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Hydrogeology and Ground-Water Monitoring of Coal-Ash Disposal Sites in a Karst Terrane near Burnside, South-Central Kentucky

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Kentucky Geological Survey
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CONTENTS

	Page
Abstract	1
Introduction	1
Methods	2
Sinkhole and Spring Survey	2
Dye Tracing	2
Monitoring Wells	3
Water-Quality Sampling and Analysis	4
Ash Disposal	4
Site Hydrogeology	4
Kidder Limestone	5
Ste. Genevieve Limestone	5
St. Louis Limestone	5
Salem and Warsaw Formations	6
Background Spring and Well Data	7
Flow System at the Closed-Out Ash Pond	7
Dye Tracing	7
Water Levels in Wells	7
Water Quality	7
Flow System at the Active Ash Pond	9
Dye Tracing	9
Water Quality	9
Flow System at the Coal Stockpile	13
Delineation of Boundaries	13
Water Quality	13
Conclusions	13
Flow Systems	13
Water Quality	17
Closed-Out Ash-Pond Flow System	17
Active Ash-Pond Flow System	17
Coal-Stockpile Flow System	17
Monitoring Strategy in Karst Systems	20
Epilogue	20
Acknowledgments	20
References Cited	21

FIGURES

	Page
1. Map showing location of John Sherman Cooper Power Plant and ash-disposal facilities and relationship to physiographic provinces	2
2. Map showing locations of sinkholes, springs, dye injection points, and wells	3
3. Geologic map of the study area and locations of cross sections A–A' (Fig. 4) and B–B' (Fig. 5)	4
4. Geologic cross section A–A' through the closed-out ash pond	5
5. Geologic cross section B–B' through the active ash pond	6
6. Diagram showing stratigraphic relationship of springs to Salem and Warsaw Formations, and the proximity of the springs to Lake Cumberland	6
7. Map showing locations of positive dye traces	8
8. Diagram showing comparison of mean values for major ions at background sites and values for sites associated with the closed-out ash pond	9
9. Diagram showing comparison of mean values for major ions at background sites and values for sites associated with the active ash pond	13
10. Diagram showing comparison of mean values for major ions at background sites and values for sites associated with the coal stockpile	17

TABLES

	Page
1. Comparison of concentrations of dissolved metals at background sites with concentrations at site J springs, located downgradient from the closed-out ash pond	10
2. Comparison of concentrations of dissolved metals at background sites with concentrations in monitoring wells in the closed-out ash pond	11
3. Comparison of concentrations of dissolved metals at background sites with concentrations in pore water in the closed-out ash pond	12
4. Comparison of concentrations of dissolved metals at background sites with concentrations in site H springs, located downgradient from the active ash pond	14
5. Comparison of concentrations of dissolved metals in Lake Cumberland with concentrations in water in the active ash pond	15
6. Comparison of concentrations of dissolved metals at background sites with concentrations in pore water in the active ash pond.....	16
7. Comparison of concentrations of dissolved metals at background sites with concentrations in springs in the coal stockpile	18
8. Summary of monitored locations associated with the closed-out ash pond with constituents that exceed MCL's or SMCL's	19
9. Summary of monitored locations associated with the active ash pond with constituents that exceed MCL's or SMCL's.....	19
10. Summary of coal-stockpile springs with constituents that exceed MCL's or SMCL's	20

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HYDROGEOLOGY AND GROUND-WATER MONITORING OF COAL-ASH DISPOSAL SITES IN A KARST TERRANE NEAR BURNSIDE, SOUTH-CENTRAL KENTUCKY

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James S. Dinger¹, James C. Currens¹, and
Arsin M. Sahba³

ABSTRACT

The effects of two coal-ash disposal facilities on ground-water quality at the John Sherman Cooper Power Plant, located in a karst region of south-central Kentucky, were evaluated using dye traces in springs. Springs were used for monitoring rather than wells, because in a karst terrane wells are unlikely to intercept individual conduits.

A closed-out ash pond located over a conduit-flow system discharges to three springs in the upper Salem and Warsaw Formations along Lake Cumberland. Water discharging from these downgradient springs is similar to springs unaffected by ash-disposal facilities and is a calcium-bicarbonate type. No constituent concentrations found in this flow system exceeded maximum contaminant levels (MCL's) or secondary maximum contaminant levels (SMCL's) defined by the U.S. Environmental Protection Agency.

An active ash pond is situated over another conduit-flow system that discharges to springs in the lower St. Louis Limestone. Water discharging from these downgradient springs is intermediate between the calcium-bicarbonate type of the unaffected springs and the calcium-sulfate type of the active ash pond. No constituent concentrations found in this flow system exceeded MCL's or SMCL's.

A third flow system associated with a coal stockpile adjacent to the plant is delineated by springs in the St. Louis Limestone and the Salem and Warsaw Formations that discharge calcium-sulfate type water. Chromium and cadmium concentrations exceeded MCL's in at least one sample from this flow system. Iron, manganese, sulfate, and total dissolved solid concentrations exceeded SMCL's in at least one sample.

The closed-out ash pond appears to have no adverse impact on the water quality, nor does the active ash pond. In general, the coal stockpile has a more adverse impact on ground-water quality in the study area than the ash-disposal facilities.

INTRODUCTION

This report culminates an 18-month hydrogeologic study from 1989 to 1990 at the John Sherman Cooper coal-fired power plant in south-central Kentucky. The study was conducted jointly by the Kentucky Geological Survey and the Institute for Mining and Minerals Research at the University of Kentucky. Selected data collected by Battelle Pacific Northwest Laboratories were also incorporated into this report. The purpose of this project was to describe the ground-water flow system and ground-water quality surrounding ash-disposal facilities in a karst terrane.

The monitoring approach used differs from monitoring methods typically applied in nonkarst settings. In a karst setting, the primary avenues for ground-water movement are solution-weathered conduits that discharge water at springs. Ground water in pore spaces between conduits is not likely to be representative of water affected by land uses that moves rapidly through the conduit system. According to Quinlan and Ewers (1985), wells drilled in karst terranes will probably not intercept conduits through which pollutants move; therefore, springs rather than wells are the most efficient and reliable monitoring points. Because springs, where present, provide an effective and convenient way to trace movement

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of water and associated pollutants in the subsurface in karst areas, springs and surface-water sites were used to evaluate water quality in the study area. Wells were only used to evaluate water quality in the ash fill.

Cooper station, operated by East Kentucky Power Cooperative, is located in Pulaski County on the north side of Lake Cumberland, approximately 0.75 mi northeast of Burnside, off county highway 1247 (Fig. 1). The site straddles the northern edge of the Burnside and southern edge of the Somerset 7.5-minute quadrangles. The plant burns bituminous coal from eastern Kentucky that has an average sulfur content of 1.5 percent and a mineral content (noncombustible) of 10 to 11 percent. Approximately 150,000 tons of coal are stockpiled adjacent to the plant. Untreated water from Lake Cumberland is used for plant cooling and as sluice water for ash disposal.

Two ponds, one active and one closed out, have been used for ash disposal.

METHODS

Sinkhole and Spring Survey

The study area was extensively field mapped to locate sinkholes, swallow holes, and springs. The mapping located 132 sinkholes and 32 springs (Fig. 2). The sinkhole depressions have length and width dimensions ranging from a few feet to 250 ft; depths varied from 1 to 20 ft. Spring morphology varied from small, diffuse seeps to large springs flowing from discrete openings. Some springs along the lakeshore are alternately submerged and exposed.

Dye Tracing

A qualitative dye-tracing program was initiated in the spring of 1990 to establish hydraulic connections between sinkholes and swallets located on the upland region, and springs located around the periphery of the site. The fluorescent tracers fluorescein (acid yellow 73, CI 45350) and Tinopal CBS-X optical brightener (CI 351) were chosen for this study. A background test of fluorescence found no evidence of potential interference with either dye.

Eight sites were selected for introduction of dye: four in the vicinity of each disposal site (Fig. 2). Dye was added directly to sites where flow was visible. Locations that did not have flowing water were primed with

1,000 gallons of water and flushed with an additional 1,000 gallons of water after the introduction of dye. Detectors placed at selected springs were checked weekly. Fluorescein flushed through the system quickly, but optical brightener showed residual fluorescence for several weeks.

Seven of eight dye traces were successful. One fluorescein dye trace was lost. Laboratory tests conducted at the Kentucky Geological Survey showed that fluorescein is strongly adsorbed onto coal ash, so this trace could have been lost as a result of adsorption onto ash present in the conduit system. Alternatively, the dye may not have flushed through the system.

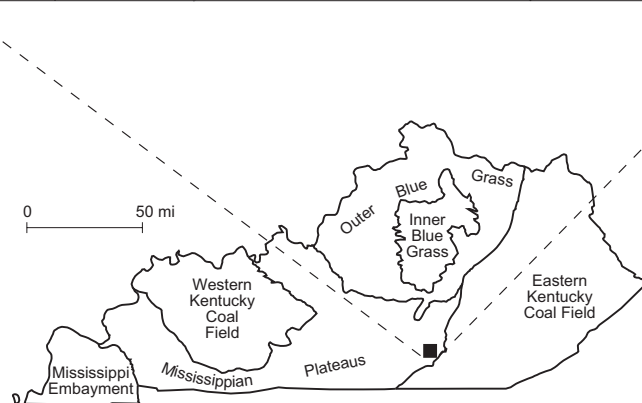
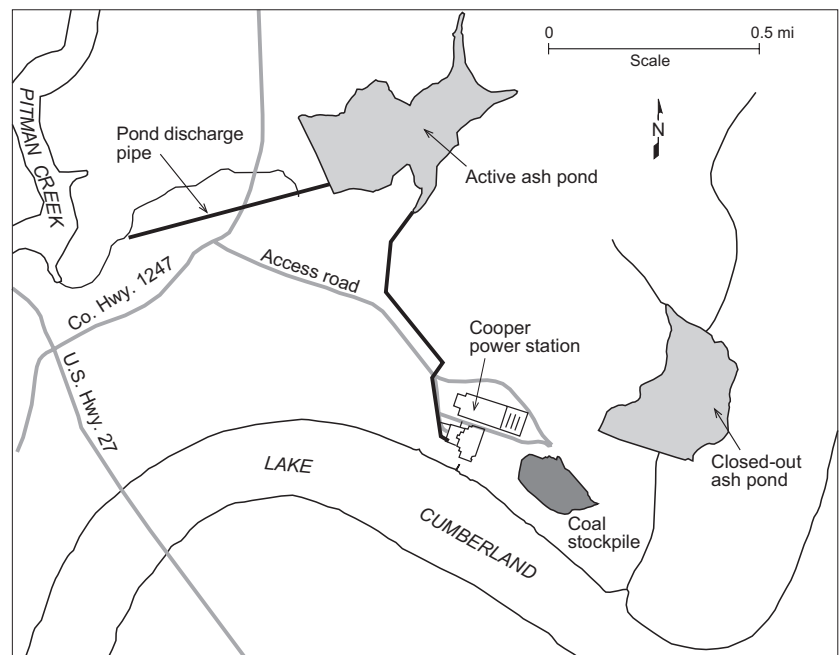
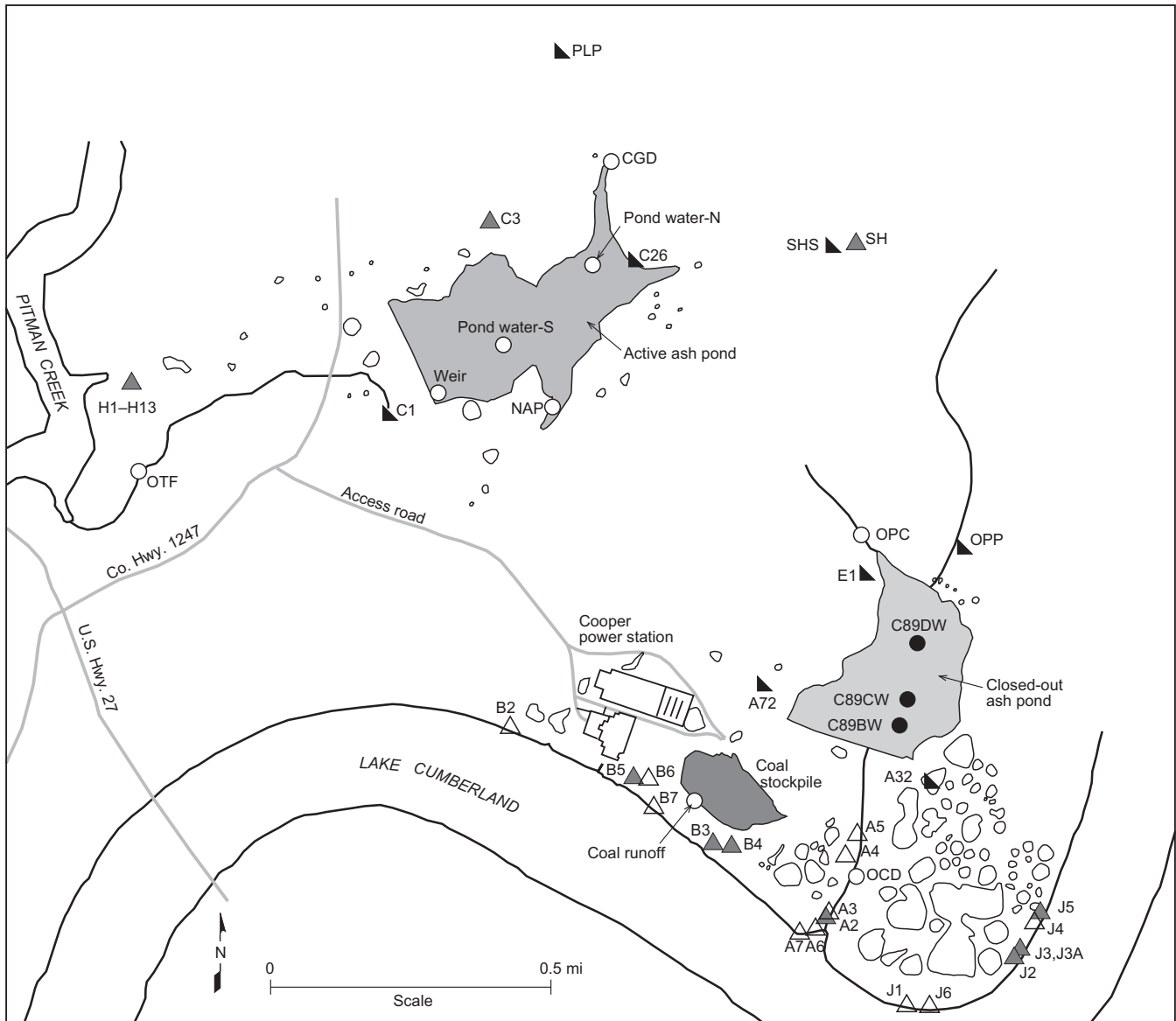


Figure 1. Location of John Sherman Cooper Power Plant and ash-disposal facilities and relationship to physiographic provinces.



EXPLANATION

- Surface-water site
- Ash monitoring well
- ▲ Dye input point
- ▲ Sampled spring
- △ Spring
- Sinkhole

Figure 2. Locations of sinkholes, springs, dye injection points, and wells.

Monitoring Wells

Three ground-water monitoring wells were drilled in the closed-out ash pond to assess the quality of ground water in the ash (Fig. 2). The wells were constructed in fly ash, and

the bottom of the screen rested on limestone bedrock. A bentonite seal was placed above the sand pack a few feet above the screen. The remainder of the annulus was filled with ash. Boreholes were drilled using a hollow-stem auger and were completed with 2-in.-diameter PVC well casing.

Water-Quality Sampling and Analysis

Water samples were obtained from springs, surface water, and monitoring wells by personnel from both the University of Kentucky and Battelle Pacific Northwest Laboratories. Pore-water samples were collected from the active and closed-out ash ponds by Battelle personnel. Water samples were analyzed for a wide range of chemical constituents in order to characterize the surface- and ground-water quality upgradient and downgradient from the ash-disposal sites, in the closed-out ash pond, and in the active ash pond.

ASH DISPOSAL

Coal ash is an aluminosilicate glass composed primarily of silicon, aluminum, iron, and calcium oxides and lesser amounts of sodium, magnesium, potassium, and sulfur (Cherkauer, 1980; Elseewi and others, 1980). Trace metals are also common. The composition of coal ash is highly dependent on the composition of the precombusted coal. Elements associated with ash may be incorporated into the aluminosilicate matrix of individual particles or may accumulate on the outer surface of the particles. Leaching of metals and other constituents into ground and surface waters is the primary concern with disposal of coal ash.

Beginning in 1964, ash was sluiced to what is now referred to as the closed-out ash pond, an unlined disposal pond that was dewatered after storage capacity was reached in 1978 (Fig. 1). The closed-out ash pond has a surface area of 40 acres and an ash thickness of 35 ft. Plant personnel indicate that sinkholes have occasionally opened up and drained ash-laden water into the subsurface along the eastern edge of and within the pond. These sinkholes were periodically plugged with rock and gravel.

Since 1978, ash has been disposed of in an unlined disposal pond, termed the active ash pond, located 4,100 ft northeast of the plant (Fig. 1). The active pond has a total surface area of 50 acres. Ash from the plant is sluiced 3,550 ft via pipeline to the pond, which also receives runoff from the watershed above it and piped storm runoff from the plant. Pond water discharges to a small, unnamed tributary of Pitman Creek.

SITE HYDROGEOLOGY

The plant lies along the eastern edge of the Mississippian Plateaus physiographic province, adjacent to the Eastern Kentucky Coal Field (Fig. 1). Surficial geology in the

Mississippian Plateaus consists of Mississippian carbonates. Topography is a rolling, upland karst plain with subsurface drainage, except for major rivers. In the Burnside area, however, topography is noticeably dissected by small, V-shaped valleys, although sinkholes and subsurface drainage are the dominant drainage. Knobs capped with Pennsylvanian sandstone and shale typical of the Eastern Kentucky Coal Field are located northeast of the site. The lower, moderately steep slopes of these knobs are Mississippian limestones and shales.

The power plant is adjacent to Lake Cumberland. The lake level generally drops throughout late spring, summer, and fall, and briefly increases during periods of heavy precipitation. Levels are normally lower during early winter, to provide adequate storage for winter and spring precipitation.

Structures associated with the plant lie on a rolling karst upland characterized by sinkholes. The headwaters of a well-defined surface drainage pattern originate in the Pennsylvanian knobs northeast of the site (Lewis, 1974; Taylor and others, 1975). As these streams descend into the carbonate sequence, swallow holes, sinkholes, and surface fractures direct drainage underground, where it later emerges at springs along Lake Cumberland. Lateral facies changes within the Salem and Warsaw are common and influence the location of springs. A generalized geologic map (Fig. 3) shows the

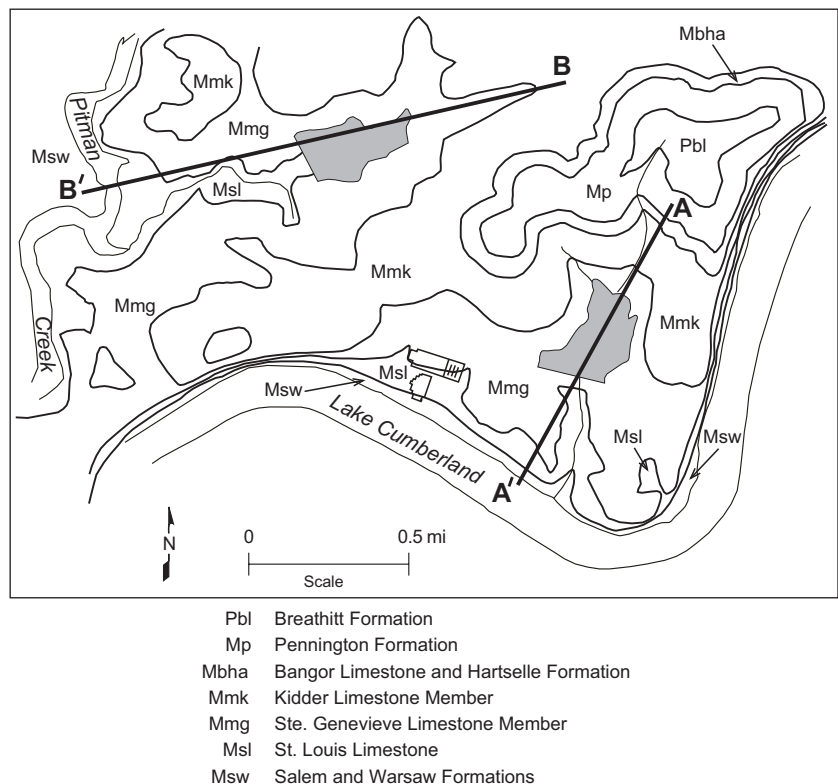


Figure 3. Geology of the study area and locations of cross sections A-A' (Fig. 4) and B-B' (Fig. 5).

location of disposal facilities relative to the geologic formations. Geologic cross sections constructed through both ash-disposal facilities are shown in Figures 4 and 5.

Kidder Limestone

The Kidder Limestone, comprising the upper member of the Monteagle Limestone, crops out around the flank of the high knobs northeast of the plant. The member is composed primarily of limestone that contains minor amounts of siltstone and shale distributed as thin beds throughout. Lambert and Brown (1963), in the hydrologic atlas for Pulaski County, indicated that springs from solution openings in the Kidder Limestone may discharge up to 7,200 gallons per day (gal/d). Some springs, however, barely produce enough for a domestic supply. Spring SH, which occurs in the Kidder Limestone (Fig. 2), was previously used as a domestic water source. This is a high-capacity spring that consistently flows at an estimated rate of 21,000 gal/d.

Ste. Genevieve Limestone

The Ste. Genevieve Limestone, the youngest formation that directly underlies plant facilities, forms the lower member of the Monteagle Limestone and is predominantly limestone with minor amounts of chert. Lambert and Brown (1963) reported that wells intercepting large conduits in the Ste. Genevieve may yield as much as 72,000 gal/d, although most wells intercepting small conduits yield only enough water for a domestic supply. Large-capacity springs gener-

ally occur at or near stream level or at the Ste. Genevieve-St. Louis contact. Three springs (A4, A5, and C3) occur in the Ste. Genevieve on the rolling upland (Fig. 2). Springs A4 and A5 are diffuse seeps along an outcrop, whereas spring C3 emerges from a distinct opening and flows at an estimated rate of 14,000 gal/d year-round.

St. Louis Limestone

The St. Louis Limestone lies directly below the Ste. Genevieve Limestone and is a predominantly cherty, argillaceous, fossiliferous limestone with interbeds of claystone and siltstone. Siltstone is more common in the lower 20 ft. The St. Louis Limestone crops out in the valley wall above Lake Cumberland and in places forms a prominent escarpment. According to Lambert and Brown (1963), wells intercepting large conduits in the St. Louis yield more than 72,000 gal/d. Most wells penetrate some conduits, but wells penetrating only small conduits are generally inadequate for domestic supplies. The lower 20 ft of the St. Louis usually produces inadequate yields for domestic use.

In the study area, 22 springs occur in the St. Louis Limestone. All except for spring C1 are located along the valley wall. The stratigraphic relationship of these springs to the underlying Salem and Warsaw Formations, and the proximity of the springs to Lake Cumberland are shown in Figure 6.

Two springs (A2 and A3) are in a dolomite bed in the St. Louis Limestone south of the plant (Fig. 2). Spring A2 rests on an argillaceous layer and flows at a rate of about 11,000 gal/d year-round. Spring A3 is a diffuse seep that is present throughout the year. Water from spring A2 was visibly iron stained, indicating a likely shallow flow connection with the nearby coal stockpile.

Five springs (B2, B3, B4, B5, and B6) (Fig. 2), situated downslope of the coal stockpile area and plant, are located in the St. Louis Limestone. Flows from these springs range from diffuse drips up to a steady rate of 14,000 gal/d. Flows during both wet and dry weather are similar. The four springs located directly below the coal stockpile are visibly iron stained, indicating connection with the coal stockpile.

Spring C1 is located on the upland, downgradient from the active ash pond. Discharge from this spring is approximately 7,000 gal/d.

Site H consists of 13 springs located over a 500-ft-wide zone in an unnamed tributary of Pitman Creek west of the active ash

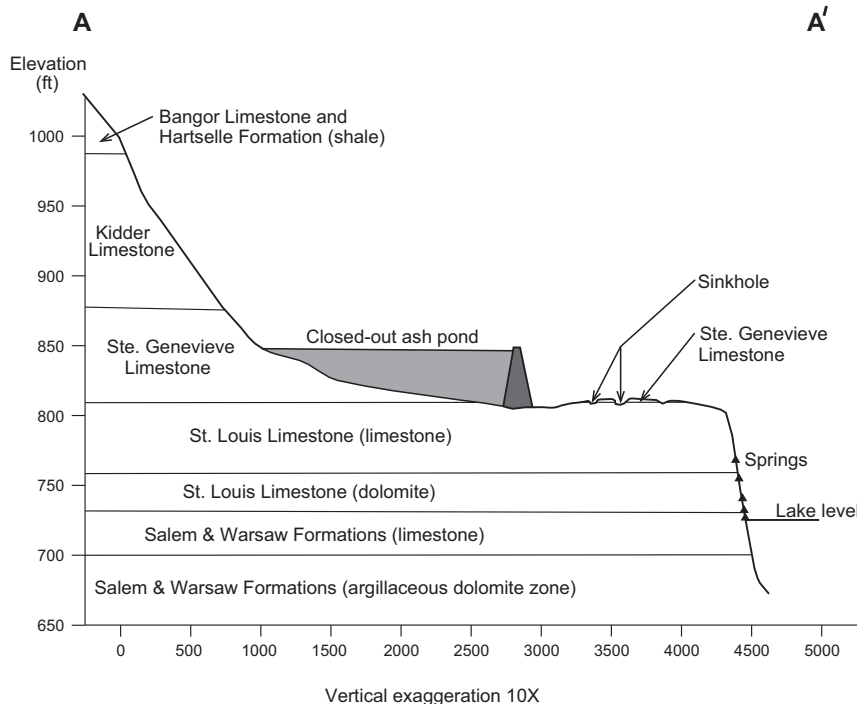


Figure 4. Geologic cross section A–A’ through the closed-out ash pond.

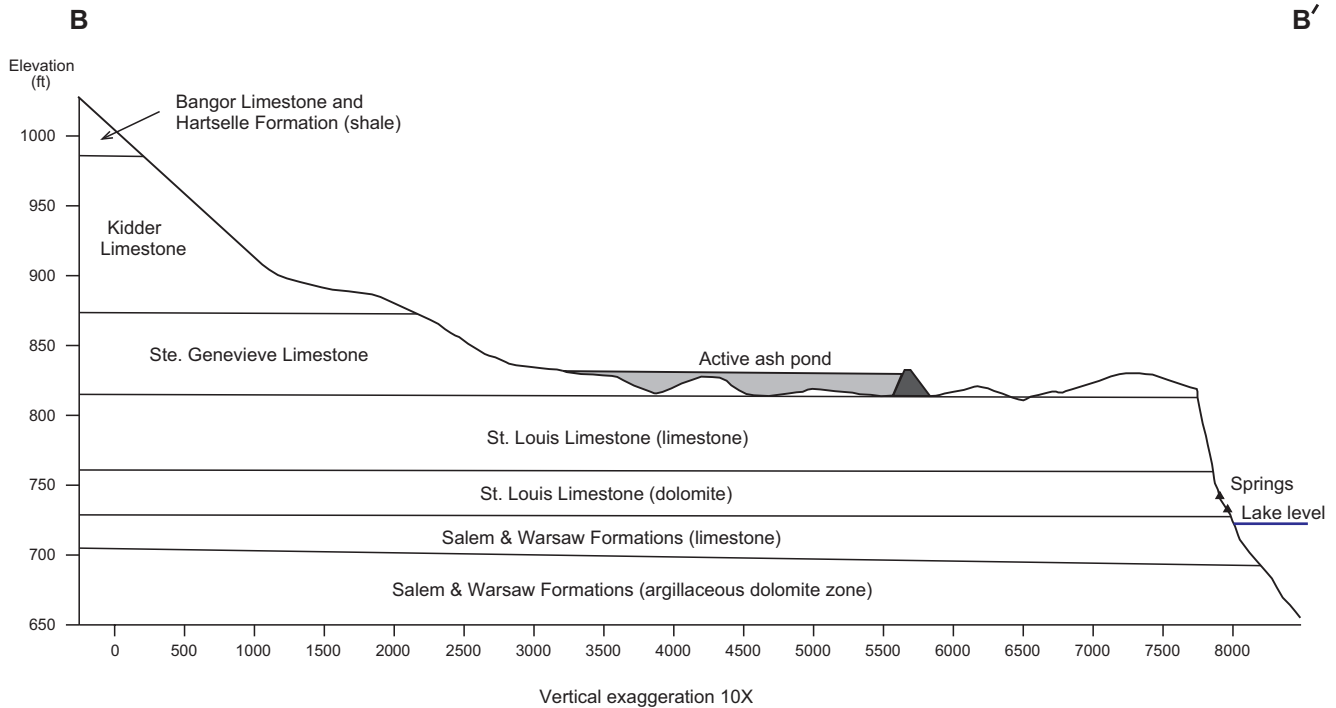


Figure 5. Geologic cross section B–B’ through the active ash pond.

pond (Fig. 2). This zone consistently discharges an estimated 2 million gal/d. Numerous sinkholes identified during the site investigation for the active ash pond (Bowser-Morner

Testing Laboratories, Inc., 1976; Sahba, 1991) are direct avenues linking the active pond to the springs at site H. The springs at site H are located primarily in two stratigraphic zones. The stratigraphically higher springs are located in the St. Louis Limestone and have the greater discharge. The other spring zone is 10 to 15 ft lower, probably at the contact between the St. Louis Limestone and the Salem and Warsaw Formations.

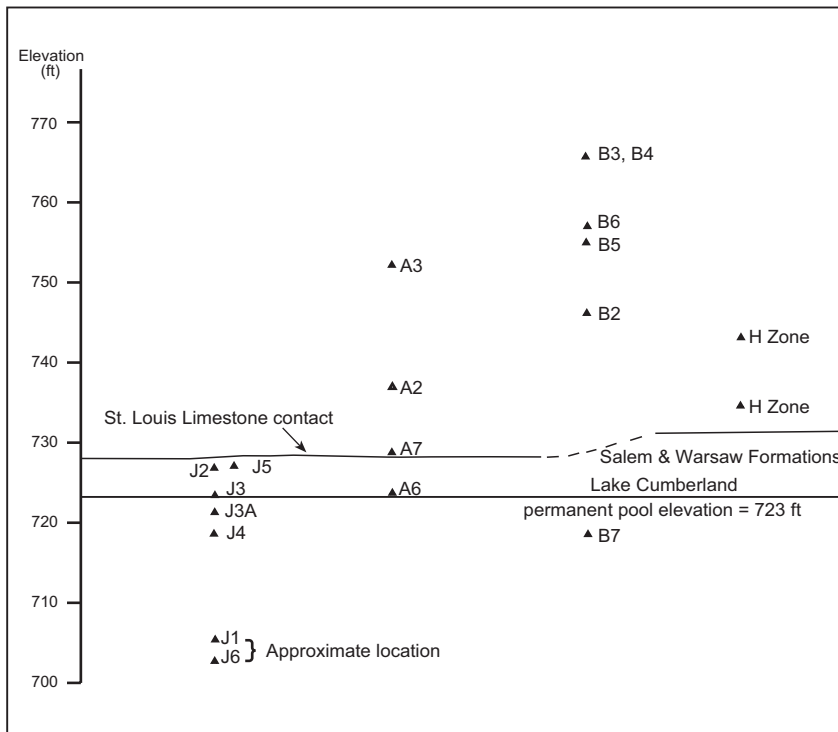


Figure 6. Stratigraphic relationship of springs to Salem and Warsaw Formations, and the proximity of the springs to Lake Cumberland.

Salem and Warsaw Formations

The Salem and Warsaw Formations are the oldest rocks that crop out near the station. These two formations are considered a single unit in this region because of their lithologic similarity. They are an intertonguing sequence of dolomite, limestone, shale, siltstone, and sandstone that exhibits significant lateral variation. The exposed section of the Salem and Warsaw near the plant is predominantly limestone underlain by argillaceous dolomite. The dolomite thins and dips below lake level in Pitman Creek. Lambert and Brown (1963) reported that the Salem (which they called the “Spergen Limestone”) and Warsaw yield enough water for domestic supplies where

the formations are predominantly limestone, but have poor yield in argillaceous zones. A minor stratigraphic horizon that commonly contains springs is often present where limestone is in contact with underlying argillaceous strata. Another spring horizon is at the base of the Salem and Warsaw (below lake level at this site).

Ten springs occur in the Salem and Warsaw Formations. Approximate stratigraphic positions are shown in Figure 6. Seven springs, referred to as J springs, are located along the shoreline of Lake Cumberland, south-southeast of the closed-out ash pond (Fig. 2). The locations of five of the springs (J2, J3, J3A, J4, and J5), near the upper part of these formations, appear to be controlled by an argillaceous bed below spring J4. Flow from these springs was estimated to range from 1,440 to 14,000 gal/d during the winter and spring. Observed discharge decreased or ceased altogether during the summer and fall.

Springs J1 and J6, located on top of the aforementioned argillaceous dolomite bed, are stratigraphically lower in the Salem and Warsaw than the other J springs and are below the normal pool elevation of Lake Cumberland. Large volumes of water are reported to have commonly discharged from spring J6 during low lake stages when the closed-out ash pond was an active facility. This was most likely the result of direct conduit connection of this spring to the once-active pond.

Springs designated with an "A" prefix (Fig. 2) are located along a drainage way south of the closed-out pond. Springs A6 and A7 are iron-stained diffuse seeps. One small spring (B7) at site B is located in the Salem and Warsaw Formations. All these springs are associated with argillaceous zones in the Salem and Warsaw Formations.

West of the active ash pond (near site H), at least 25 to 30 ft of interbedded limestone and argillaceous dolomite is exposed in the Salem and Warsaw immediately below the St. Louis Limestone. No observable springs flow from the Salem and Warsaw at this site; all springs are in the St. Louis Limestone. The interval containing the argillaceous dolomite that is exposed at sites J, A, and B is either submerged by the lake or absent at site H. The apparent lack of spring development in any part of the Salem and Warsaw at this location suggests that an argillaceous zone near the top of the Salem and Warsaw may impede downward groundwater flow.

Background Spring and Well Data

Background data (from sites not affected by the ash-disposal facilities) were compared with other water-quality data to assess the impact of facilities on ground-water quality. The following sites were used to establish background water quality at the study area:

- Two springs (C3 and SH) and one surface-water site (OPC), located upstream of the disposal facility
- Lake Cumberland.

FLOW SYSTEM AT THE CLOSED-OUT ASH POND

Dye Tracing

Dye traces defined flow paths that encompass the closed-out pond (straight lines on Figure 7). In reality, however, subsurface karst forms complex, multichannel flow systems rather than straight-line flow systems. Positive traces were observed between sinkhole A72 (input) and spring J6 (detector) and sinkhole OPP (input) and springs J2, J3, and J5 (detectors). Another trace from sinkhole A32 (input) to springs J2 and J3 (detectors) lies within the two outer traces. Flow direction for all traces is southeast. A fourth trace was conducted from sinkhole E1 (input), but dye did not reappear.

Water Levels in Wells

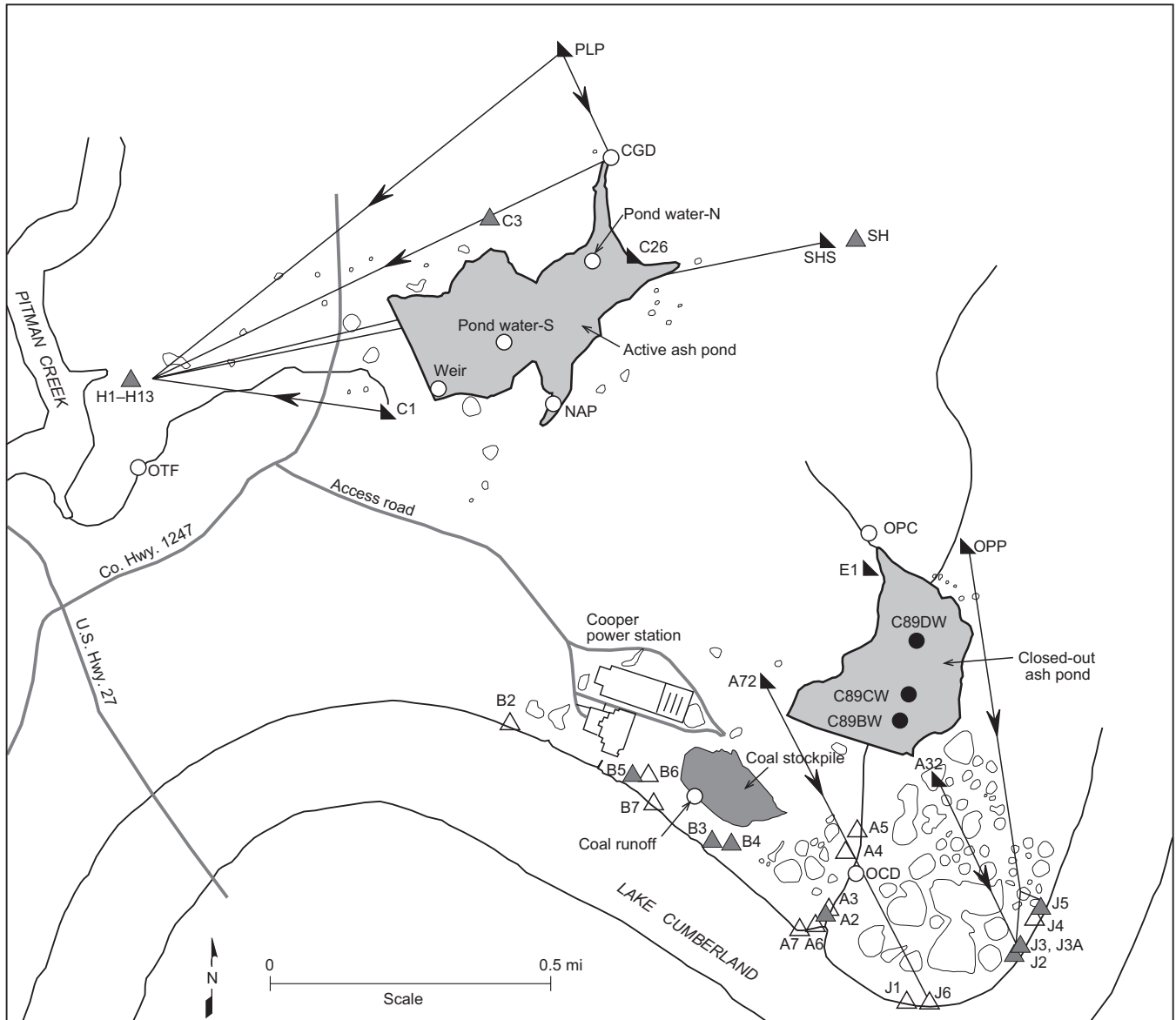
Water levels measured in wells from March through August 1990 were normally within a few feet of the bottom of the wells (see water-level data in Minns and others, 1995). Water-level data were not collected during the wet season. The largest decline was observed in well C89BW, at the south end of the closed-out pond. Water levels dropped 4.8 ft during the summer of 1990 and the well went dry. Well C89CW, located in the middle of the ash fill, declined 2 ft during the summer and was within 1.4 ft of the bottom of the well at the end of the monitoring period. Well C89DW, located near the head of the ash fill, contained the most water throughout the summer, although the water level fell about 2 ft to within 3 ft of the bottom of the well by August. Flow direction in the closed-out pond is from the head of the fill down the buried valley.

Water Quality

The following sites were used to evaluate water quality in the closed-out ash pond system (Fig. 2):

- Three ash wells (C89BW, C89CW, and C89DW)
- Three downgradient springs in the closed-out ash-pond flow system (J2, J3, and J5)
- Twenty samples of pore water from the closed-out ash pond (collected by Battelle Pacific Northwest Laboratories).

Diagrams comparing mean values for major ionic species at sites associated with the closed-out ash pond are illustrated in Figure 8. Analyses from wells and downgradient



EXPLANATION

- Surface-water site
- Ash monitoring well
- ▲ Dye input point
- ▲ Sampled spring
- △ Spring
- Sinkhole
- Dye trace

Figure 7. Locations of positive dye traces.

springs, as well as from background sites, indicate that the water type for all sites is calcium bicarbonate. Ash wells are slightly deficient in calcium compared to springs. Mean specific conductance for these three sites is similar, however,

ranging from 270 microSiemens per cm ($\mu\text{S}/\text{cm}$) for wells to 378 $\mu\text{S}/\text{cm}$ for background sites. Pore-water data were not included in the comparison because bicarbonate values were not available.

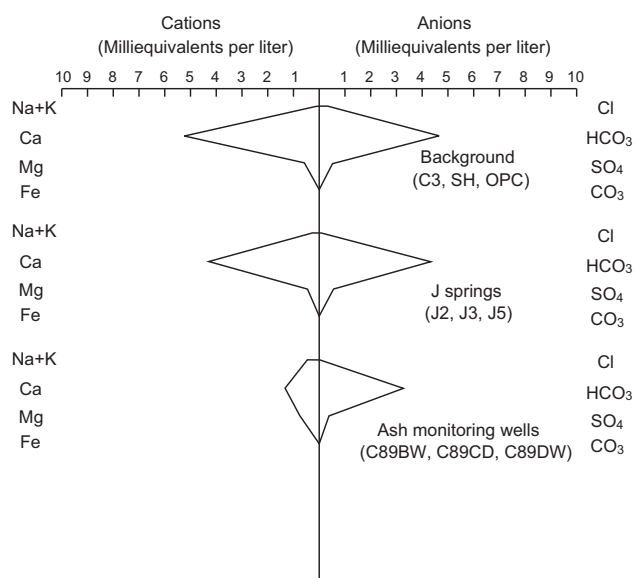


Figure 8. Comparison of mean values for major ions at background sites and values for sites associated with the closed-out ash pond.

Table 1, comparing dissolved metal concentrations in the downgradient springs at site J to background values, shows that values at site J are very similar to background values. Table 2, comparing dissolved metal concentrations in the ash wells to background concentrations, shows that only lithium and manganese concentrations are at least one order of magnitude greater in the ash wells than at the background sites. Strontium and boron concentrations in ash wells are seven and eight times greater than background concentrations, respectively.

Table 3 compares pore water from the closed-out ash pond with water from background sites. Boron, iron, manganese, and zinc concentrations for pore waters are an order of magnitude greater than at background sites. Barium values for pore water are approximately eight times greater than background values.

FLOW SYSTEM AT THE ACTIVE ASH POND

Dye Tracing

Dye traces defined flow paths that encompass the active ash pond (straight lines on Figure 7). In reality, however, subsurface karst forms complex, multichannel flow systems that cannot be defined by straight lines. Dye movement was traced from sinkhole PLP (input) to the springs at site H along Pitman Creek (detectors). The trace from swallet C1 (input) to the springs at site H (detectors) was also successful. Addi-

tional traces lie between sinkhole C26 (input), swallet SHS (input), sinkhole C26 (input), and the H springs (detectors). Flow direction is to the southwest.

Water Quality

The following sites were used to evaluate water quality in the active ash-pond flow system (Fig. 2):

- Five surface-water sites in the active ash-pond flow system (pond water-N, pond water-S, and weir, collected by Battelle personnel; OTF and NAP, collected by University of Kentucky personnel)
- Six downgradient springs in the active ash-pond flow system (H1, H3, H6, H8, H9, and H12)
- Fifteen pore-water samples from the active ash-pond flow system (collected by Battelle personnel).

Diagrams comparing mean values for major ionic species at sites associated with the active ash-pond flow system are illustrated in Figure 9. Sluice water from Lake Cumberland is a mixed water type containing approximately equal percentages of calcium, magnesium, sodium, bicarbonate, and sulfate. Sluice water mixed with ash in the active ash pond is primarily calcium-sulfate type. Discharge from the group of downgradient springs at site H is primarily calcium-bicarbonate water that has a sulfate content greater than at background sites, indicating mixing of ash-pond water and natural spring flow. Specific conductances range from a low of 156 $\mu\text{S}/\text{cm}$ for one lake sample to a mean high of 319 $\mu\text{S}/\text{cm}$ in the downgradient springs.

Table 4 compares dissolved metal concentrations in the downgradient springs at site H with background values. Dissolved metal concentrations in the downgradient springs are similar to background concentrations; Ba, B, Cu, Fe, Li, Mn, Sr, and S range between approximately two and nine times greater than background. Only the concentration of boron exceeds background concentrations by nearly an order of magnitude.

Table 5 compares dissolved metal concentrations in the active ash-pond water with water collected from Lake Cumberland that is used for sluicing. Concentrations of Ba, B, Cd, Cu, Fe, Li, Mn, Ni, S, and Sn in the ash pond are 2 to 21 times greater than in the lake water.

Table 6 compares dissolved metal concentrations at background sites with concentrations in pore water from the active ash-pond flow system. Concentrations of boron, manganese, and zinc in the pore water range from 47 to 66 times higher than background levels. Concentrations of arsenic, lithium, and vanadium in the pore water are 13 to 18 times greater than background values.

Table 1. Comparison of concentrations of dissolved metals at background sites with concentrations at site J springs, located downgradient from the closed-out ash pond. All values in mg/L.

Constituent	Detection Limit		MCL	SMCL	Background		Downgradient J Springs		Comparison of J Springs to Background
	KGS	Battelle			Mean	Maximum	Mean	Maximum	
Aluminum	0.027	0.3				0.139	0.108		less
Antimony	0.017				< 0.017			0.02	same
Arsenic	0.028	0.08	0.05			< 0.08		0.029	unknown
Barium	0.001	0.002	1.0		0.03		0.036		same
Beryllium	0.0005				< 0.0005		< 0.001		same
Boron	0.006	0.01				0.02	0.071		4X
Cadmium	0.003		0.01		<0.003		< 0.003		same
Chromium	0.006	0.02	0.05			0.01	0.01		same
Cobalt	0.004				< 0.004		< 0.004		same
Copper	0.004	0.004		1.0	0.006			0.001	< 2X
Iron	0.004	0.005		0.3		0.116	0.176		< 2X
Gold	0.004				< 0.004		< 0.004		same
Lead	0.038		0.05		< 0.038		< 0.038		same
Lithium	0.006	0.004				< 0.006	0.012		2X
Manganese	0.001	0.002		0.05		0.01		0.005	less
Nickel	0.012	0.02				< 0.02		0.013	unknown
Phosphorus	0.06	0.1				< 0.1	< 0.068		same
Selenium	0.052		0.01		< 0.052		< 0.052		same
Silicon	0.02	0.02			1.66		1.19		less
Silver	0.003		0.05		< 0.003		< 0.003		same
Strontium	0.0008	0.002			0.276		0.398		< 2X
Sulfur	0.05				12.9		10.4		same
Thallium	0.026				< 0.026		< 0.026		same
Tin	0.026				< 0.026		< 0.026		same
Vanadium	0.003	0.01				0.01	< 0.003		less
Zinc	0.002	0.02		5.0	0.008		0.012		< 2X

Maximum values are used for comparisons where mean values are not calculated.
Mean values are not calculated where constituent values are below detection limits.

Table 2. Comparison of concentrations of dissolved metals at background sites with concentrations in monitoring wells in the closed-out ash pond. All values in mg/L.

Constituent	Detection Limit		MCL	SMCL	Background		Ash Wells		Comparison of Ash Wells to Background
	KGS	Battelle			Mean	Maximum	Mean	Maximum	
Aluminum	0.027	0.3				0.139		0.057	less
Antimony	0.017				< 0.017		< 0.017		same
Arsenic	0.028	0.08	0.05			< 0.08		0.071	unknown
Barium	0.001	0.002	1.0		0.03			0.104	3X
Beryllium	0.0005				< 0.0005		< 0.001		same
Boron	0.006	0.01				0.02	0.168		8X
Cadmium	0.003		0.01		<0.003		< 0.003		same
Chromium	0.006	0.02	0.05			0.01	< 0.006		same
Cobalt	0.004				< 0.004		< 0.004		same
Copper	0.004	0.004		1.0	0.006			0.005	same
Iron	0.004	0.005		0.3		0.116	0.204		< 2X
Gold	0.004				< 0.004		0.006		same
Lead	0.038		0.05		< 0.038		< 0.038		same
Lithium	0.006	0.004				< 0.006	0.114		19X
Manganese	0.001	0.002		0.05		0.01	0.407		41X
Nickel	0.012	0.02				< 0.02	< 0.012		same
Phosphorus	0.06	0.1				< 0.1		0.463	5X
Selenium	0.052	0.01	0.01		< 0.052			< 0.052	same
Silicon	0.02	0.02			1.66		7.56		5X
Silver	0.003		0.05		< 0.003		< 0.003		same
Strontium	0.0008	0.002			0.276		2.00		7X
Sulfur	0.05				12.9		25.5		2X
Thallium	0.026				< 0.026		< 0.026		same
Tin	0.026				< 0.026		< 0.026		same
Vanadium	0.003	0.01				< 0.01	0.031		3X
Zinc	0.002	0.02		5.0	0.008		0.009		same

Maximum values are used for comparisons where mean values are not calculated.
Mean values are not calculated where constituent values are below detection limits.

Table 3. Comparison of concentrations of dissolved metals at background sites with concentrations in pore water in the closed-out ash pond. All values in mg/L.

Constituent	Detection Limit		MCL	SMCL	Background		Closed-Out Pond Pore Water		Comparison of Pore Water to Background
	KGS	Battelle			Mean	Maximum	Mean	Maximum	
Aluminum	0.027	0.3				0.139	not run		
Antimony	0.017				< 0.017		not run		
Arsenic	0.028	0.08	0.05			< 0.08	not run		
Barium	0.001	0.002	1.0		0.03		0.249		8X
Beryllium	0.0005				< 0.0005		not run		
Boron	0.006	0.01				0.02	0.551		28X
Cadmium	0.003		0.01		< 0.003		not run		
Chromium	0.006	0.02	0.05			0.01	not run		
Cobalt	0.004				< 0.004		not run		
Copper	0.004	0.004		1.0	0.006		not run		
Iron	0.004	0.005		0.3		0.116		1.92	17X
Gold	0.004				< 0.004		not run		
Lead	0.038		0.05		< 0.038		not run		
Lithium	0.006	0.004				< 0.006	not run		
Manganese	0.001	0.002		0.05		0.01		0.36	36X
Nickel	0.012	0.02				< 0.02	not run		
Phosphorus	0.06	0.1				< 0.1	not run		
Selenium	0.052		0.01		< 0.052		not run		
Silicon	0.02	0.02			1.66		10.02		6X
Silver	0.003		0.05		< 0.003		not run		
Strontium	0.0008	0.002			0.276		1.05		4X
Sulfur	0.05				12.9		not run		
Thallium	0.026				< 0.026		not run		
Tin	0.026				< 0.026		not run		
Vanadium	0.003	0.01				< 0.01	not run		
Zinc	0.002	0.02		5.0	0.008		0.171		21X

Maximum values are used for comparisons where mean values are not calculated.
Mean values are not calculated where constituent values are below detection limits.

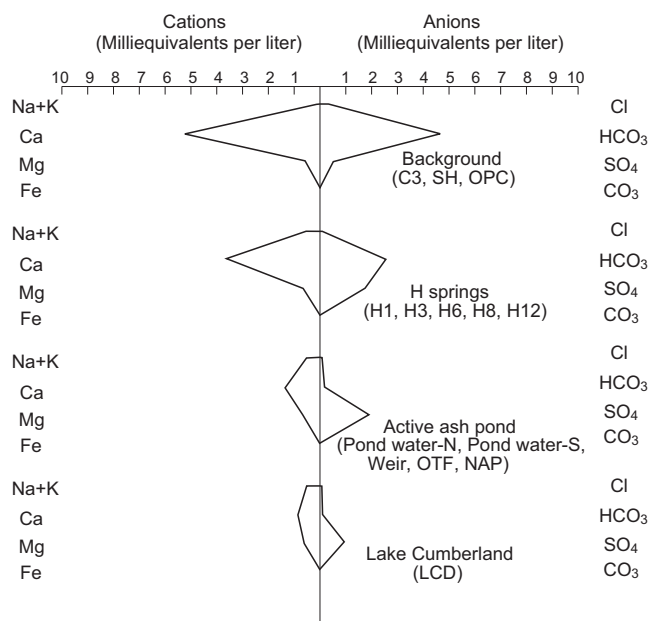


Figure 9. Comparison of mean values for major ions at background sites and values for sites associated with the active ash pond.

FLOW SYSTEM AT THE COAL STOCKPILE

Delineation of Boundaries

Springs affected by coal runoff were identified by iron staining at spring mouths. This system is roughly defined by six springs: A2, A6, A7, B3, B4, and B5. Runoff from the stockpile, located on the upland adjacent to the plant, is infiltrating the bedrock and flowing toward Lake Cumberland. No positive dye traces were found in springs affected by coal runoff. Perhaps none of the springs are connected to dye input points, or perhaps adsorption or interference occurred along flow paths.

Water Quality

The following sites were used to evaluate water quality in the coal-stockpile flow system (Fig. 2):

- Three springs associated with the coal stockpile (A2, B4, and B5)
- One sample of surface runoff from the coal stockpile (collected by Battelle personnel).

Springs affected by the coal stockpile discharge a calcium-sulfate type water (Fig. 10) rather than the calcium-bicarbonate type characteristic of the other sites. Specific conductance for these springs ranges from 508 to 3,640 $\mu\text{S}/\text{cm}$, considerably higher than the average value of 378

$\mu\text{S}/\text{cm}$ for the background sites. Sulfate, a common constituent in water affected by coal runoff, has a concentration ranging from 139 mg/L to 477 mg/L, whereas the mean sulfate concentration at background sites is about 28 mg/L. Spring B4, located closest to the stockpile, has the lowest pH and highest concentrations of metals. Two other springs, located farther away from the stockpile, have higher pH and lower concentrations of metals. Residence time within the carbonate flow system appears to have buffered these springs. Table 7 compares concentrations of dissolved metals in coal-affected springs with background concentrations. Al, Be, Co, Fe, Mn, Ni, and Zn concentrations are more than 100 times higher for sites affected by the coal stockpile than background values. Cd, Cu, Au, Li, and S are at least 10 times greater for sites affected by the coal stockpile than background values.

CONCLUSIONS

Flow Systems

Dye-trace studies identified two major ground-water flow systems at the study area. One flow system encompasses the closed-out ash pond. The second system incorporates the active ash pond. Flow from both systems emerges as springs along the shoreline of Lake Cumberland. A minor third system, identified on the basis of iron precipitates, encompasses the coal stockpile.

The base of the ground-water flow system near Cooper station appears to be associated with two stratigraphic intervals. The base of karst development in the closed-out ash-pond flow system is an argillaceous dolomite layer in the Salem and Warsaw Formations, located approximately 30 ft below the St. Louis Limestone-Salem and Warsaw Formation contact. Numerous springs are in the upper 30 ft of the Salem and Warsaw at this location. The lower limit of ground-water flow in the coal-stockpile flow system, south of the coal stockpile, is similar.

The lower limit of karst development in the active ash-pond flow system west of the plant near Pitman Creek is the St. Louis-Salem and Warsaw contact. The upper Salem and Warsaw in this area contains numerous argillaceous interbeds not present in the eastern part of the study area. This facies change apparently inhibits deeper development of the ground-water flow system into the Salem and Warsaw. Therefore, springs associated with the active ash-pond system are in the lower St. Louis Limestone.

Discharge for downgradient springs at site H in the active ash-pond flow system is approximately two orders of magnitude greater than in the closed-out ash pond system. Most of this flow originates in the active ash pond, where it enters the ground-water system through fractures and sinkholes. This conclusion is supported by the mixed water types

Table 4. Comparison of concentrations of dissolved metals at background sites with concentrations in site H springs, located downgradient from the active ash pond. All values in mg/L.

Constituent	Detection Limit		MCL	SMCL	Background		Downgradient H Springs		Comparison of H Springs to Background
	KGS	Battelle			Mean	Maximum	Mean	Maximum	
Aluminum	0.027	0.3				0.139	0.11		less
Antimony	0.017				< 0.017		< 0.017		same
Arsenic	0.028	0.08	0.05			< 0.08	< 0.028		same
Barium	0.001	0.002	1.0		0.03		0.044		< 2X
Beryllium	0.0005				< 0.0005		< 0.001		same
Boron	0.006	0.01				0.02	0.175		9X
Cadmium	0.003		0.01		< 0.003			0.003	same
Chromium	0.006	0.02	0.05			0.01	0.009		less
Cobalt	0.004				< 0.004		< 0.004		same
Copper	0.004	0.004		1.0	0.006		0.01		< 2X
Iron	0.004	0.005		0.3		0.116	0.15		< 2X
Gold	0.004				< 0.004		< 0.004		same
Lead	0.038		0.05		< 0.038		< 0.038		same
Lithium	0.006	0.004				< 0.006	0.026		4X
Manganese	0.001	0.002		0.05		0.01	0.028		3X
Nickel	0.012	0.02				< 0.02	< 0.012		same
Phosphorus	0.06	0.1				< 0.1	< 0.06		same
Selenium	0.052		0.01		< 0.052		< 0.052		same
Silicon	0.02	0.02			1.66		1.36		same
Silver	0.003		0.05		< 0.003		< 0.003		same
Strontium	0.0008	0.002			0.276		0.399		< 2X
Sulfur	0.05				12.9		20.5		< 2X
Thallium	0.026				< 0.026		< 0.026		same
Tin	0.026				< 0.026				3X
Vanadium	0.003	0.01				< 0.01	< 0.003		less
Zinc	0.002	0.02		5.0	0.008		0.05		6X

Maximum values are used for comparisons where mean values are not calculated.

Mean values are not calculated where constituent values are below detection limits.

Table 5. Comparison of concentrations of dissolved metals in Lake Cumberland with concentrations in water in the active ash pond. All values in mg/L.

Constituent	Detection Limit		MCL	SMCL	Background		Active Ash Pond Water		Comparison of Active Ash Pond to Lake Cumberland
	KGS	Battelle			Mean	Maximum	Mean	Maximum	
Aluminum	0.027	0.3				0.139		0.047	less
Antimony	0.017				< 0.017		< 0.017		same
Arsenic	0.028	0.08	0.05			< 0.08		< 0.08	same
Barium	0.001	0.002	1.0		0.03		0.203		7X
Beryllium	0.0005				< 0.0005		< 0.001		same
Boron	0.006	0.01				0.02	0.168		8X
Cadmium	0.003		0.01		< 0.003			0.006	2X
Chromium	0.006	0.02	0.05			0.01		< 0.02	less
Cobalt	0.004				< 0.004			0.005	same
Copper	0.004	0.004		1.0	0.006		0.031		5X
Iron	0.004	0.005		0.3		0.116	0.204		2X
Gold	0.004				< 0.004		< 0.004		same
Lead	0.038		0.05		< 0.038		< 0.038		same
Lithium	0.006	0.004				< 0.006	0.128		21X
Manganese	0.001	0.002		0.05		0.01	0.071		7X
Nickel	0.012	0.02				< 0.02		0.035	2X
Phosphorus	0.06	0.1				< 0.1		< 0.1	same
Selenium	0.052		0.01		< 0.052		< 0.052		same
Silicon	0.02	0.02			1.66		1.72		same
Silver	0.003		0.05		< 0.003		< 0.003		same
Strontium	0.0008	0.002			0.276		0.237		same
Sulfur	0.05				12.9		25.5		2X
Thallium	0.026				< 0.026			0.029	same
Tin	0.026				< 0.026			0.116	4X
Vanadium	0.003	0.01				< 0.01		0.011	same
Zinc	0.002	0.02		5.0	0.008		0.013		< 2X

Maximum values are used for comparisons where mean values are not calculated.
 Mean values are not calculated where constituent values are below detection limits.

Table 6. Comparison of concentrations of dissolved metals at background sites with concentrations in pore water in the active ash pond. All values in mg/L.

Constituent	Detection Limit		MCL	SMCL	Background		Active Ash Pond Pore Water		Comparison of Active Ash Pond Pore Water to Background
	KGS	Battelle			Mean	Maximum	Mean	Maximum	
Aluminum	0.027	0.3				0.139		0.038	less
Antimony	0.017				< 0.017		not run		
Arsenic	0.028	0.08	0.05			< 0.08		1.43	18X
Barium	0.001	0.002	1.0		0.03		0.129		4X
Beryllium	0.0005				< 0.0005		not run		
Boron	0.006	0.01				0.02	0.943		47X
Cadmium	0.003		0.01		< 0.003		not run		
Chromium	0.006	0.02	0.05			0.01	<0.006		less
Cobalt	0.004				< 0.004		not run		
Copper	0.004	0.004		1.0	0.006			0.007	same
Iron	0.004	0.005		0.3		0.116		1.08	9X
Gold	0.004				< 0.004		not run		
Lead	0.038		0.05		< 0.038		not run		
Lithium	0.006	0.004				< 0.006	0.084		14X
Manganese	0.001	0.002		0.05		0.01		0.658	66X
Nickel	0.012	0.02				< 0.02		0.037	2X
Phosphorus	0.06	0.1				< 0.1		0.50	5X
Selenium	0.052		0.01		< 0.052		not run		
Silicon	0.02	0.02			1.66		10.8		7X
Silver	0.003		0.05		< 0.003		not run		
Strontium	0.0008	0.002			0.276		1.26		5X
Sulfur	0.05				12.9		not run		
Thallium	0.026				< 0.026		not run		
Tin	0.026				< 0.026		not run		
Vanadium	0.003	0.01				< 0.01	0.130		13X
Zinc	0.002	0.02		5.0	0.008			0.39	49X

Maximum values are used for comparisons where mean values are not calculated.

Mean values are not calculated where constituent values are below detection limits.

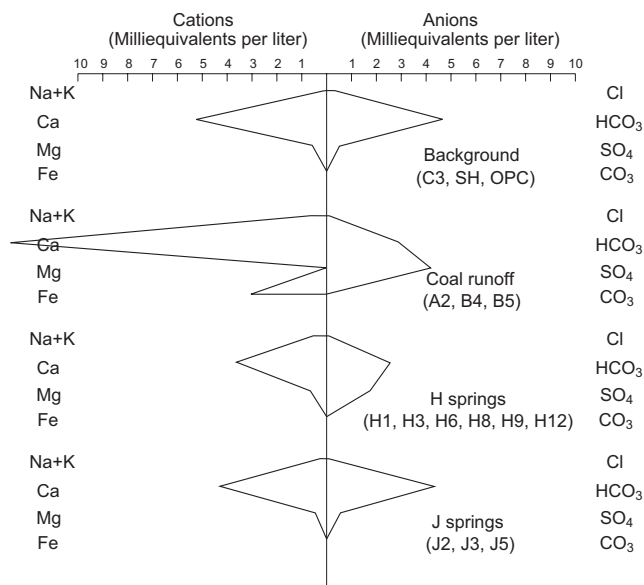


Figure 10. Comparison of mean values for major ions at background sites and values for sites associated with the coal stockpile.

encountered in the system and verified by ash that has been transported from the active ash pond, through the karst ground-water flow system, and deposited near spring outfalls.

Water Quality

Closed-Out Ash-Pond Flow System. Wells completed in the closed-out ash pond, downgradient from springs at site J, and background sites all have similar water-quality characteristics. Major-ion composition for all sites associated with the closed-out ash pond is similar; all water is a calcium-bicarbonate type with average specific conductances of 270 $\mu\text{S}/\text{cm}$ for wells and 371 $\mu\text{S}/\text{cm}$ for springs at site J. The average specific conductance for background sites is 378 $\mu\text{S}/\text{cm}$.

There are some differences in trace-element concentrations. Wells in the ash have mean concentrations for lithium and manganese that are at least one order of magnitude above average background values (Table 2). Pore water, analyzed by Battelle Pacific Northwest Laboratories, was at least one order of magnitude greater than background values for boron, iron, manganese, and zinc (Table 3). Downgradient springs at site J show no elevated metal concentrations (Table 1).

Table 8 summarizes constituents for which concentrations exceeded maximum contaminant levels (MCL's) or secondary maximum contaminant levels (SMCL's) established by the U.S. Environmental Protection Agency in at least one sample. Arsenic concentration exceeded the MCL for one of the samples that was collected in well D. Iron and manganese concentrations exceeded SMCL's in some pore-water

samples. No constituents from the downgradient springs at site J exceeded established MCL's or SMCL's. The closed-out ash pond appears to have no adverse impact on water leaving downgradient springs.

Active Ash-Pond Flow System. Water in the active ash pond is similar in major-ion composition to Lake Cumberland. Specific conductance values are 156 $\mu\text{S}/\text{cm}$ in Lake Cumberland and 219 $\mu\text{S}/\text{cm}$ in the active ash pond. Water discharging from the downgradient springs at site H is intermediate in composition between lake water and background water, indicating mixing of water along the flow path. The mean specific conductance in the downgradient springs (319 $\mu\text{S}/\text{cm}$) is slightly lower than background values (378 $\mu\text{S}/\text{cm}$) because of the mixing effect in the system.

Ash-pond water has concentrations of barium, boron, manganese, and lithium (Table 5) that are approximately one order of magnitude greater than lake-water concentrations. Pore waters, analyzed by Battelle Pacific Northwest Laboratories, have concentrations of As, B, Fe, Li, Mn, V, and Zn (Table 6) that are approximately one to two orders of magnitude greater than background ground-water concentrations. Water-quality analyses indicate that springs at site H contain similar concentrations of dissolved metals as background sites (Table 4).

Table 9 summarizes concentrations of constituents that exceeded established MCL's and SMCL's in at least one sample. The mean value for manganese in the active pond slightly exceeded the SMCL. Most pore-water samples exceeded the MCL for arsenic. Iron and manganese exceeded SMCL's for some pore-water samples. No constituents in the springs at site H exceeded established MCL's or SMCL's. Although near an active ash-disposal facility, the downgradient springs at site H have good water quality.

Coal-Stockpile Flow System. Springs that have been affected by runoff from the coal stockpile have much different water quality than at background sites. Springs affected by coal have a calcium-sulfate type water with a high specific conductance (mean=1,472 $\mu\text{S}/\text{cm}$), whereas background water is a calcium-bicarbonate type. The pH of the coal-stockpile springs ranges from 2.93 to 7.43, with an average specific conductance of 378 $\mu\text{S}/\text{cm}$.

Concentrations of seven metals (Al, Be, Co, Fe, Mn, Ni, Zn) (Table 7) exceeded background concentrations by at least two orders of magnitude. Concentrations of five metals (Cd, Cu, Au, Li, and S) (Table 7) exceeded background concentrations by at least one order of magnitude.

Table 10 summarizes concentrations of constituents that exceeded established MCL's and SMCL's in at least one sample. Concentrations for cadmium and chromium exceeded MCL's at spring B4. The concentration of iron exceeds the

Table 7. Comparison of concentrations of dissolved metals at background sites with concentrations in springs in the coal stockpile. All values in mg/L.

Constituent	Detection Limit		MCL	SMCL	Background		Coal Stockpile		Comparison of Coal Stockpile to Background
	KGS	Battelle			Mean	Maximum	Mean	Maximum	
Aluminum	0.027	0.3				0.139	48.8		351X
Antimony	0.017				< 0.017		< 0.017		same
Arsenic	0.028	0.08	0.05			< 0.08	< 0.028		unknown
Barium	0.001	0.002	1.0		0.03		0.029		same
Beryllium	0.0005				< 0.0005			0.053	106X
Boron	0.006	0.01				0.02	0.058		3X
Cadmium	0.003		0.01		< 0.003			0.102	34X
Chromium	0.006	0.02	0.05			0.01	0.033		3X
Cobalt	0.004				< 0.004			1.23	308X
Copper	0.004	0.004		1.0	0.006			0.152	25X
Iron	0.004	0.005		0.3		0.116	81.9		706X
Gold	0.004				< 0.004			0.239	60X
Lead	0.038		0.05		< 0.038			0.042	same
Lithium	0.006	0.004				< 0.006	0.130		22X
Manganese	0.001	0.002		0.05		0.01	6.79		679X
Nickel	0.012	0.02				< 0.02		2.1	105X
Phosphorus	0.06	0.1				< 0.1		0.281	3X
Selenium	0.052		0.01		< 0.052		< 0.052		same
Silicon	0.02	0.02			1.66		7.01		4X
Silver	0.003		0.05		< 0.003		< 0.003		same
Strontium	0.0008	0.002			0.276		0.866		3X
Sulfur	0.05				12.9		236		18X
Thallium	0.026				< 0.026		< 0.026		same
Tin	0.026				< 0.026			0.066	2.5X
Vanadium	0.003	0.01				0.01		0.004	less
Zinc	0.002	0.02		5.0	0.008		1.44		180X

Maximum values are used for comparisons where mean values are not calculated.
Mean values are not calculated where constituent values are below detection limits.

Table 8. Summary of monitored locations associated with the closed-out ash pond with constituents that exceed MCL's or SMCL's.

	<i>Constituent</i>	<i>MCL or SMCL (mg/L)</i>	<i>Downgradient J Springs (J2, J3, J5)</i>	<i>Closed-Out Pond Pore Water</i>	<i>Ash Wells (C89BW, C89CW, C89DW)</i>
Exceed MCL	arsenic	0.05			1 of 2 samples (C89DW)
	barium	1.0			
	cadmium	0.01			
	chromium	0.05			
	lead	0.05			
	selenium	0.01			
	silver	0.05			
	fluoride	2.2			
Exceed SMCL	copper	1.0			
	iron	0.3		2 of 20 samples	
	manganese	0.05		10 of 20 samples	2 of 2 samples
	zinc	5.0			
	total dissolved solids	500			
	sulfate	250			
	chloride	250			

Table 9. Summary of monitored locations associated with the active ash pond with constituents that exceed MCL's or SMCL's.

	<i>Constituent</i>	<i>MCL or SMCL (mg/L)</i>	<i>Ash Pond Water (Pond water-N, Pond water-S, Weir, OTF, NAP)</i>	<i>Active Ash Pond Pore Water</i>	<i>Downgradient H Springs (H1, H3, H6, H8, H9, H12)</i>
Exceed MCL	arsenic	0.05		11 of 15 samples	
	barium	1.0			
	cadmium	0.01			
	chromium	0.05			
	lead	0.05			
	selenium	0.01			
	silver	0.05			
	fluoride	2.2			
Exceed SMCL	copper	1.0			
	iron	0.3		5 of 15 samples	
	manganese	0.05	3 of 5 samples	10 of 15 samples	
	zinc	5.0			
	total dissolved solids	500			
	sulfate	250			
	chloride	250			

Table 10. Summary of coal-stockpile springs with constituents that exceed MCL's or SMCL's.			
	<i>Constituent</i>	<i>MCL or SMCL (mg/L)</i>	<i>Coal Stockpile Springs (A2, B4, B5)</i>
Exceed MCL	arsenic	0.05	
	barium	1.0	
	cadmium	0.01	1 of 3 samples (B4)
	chromium	0.05	1 of 3 samples (B4)
	lead	0.05	
	selenium	0.01	
	silver	0.05	
	fluoride	2.2	
Exceed SMCL	copper	1.0	
	iron	0.3	1 of 3 samples (B4)
	manganese	0.05	2 of 3 samples (A2, B4)
	zinc	5.0	
	total dissolved solids	500	3 of 4 samples (A2, B4)*
	sulfate	250	2 of 3 samples (A2, B4)†
	chloride	250	
*Total dissolved solids not available for B4, but specific conductance is 3,640 µS/cm.			
†Sulfate value is not available for B4, but sulfur is 167 mg/L.			

SMCL at spring B4. Concentrations of total dissolved solids, sulfate, and manganese exceeded SMCL's at springs A2 and B4.

In general, the coal stockpile has a more adverse impact on ground-water quality in the study area than the ash-disposal facilities.

Monitoring Strategy in Karst Systems

Springs and other karst-related features provide effective ground-water monitoring locations. Because flow may occur along discrete paths rather than as diffuse flow through porous media, springs are more effective monitoring sites than wells. The complexity of conduit systems may result in conduits that do not interconnect, even within a relatively small area. Because the exact flow path between the dye input and dye detection point is unknown, a well may or may not intercept the appropriate conduit network. Drilling a series of wells to monitor ground-water flow paths could be financially burdensome and may not result in monitoring ground water emanating from the potential source of contamination.

EPILOGUE

Since this study was completed, several changes have occurred at the site. The waste ash is no longer sluiced to a pond, but collected in a dry state and stored in a dry landfill, which is located over the site of the closed-out ash pond. The active ash pond has been closed, and no water is discharged from that location. The coal stockpile has been completely changed. An asphalt pad has been constructed, and all runoff from the pad is directed to a holding pond and pumped to an adjacent treatment facility, where the pH is adjusted and the water clarified before being discharged with the cooling water into Lake Cumberland.

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