnson Coal Company	3,780	-
Hartford-Huntington	Central Coal & Coke Company	1,970	10
Hartford-Huntington	Central Coal & Coke Company #14	1,960	6
Excelsior-Greenwood	Barr Excelsior Coal Company/ Peerless Coal Company #3	570	8 and 9
Denning-Coal Hill	Altus Valley Coal Company 1 and 2	510	11
Paris	Local Coal Company	390	1 and 2
Paris	Eureka Coal Company/ H & H Coal Company	270	3
Scranton-Prairie View	K & S Coal Company	170	4 and 5

ANALYSIS OF SUBSURFACE MINE WATER QUALITY USING SURFACE ELECTRICAL RESISTIVITY

The use of surface electrical resistivity methods to locate areas of contamination, or more specifically, areas of high ion concentration, in the subsurface environment is not a new technique. The use of this technique to interpret the quality of water in a contaminated zone in terms of an absolute value for its ionic concentration is a much more difficult task and one that is still being actively researched. Basically, the relation is: the higher the ion concentration in the water at a given depth or layer, the lower will be the apparent resistivity; also, the deeper the layer of investigation, the less its effect on the overall resistivity of the overlying rock strata.

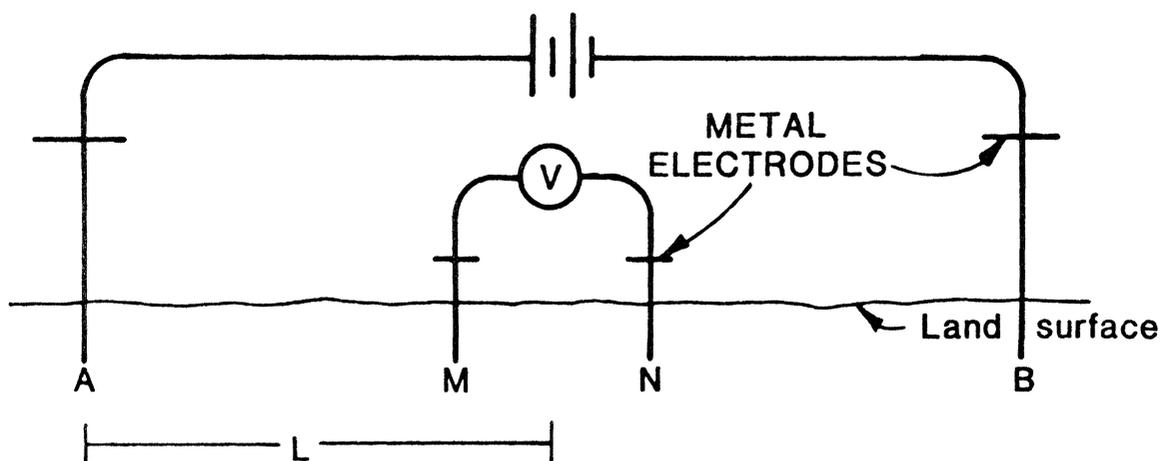
From the study and analyses of water contained in these old mine workings, it was known that the total ion concentration in old mine workings was higher than that of the surrounding natural ground water; this makes these sites likely candidates for the surface resistivity technique of analysis. The geology of the area is not complex, although some faults are present and the strata are not flat.

Electrical resistivity soundings were made over areas of known mining where the water was readily obtainable to check the ion concentration, and where ion concentrations were found to be the highest. These areas were chosen because of the above mentioned relation between resistivity and ion concentration. Also important was the requirement that the old mine workings be sufficiently shallow (less than 100 ft deep) so that they would be within the theoretical penetration depth of the instrument. Two of the locations fit these criteria most closely: site 4 near Prairie View and site 11 near Coal Hill. The purpose of this work was to establish, if possible, the relation between the quality of water contained in the underground workings and the resistivity signature obtained using surface electrical resistivity and to extrapolate the technique to other areas of known underground mining activity but which may not presently have any access to the contained water.

Electrical resistivity soundings were performed using the Schlumberger array for electrode spacing. Most of the soundings were taken out to a current electrode spacing of 656 ft (200 meters), although a few were longer or shorter. Although there is no practical relation between electrode spacing and depth of resolution, in general the distance between current electrodes divided by 2 will yield the theoretical maximum depth of penetration. Conditions of lower resistivity near the surface can affect the readings from deeper layers and reduce the depth of resolution. Figure 4 illustrates the Schlumberger electrode arrangement.

For comparison, a few soundings were performed near but not over the area of known mining in a similar geologic framework to try to determine the signal differences due to the more highly ionized water in the old mine workings. Figures 5 and 6 show the approximate location and orientation of the sounding, and the relative position to the abandoned underground workings.

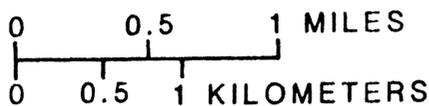
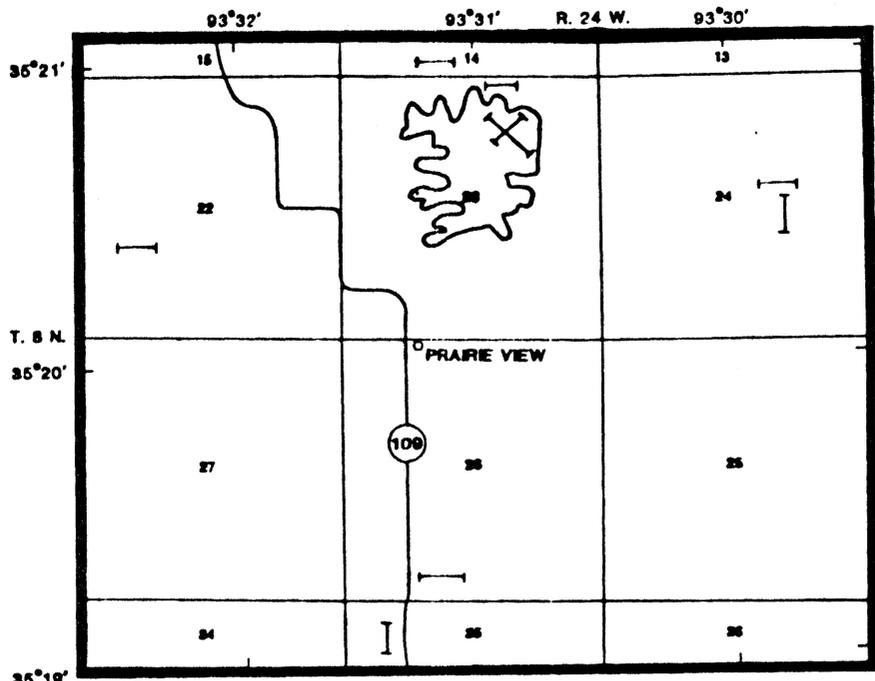
Several theoretical resistivity sounding curves were generated using the computer program Resist (Moody, 1980) to determine the possibility of detecting a layer of water at various depths which contained a high ion concentration. To do this properly, the number of layers of differing resistivity (corresponding to layers of rock and soil) and the resistivity values of the various layers had to be determined.



EXPLANATION

- L DISTANCE FROM CENTER TO OUTER MOST ELECTRODE
- A B CURRENT ELECTRODES
- M N POTENTIAL ELECTRODES

Figure 4.--Schlumberger electrode array.



EXPLANATION

-  UNDERMINED AREA
-  RESISTIVITY SOUNDING TRACE

Figure 5.--Resistivity sounding locations, Prairie View area.

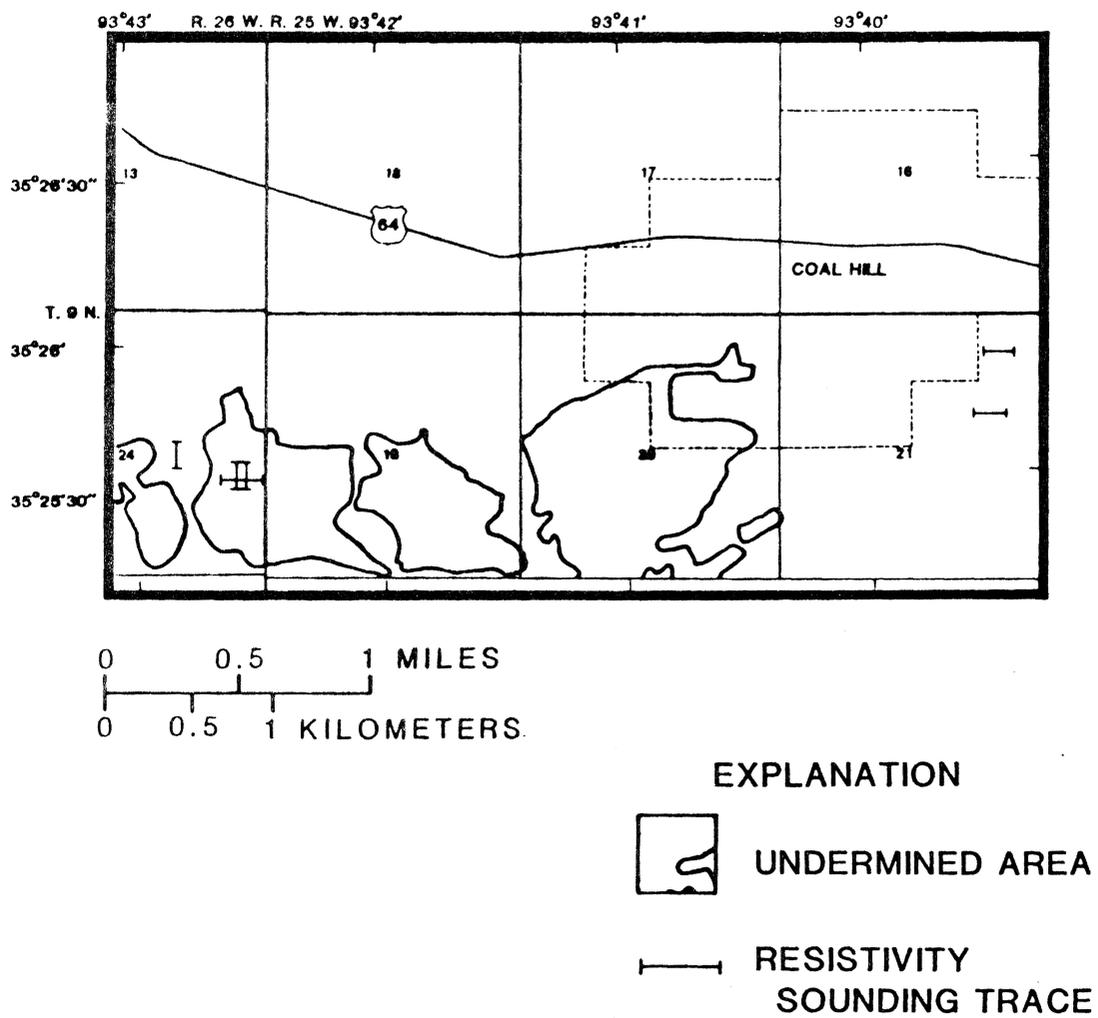


Figure 6.--Resistivity sounding locations, Coal Hill area.

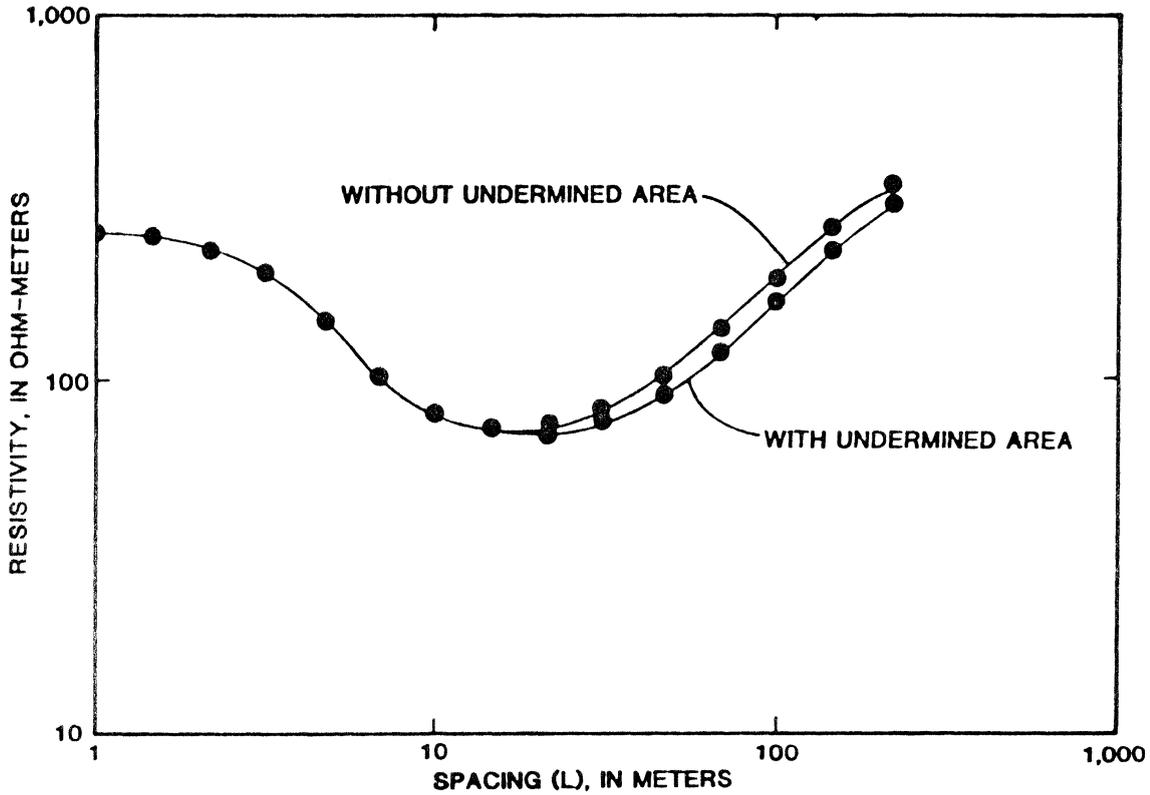
To determine the individual resistivity values of shale in the McAlester Formation and the underlying Hartshorne Sandstone, measurements were taken directly on nearby outcrops of the formations. Two measurements were taken in different locations for each formation. The shale had a resistivity of 65 to 70 ohm-meters, and the sandstone had a resistivity of 2,000 to 2,200 ohm-meters. In all instances, it appeared that there was abundant water in the rock, as water was seeping out at several spots, which should closely parallel the conditions in the subsurface.

Several computer generated sounding curves were made to test theoretical changes in the subsurface. Basically this involved generating pairs of curves corresponding to identical conditions in the subsurface, with the exception of one curve reflecting the inclusion of a water-filled mine, and then comparing the shape of these curves to see the effect of the water-filled mine on the generated sounding curves.

During the theoretical modeling runs, the deeper the water-filled mine was placed for a given value of resistivity, the less effect it would have as compared to a curve generated by using identical parameters with the exception of modeling the water-filled mine. Also, as the resistivity of the mined layer (in the model) increased, the less effect was observed as compared to the curve without a mined layer. An example of a theoretical four layer curve where the mined layer is 100 ft deep is given in figure 7 alongside a curve for the identical conditions without a mined layer. As can be seen, the presence of a mined layer 3 ft thick with a resistivity of 10 ohm-meters has an influence on the right side of the curve, bringing it down in value by over 13 percent at the 100 m (328 ft) L-spacing (fig. 4).

As a starting point for field data collection, resistivity soundings were conducted over the site having the highest recorded electrical conductivity in water from the mine workings. This was site number 4, near Prairie View, where conductivity values of between 1,600 and 1,800 microsiemens per centimeter were found. These values correspond to resistivities of 10 and 8 ohm-meters respectively, as resistivity is inversely proportional to conductivity. The field curves generated at this site indicated a four or possibly five layer condition in the subsurface. One of the curves used to make these determinations is shown in figure 8. It was therefore decided that the top layer, of 3 to 7 ft, was composed of topsoil and weathered rock; a second layer of McAlester shale extended down to the mine workings; the third layer was the mine itself, which was approximately 3 ft thick; and a fourth and possible fifth layer was composed of a continuation of McAlester shale and(or) the beginning of Hartshorne Sandstone. From the field curves it was obvious that the top layer of weathered rock and soil had a much higher value of resistivity (about 250 ohm-meters) than the McAlester shale.

In analyzing the field data curves and comparing them with the computer generated theoretical curves, it is apparent that the fluctuation in readings of the field resistivity points equalled or exceeded the values by which a mined layer would theoretically move the non-mined curve, thereby masking detection of the mined layer. Also, many of the field curves did not ascend as rapidly as predicted at the larger L spacings (with the high resistivity Hartshorne Sandstone immediately below the mined out areas). There are at least two reasons as to why this might be so. Possibly the mined-out areas



THEORETICAL PARAMETERS USED TO GENERATE CURVES

<u>Layer no.</u>	<u>Non-mined thickness (feet)</u>	<u>Resistivity (ohm-meters)</u>	<u>Mined thickness (feet)</u>	<u>Resistivity (ohm-meters)</u>
1	7	250	7	250
2	95	65	92	65
3	--	1,000	3	10
4	--	--	--	1,000

Figure 7.--Theoretical curves comparing mined and non-mined subsurface.

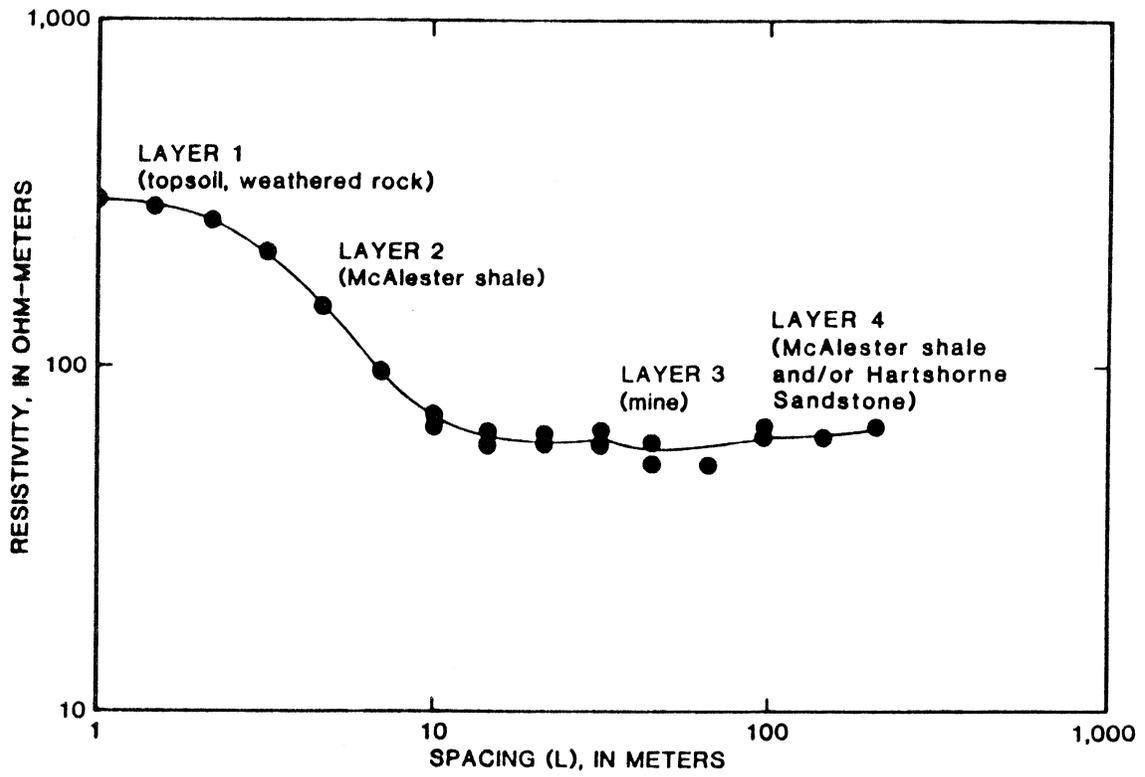


Figure 8.--Typical field sounding curve over mined area.

are underlain by shale of greater thickness or lower resistivity than anticipated. It is more likely that some of the highly ionized water coming from the old workings has penetrated into the sandstone which is thought to lie about 3 to 15 ft beneath the coal which was mined. This would significantly lower the resistivity of the sandstone formation and give a false impression of the thickness of the mined-out layer.

In addition to the above mentioned problems, the resistivity soundings made over areas of similar geology, but having no mines underneath, look very much like the ones done over the mined-out areas. It appears that they may ascend more rapidly on the right side of the curve than those over the mined areas, but it is a subtle distinction, and there appeared to be so much variability in the curves and data points as to question the value of this technique in areas of such low resistivity shales.

CONCLUSIONS

The purpose of this report is to describe the results of a study to determine the general water quality in abandoned underground coal mine workings of the Arkansas Valley, to determine the quantity of water contained in these workings, and to determine if surface electrical resistivity methods could be used to estimate water quality.

The quality of water in coal mines is highly variable; dissolved solids concentrations ranged from 70 to 1,550 mg/L. In some coal mines, the water is suitable for most purposes; in other mines, the water is unsuitable. As was expected, the water was high in sulfates, which although not very desirable in high concentrations, poses no health hazards at the levels found. In many cases, water flowing out of the underground workings was used as a water supply for horses and cattle. At sample site 7 untreated water was pumped from an abandoned mine and used for drinking and cooling water for a chicken house. With treatment, all of the water contained in these old workings could be used for domestic as well as industrial and agricultural purposes.

Between 1.7 and $2.0 \times 10^9 \text{ft}^3$ (39,000 and 46,000 acre-ft) of available underground space was calculated to be contained in the underground coal mines. This would be equivalent to a surface reservoir with a storage capacity of between 3,900 and 4,600 acres averaging 10 ft deep and is approximately 1.7 times the volume of water stored in Blue Mountain Lake. Because locations of mines are known and because maps of many mine workings are on file in various government agency offices, it is possible to locate and develop individual mine sites for water supply.

The use of surface electrical resistivity to determine water quality in this particular study area was unsuccessful. This can be attributed primarily to two factors: the overlying shale has a low resistivity which makes the resistivity values of it and mine water about equal; and the mine water itself is confined to a relatively small zone, only about 3 ft or so in thickness, which makes it increasingly difficult to detect at depth. This was found to be true for the "best case" situation which had the lowest values of resistivity in the mine water. This would therefore mean that in the many mined-out areas having even higher resistivity values for the contained water, the ratio of shale to water resistivity approaches unity, making it virtually impossible to differentiate electrically.

In areas where the overlying rock has significantly higher values of resistivity, increasing the resistivity ratio between mined-out area water and the rock, this technique should have better results. It is the intention of the author to continue the study, as time and funds permit, in order to broaden the data base of resistivity soundings over mined-out areas.

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