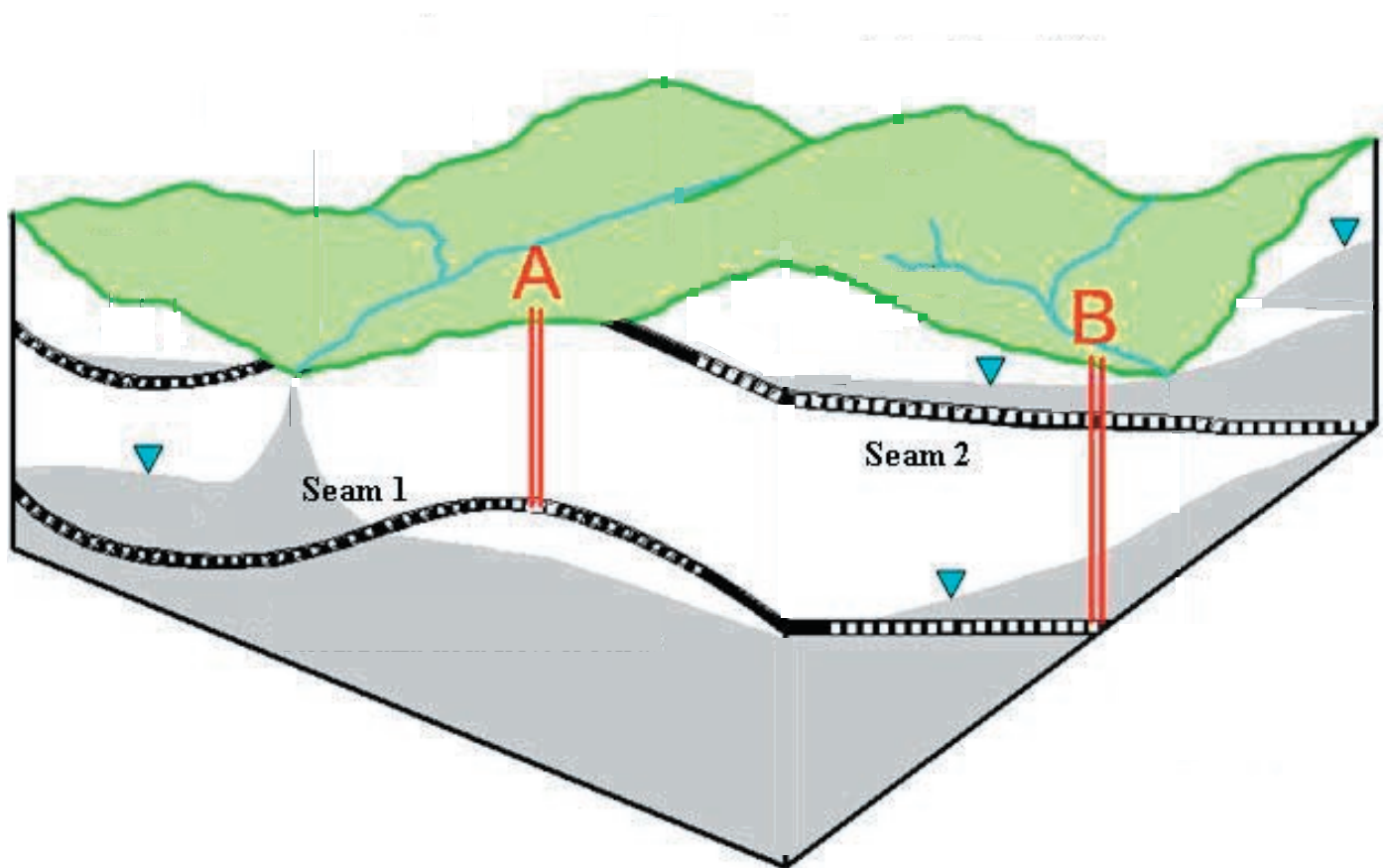


Assessing Water-Supply Potential of Abandoned Underground Coal Mines in Eastern Kentucky



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James S. Dinger, Dennis H. Cumbie, and Bart Davidson

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ISSN 0075-5591

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Assessing Water-Supply Potential of Abandoned Underground Coal Mines in Eastern Kentucky

James S. Dinger, Dennis H. Cumbie,
and Bart Davidson

Abstract

Use of water in abandoned underground coal mines for municipal, industrial, agricultural, or domestic water supplies is dependent upon the water quantity and quality. For either of these factors, the requirements of the user will play a role in what water quantity or quality is acceptable. This report provides analysis of field-derived water-quality and -quantity characteristics for six abandoned underground coal mines in the Eastern Kentucky Coal Field. In addition, some ancillary data from State regulatory agencies were used to help characterize water quality coming from the mines.

This study demonstrates that water quality in abandoned deep mines can be quite variable. Water-quality characteristics vary from mine to mine because of the position of the mine within the groundwater flow system, the mineralogy of the coal seam and the enclosing bedrock, and the time elapsed since the mine was flooded. Total dissolved solids values ranged from 194 to 2,016 $\mu\text{S}/\text{cm}$. Based on TDS, coal mines in the Manchester and Upper Elkhorn No. 3 coals produced the poorest water quality. In the study area, these seams were mined below the elevation of local drainage. The increase in TDS is a result of increased mineralization of groundwater caused by relatively slow movement and increased age of the water in the distal ends of the groundwater flow system. Another water-quality factor to consider in below-drainage mines is the length of time since mine closure. The time since closure and subsequent flooding of the mine is important because the reduction of acid-generating salts depends on the amount of time available for flushing. For these reasons, water quality should be analyzed for each potential water source, even within a given mine. Water-quality monitoring must include sampling and analysis during water-withdrawal testing to identify any changes in quality associated with induced mobility of otherwise slow-moving to stagnant water within a mine.

Water quantity from abandoned deep mines varies greatly, depending on many variables that control flooded volume of and recharge rate to the mine. Major variables controlling groundwater discharge from a mine are the surface area overlying the mine, the position of the mine within the local and regional groundwater systems, and the structural geology of the site, which determines how groundwater drains from the mine. Recharge rates ranged from 120,000 to 1,230,000 gal/day; however, some deep mines showed net losses in storage because of lack of recharge during drought periods.

This study demonstrates that water quality and quantity in abandoned deep mines are suitable for water supplies. Both quantity and quality are variable between mines, however. Variations can be attributed to geologic controls, physical setting, the age of the mine, and the rate of flushing. Therefore, water quality and quantity must be analyzed for each potential mine source, and must be analyzed throughout the time of water withdrawal.

Introduction

Over the last several decades, city and county governments and area development districts in the Eastern Kentucky Coal Field have struggled to develop adequate water supplies for individuals, small communities, and larger population centers (Fig. 1). Steep terrain and highly dissected topography limit adequate surface-water supplies, and naturally occurring groundwater systems are sporadic, difficult to locate, limited by water-quality problems, and therefore usually incapable of supplying large quantities of water.

This study assesses the potential for developing abandoned underground coal mines as water-supply reservoirs for communities in the Eastern Kentucky Coal Field. Development potential depends on water quantity and quality, and factors that may deter the use of deep-mine supplies, such as safety concerns, inadequate recharge rates, and abrupt changes in water quality.

Review of Existing Water Systems Using Underground-Mine Water

As of 2004, six public and community water systems were using underground-mine water as principal supplies, according to the Kentucky Division of Water.

Table 1 is a summary of those water systems. Two of the six systems, Lynch and Benham in Harlan County, use underground-mine water only during the dry season, when surface water is inadequate. The Francis system in Floyd County has limited distribution, with most users collecting water from a central mine source.

Three of the six systems are municipal water suppliers for incorporated cities, using underground-mine water as a year-round principal source: the Fleming-Neon Water Company, Evarts Water Company, and Wheelwright Utility Commission.

The Fleming-Neon system has been in operation for approximately 20 years, providing service to 1,000 customers at an average water rate of 250,000 gal/day (D. Maggerd, Fleming-Neon Water Co., 1997, oral commun.). The supply is pumped from a below-drainage abandoned mine in the Upper Elkhorn No. 3 coal seam that has an estimated storage volume of approximately 41 Mgal. Through the years, water levels in this mine have shown little variation, and no broad changes in raw water quality have been detected. Kentucky Division of Water laboratory analyses of the raw water source for Fleming-Neon have approximate values for pH of 7.3, total dissolved solids of 480 mg/L, and no ionic constituents above the U.S. Environmental Protec-

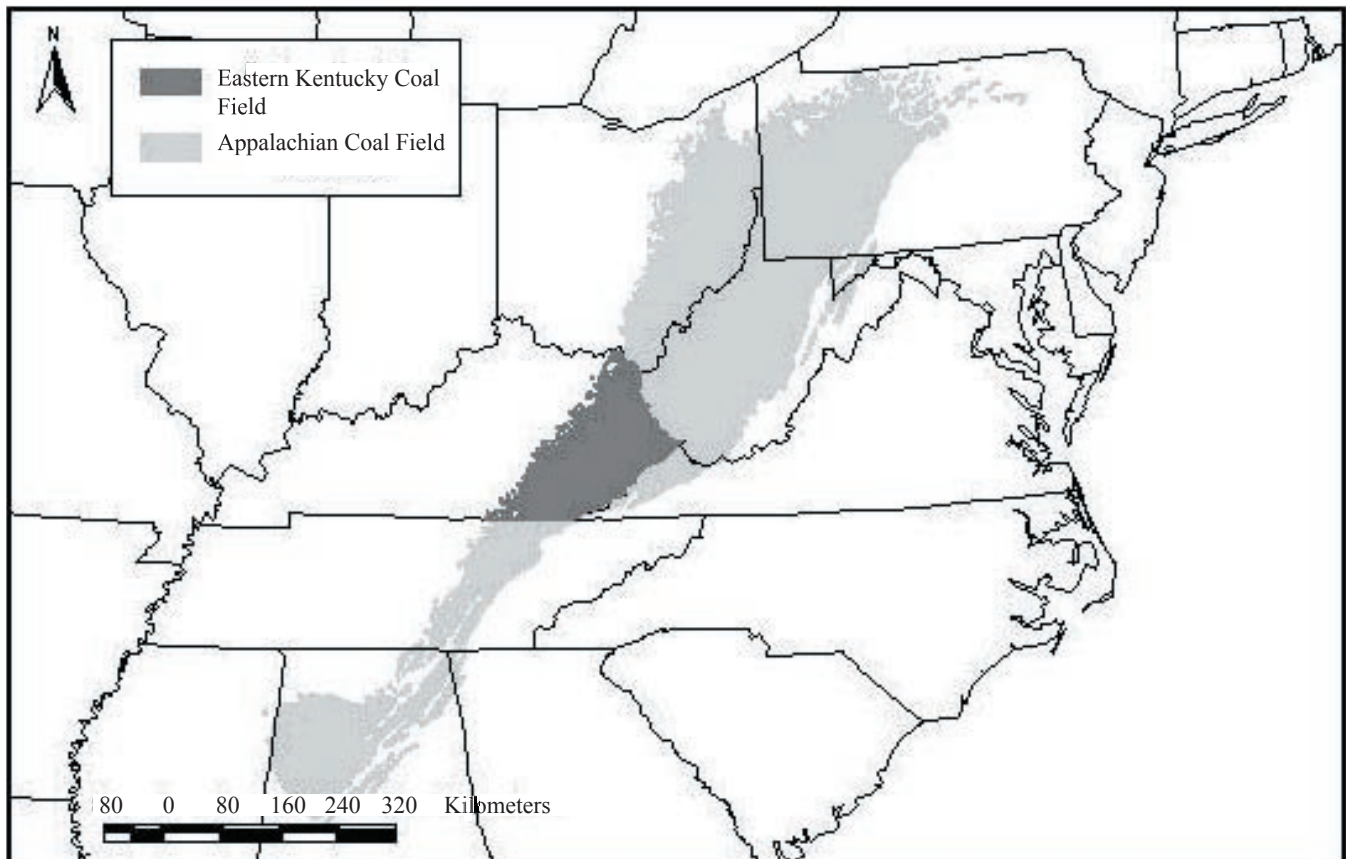


Figure 1. Location of the Eastern Kentucky Coal Field within the Appalachian Coal Field in the eastern United States.

Table 1. Regulated community water systems currently using abandoned deep-mine water sources.

<i>Community</i>	<i>County</i>	<i>Seam</i>	<i>Usage (gal/day)</i>	<i>Customers</i>	<i>Treatment</i>
Wheelwright	Floyd	Upper Elkhorn No. 3	100,000	800	chlorination, fluoridation, gravity filter
Fleming-Neon	Letcher	Upper Elkhorn No. 3	250,000	1,000	chlorination, fluoridation, gravity filter
Evarts	Harlan	Harlan (Upper Elkhorn No. 2)	250,000	850	chlorination, fluoridation, gravity filter
Benham	Harlan	Harlan (Upper Elkhorn No. 2)	unmetered	unknown	filtration
Lynch	Harlan	Harlan (Upper Elkhorn No. 2)	unmetered	unknown	filtration
Francis	Floyd	Upper Elkhorn No. 2	65,000	100	filtration, chlorination

tion Agency's maximum contaminant level (Kentucky Division of Water, Drinking Water Branch, 2006, oral commun.). Treatment at the facility includes aeration, sand filtration, chlorination, and fluoridation.

The Evarts Water Company currently draws the majority of its raw water from an above-drainage abandoned underground mine in the Harlan coal seam. The utility processes approximately 250,000 gal/day and serves over 350 customers. Water treatment includes flocculation, filtration, chlorination, and fluoridation (T. Lipfird, Evarts Water Plant, 2001, oral commun.).

The Wheelwright system has been in use since the 1930's, when the town was started as a coal camp. The system draws water from a pump in the Wheelwright No. 2 Mine in the Upper Elkhorn No. 3 coal seam. The mine has an estimated storage volume of 322 Mgal. In 1989, during a prolonged drought, the water supply went dry. Investigation of the system found that deterioration of distribution lines and unmetered consumer use combined caused 80 percent of the loss of water in the system. Replacing the damaged lines and adding a metered system decreased the average daily consumption from 360,000 gal/day to near 100,000 gal/day (G. McCoy, Wheelwright Utilities Comm., 1997, oral commun.). There have since been no supply problems. Treatment at the Wheelwright plant consists of aeration, sand filtration, chlorination, and fluoridation.

Operators for both the Wheelwright and Fleming-Neon systems have stated that the most prevalent problem associated with the use of mine water is corrosion of piping systems. This is because deep-mine waters often precipitate corrosive or plaque-causing minerals, and can be acidic. The degree of corrosiveness tends to decrease as the water's pH meets or exceeds a

value of 7.4 (G. McCoy, Wheelwright Utilities Comm., 1997, oral commun.).

Countless domestic supplies are provided by mine-water discharges or wells penetrating flooded coal mines. Many of these domestic supplies are multiple-home systems, where small communities tap into mine-water discharges through multiple supply hoses that snake through the hollows to individual homes. Often a single collection point, such as a large cistern, will be split into multiple supply lines (Fig. 2). These systems are unregulated, unmetered, and seldom provide any type of treatment.

In addition to the public systems in eastern Kentucky, over 70 public systems in West Virginia are



Figure 2. Nonregulated mine-water distribution system. Water is transported into a large cistern equipped with a 12-valve manifold; each individual supply line leads to one or more households. The cistern is covered with black plastic to block sunlight and control algae growth. Overflow at the top of the cistern prevents freezing in winter.

supplied by water from deep mines (Ferrell, 1992). Water-quality analyses of samples taken from the Exeter Mines (used by the city of Welch, W.Va.) show that there are some temporal variations in water quality. Waters from the Exeter Mines have also shown a change in quality as water level rises, attributed to the closure and subsequent flooding of mines adjacent to the Exeter Mines.

Water Rights

According to Kentucky Revised Statute Chapter 151.120, "water occurring in any stream, lake, ground water, subterranean water or other body of water in the Commonwealth which may be applied to any useful and beneficial purpose is hereby declared to be a natural resource and public water of the Commonwealth." At no time during this study did any individual, corporation, or county agency make any legal declarations contrary to KRS chapter 151.120.

Ownership of mineral rights must also be addressed, but cannot be limited to the potential supply mine. Current or future mining in the area of the mine, whether surface or underground, must be considered before water-supply development because these practices may adversely affect the quantity and quality of the water in the mine.

Study Area

The study area is located in the Eastern Kentucky Coal Field (Fig. 1), which is part of the coal-bearing rocks of the Appalachian Coal Field, which underlie parts of Kentucky, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and Alabama. The Eastern Kentucky Coal Field is highly dissected by narrow stream valleys; a few larger streams have broad floodplains. Local relief increases from 300 ft in the north near the Ohio River to about 2,500 ft in the south along Pine Mountain near the Tennessee-Kentucky-Virginia borders (Price and others, 1962). The detailed study sites are located in Perry, Letcher, Clay, and Harlan Counties (Fig. 3). Table 2 lists the mine sites and their characteristics studied for this report.

Geology

In the Eastern Kentucky Coal Field, most of the economically mineable coal seams are part of the Pennsylvanian Breathitt Group, which is composed mostly of shale, siltstone, argillaceous and lithic sandstone, coal, and some thin limestone (Chesnut, 1992). The upper part of the Breathitt Group is subdivided into formations separated by widespread marine units (Fig. 4). Between the marine units are highly discontinuous beds of shale, siltstone, and sandstone, along with numerous

economically mineable coal beds. The lower formations of the Breathitt Group are marked by formally named quartzose sandstone formations (Chesnut, 1992). The abandoned underground mines studied in this report are found in coal beds of the Grundy, Pikeville, Hyden, and Four Corners Formations of the middle and upper Breathitt Group.

The Grundy Formation is the lowest of the formations in this study. Its lower boundary is marked by the top of the Bee Rock Sandstone, and it is bounded above by the base of the Betsie Shale Member, a widespread marine shale. Just below the base of the Betsie Shale is the Manchester coal bed, which serves as the water source for the Clay County study site.

The Pikeville Formation is bounded below by the Betsie Shale Member, and above by the Kendrick Shale Member. The formation contains coal beds from the Lower Elkhorn (Pond Creek) through the Williamson. The Upper Elkhorn No. 3 seam of the Pikeville Formation is the source of water for the three Letcher County study sites.

The Hyden Formation consists of coal-bearing rocks between the Pikeville Formation and the overlying Four Corners Formation. The base of the Pikeville is the base of the Kendrick Shale Member, and the formation top is marked by the base of the Magoffin Member, another widespread marine shale. Within the Hyden Formation is the Hazard No. 4, or Fire Clay, coal seam, the water source for the BenCo site in Perry County.

The Leatherwood study source in Perry County is found in the Hazard No. 5A (Leatherwood) coal seam of the Four Corners Formation. This formation is bounded below by the Magoffin Member and at the top by the Hindman coal bed, or where absent, by the base of the Stoney Fork marine shale. The base of the Stoney Fork Member also marks the base of the overlying Princess Formation. The Princess Formation is the uppermost unit in the Breathitt Group, and is bounded above by the base of the Conemaugh Formation.

Hydrogeology

Because of low permeability and the discontinuous and heterolithic nature of middle to upper Breathitt Group sandstones, groundwater flow primarily occurs in secondary permeability features such as fractures and joints (Price and others, 1962; Kirkpatrick and others, 1963; Wyrick and Borchers, 1981). In the absence of fractures and joints, the quartzose sandstones of the lower part of the Breathitt Group, such as the Bee Rock Sandstone, transmit much more water than the sandstones in the middle and upper parts of the Breathitt Group (Price and others, 1962).

Kipp and Dinger (1991) documented the occurrence of a near-surface fracture zone in the hillside and

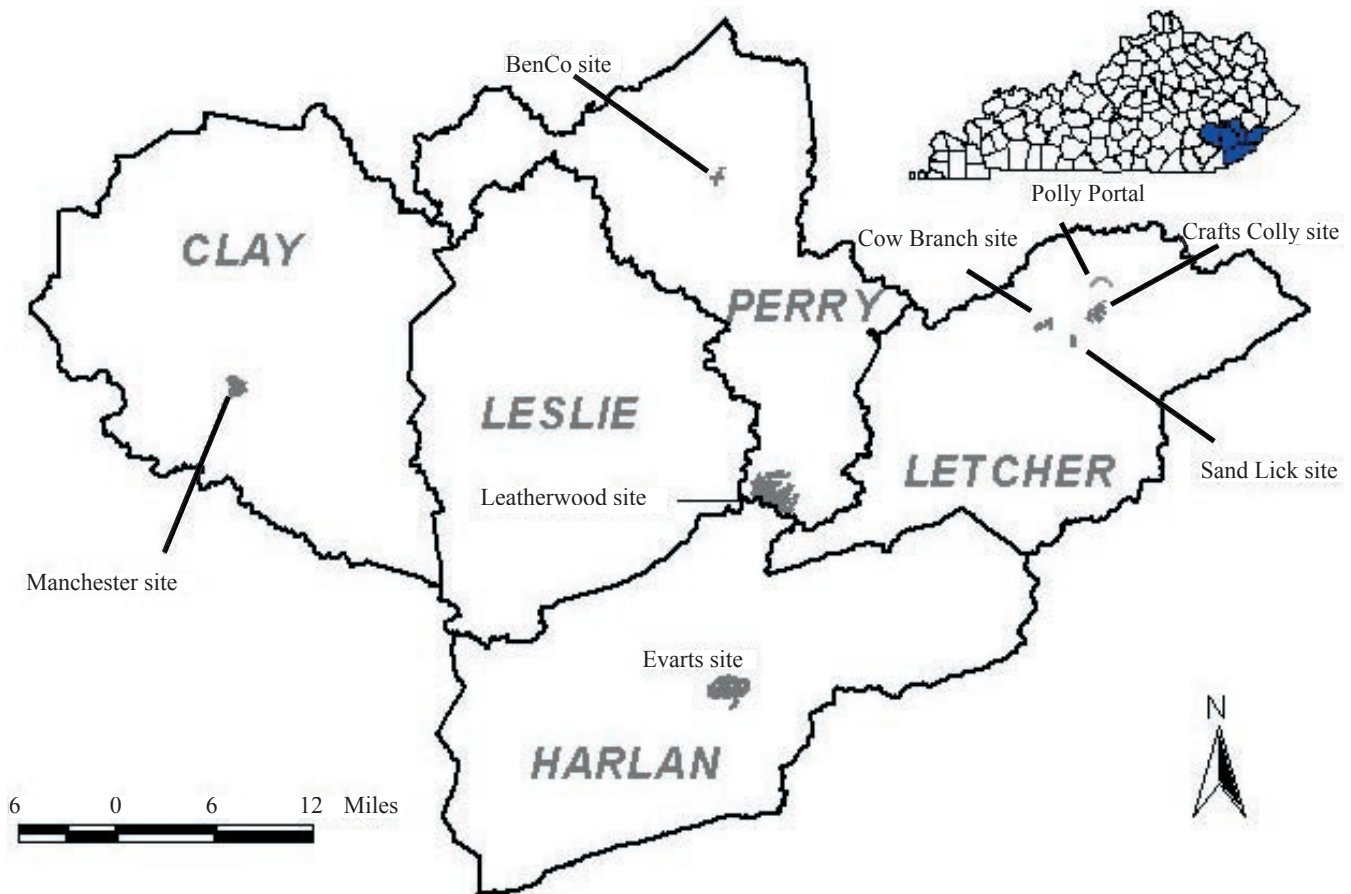


Figure 3. Location of study sites in Clay, Letcher, Perry, and Harlan Counties.

valley bottom of an unmined portion of a drainage basin in northwestern Knott County, and that such zones influence the transport of groundwater. Hydraulic conductivity studies performed on rocks of the upper part of the Breathitt Group (Kipp and Dinger, 1991; Harlow and LeCain, 1991; Minns, 1993; Wunsch, 1993) show that coals and fractured rock zones have the highest mean hydraulic conductivities of any rock type in the coal field: 2.2×10^{-4} ft/min and 1.6×10^{-3} ft/min, respectively. Locally, hydraulic conductivity of coal can exceed that of fractured rock if the fractures are clogged with limonite and clay (Wunsch, 1993).

The near-surface fracture zone, along with the higher conductivity of fractured rock and coal, are the dominant factors in the groundwater-flow conceptual models developed for the Eastern Kentucky Coal Field by Minns (1993) and Wunsch (1993). Groundwater infiltrates through the shallow fracture zone, traveling vertically until it comes in contact with a coal seam, where it is transmitted horizontally following the contour of the coal seam. If the coal crops out, groundwater emerges as seeps or springs. If the coal contours conduct the groundwater below first-order drainage, it may emerge

in second- or third-order stream valleys. Groundwater not directed laterally by coal seams moves through the bedrock and discharges at third-order (or greater) streams (Minns, 1993).

Two types of underground mines have significantly different characteristics (Mull and others, 1981): mines above the elevation of the local surface drainage system and mines below the surface drainage system. Generally, the below-drainage mines will hold a larger volume of water since they are more likely to be fully flooded. Since the mines are below the regional water table, recharge is derived from precipitation and from surrounding saturated rocks.

Above-drainage mines generally have smaller storage volumes than below-drainage mines because they are limited in areal extent by valley cuts. Water often drains out of these mines through abandoned portals, collapsed adit springs, auger holes, and coal-seam seeps; therefore, they are seldom fully flooded. Although above-drainage mines may have less storage capacity, they may have greater recharge rates because of their proximity to near-surface fracture systems. Mull and others (1981), in a study of above-drainage

Table 2. Characteristics of mine sites.

Site Name	Mine	Coal Seam Mined	Sample Site Location	Position to Local Drainage (acres)	Volume (Mgal)	Recharge Rate (Kgal/day)	Number of Water-Quality Samples Taken
Sand Lick, Letcher County	Polly No. 4, Sand Lick	Elkhorn No. 3	Well penetrating mine void	Near	109	120	7
Cow Branch, Letcher County	Polly No. 4, Cow Branch	Elkhorn No. 3	Well penetrating mine void	Below	250	450	6
Crafts Colly, Letcher County	Beth Energy No. 22, Crafts Colly	Elkhorn No. 3	Well penetrating mine void	Below	150	240	5
Leatherwood, Perry and Knott Counties	Blue Diamond-Leatherwood	Hazard No. 5A	Spring from coal outcrop	Above	6,800	*1,130	7
BenCo, Perry County	BenCo No. 4, Hazard	Hazard No. 4	Well penetrating mine void	Near	790	300	4
Manchester, Clay County	LeeCo No. 47, Manchester	Manchester	Well penetrating mine void	Below	1,000	225	6

System	Eastern Kentucky Coal Field		
	Group	Formation	Members and beds
	Upper	Conemaugh	
Pennsylvanian	Middle	Princess	Princess No. 9 coal
			<i>Stoney Fork Beds</i>
		Four Corners	Hazard 9 coal Hazard 7 coal Hazard 5A coal <i>Magoffin Beds</i>
		Pikeville	Hazard 4 coal (Fire Clay) <i>Kendrick Shale</i>
		Hyden	Ambury coal Upper Elkhorn 3 coal (Darby) Upper Elkhorn 2 coal (Harlan) <i>Betsie Shale</i>
		Grundy and older formations	Manchester coal Bee Rock sandstone
Pennsylvanian	Lower		

Figure 4. General stratigraphy of the upper and middle Breathitt Group in the Eastern Kentucky Coal Field, showing marine shale units (shaded) and coal seams in this study.

mines in Johnson and Martin Counties in Kentucky, showed a direct correlation between the size of the mine (lateral extent) and mine-water discharge. Above-drainage mines rely mostly on precipitation as the source of water replenishment. Mine-water outflows from above-drainage mines provide easy access for water-quality sampling.

When a coal seam has been mined, groundwater short-circuited by the seams will tend to travel quickly through the void spaces, often creating large pools of water in areas where the mine floor is lowest. Mines above drainage may have numerous seeps and discharges at coal outcrops or abandoned adits. Below-drainage mines may become completely filled with water at low points, creating pools of water with volumes often greater than 100 Mgal. Groundwater infiltrating into the ground in one topographic basin may travel into another

drainage basin following the contour of the coal-seam floor (Lessing and Hobba, 1981).

Methods

Locating Potential Supplies

There is no single prescribed process for locating abandoned underground mines that have potential for public water supplies. Mine maps, along with geologic and topographic maps, were used to identify mines with water-supply potential. In addition, interviews with local citizens, coal miners, and public officials provided valuable information concerning the location of flooded deep mines. These are the people who have worked in the mines, closed the mines, have lived near them, and perhaps used mine water as a source of supply.

This study does not provide a complete inventory of all underground mines in these counties, or a complete list of all underground mines that may supply

large amounts of water. This is an inventory of mines that have been identified by this study as having potentially large water reservoirs that are near populated areas in need of primary or secondary supplies, and have monitoring points from which quantity and quality parameters may be measured.

Figure 5 shows approximations of the spatial extent of mined-out areas of the Upper Elkhorn No. 3 and Fire Clay coal seams in the study area. These seams are only two of several that have been mined extensively throughout the study area; therefore, the volume of void space created by years of underground mining in all seams is immense.

Water-Quantity Determination

The quantity of water available from abandoned underground mines is dependent on several factors, the most important of which are void-space volume and the

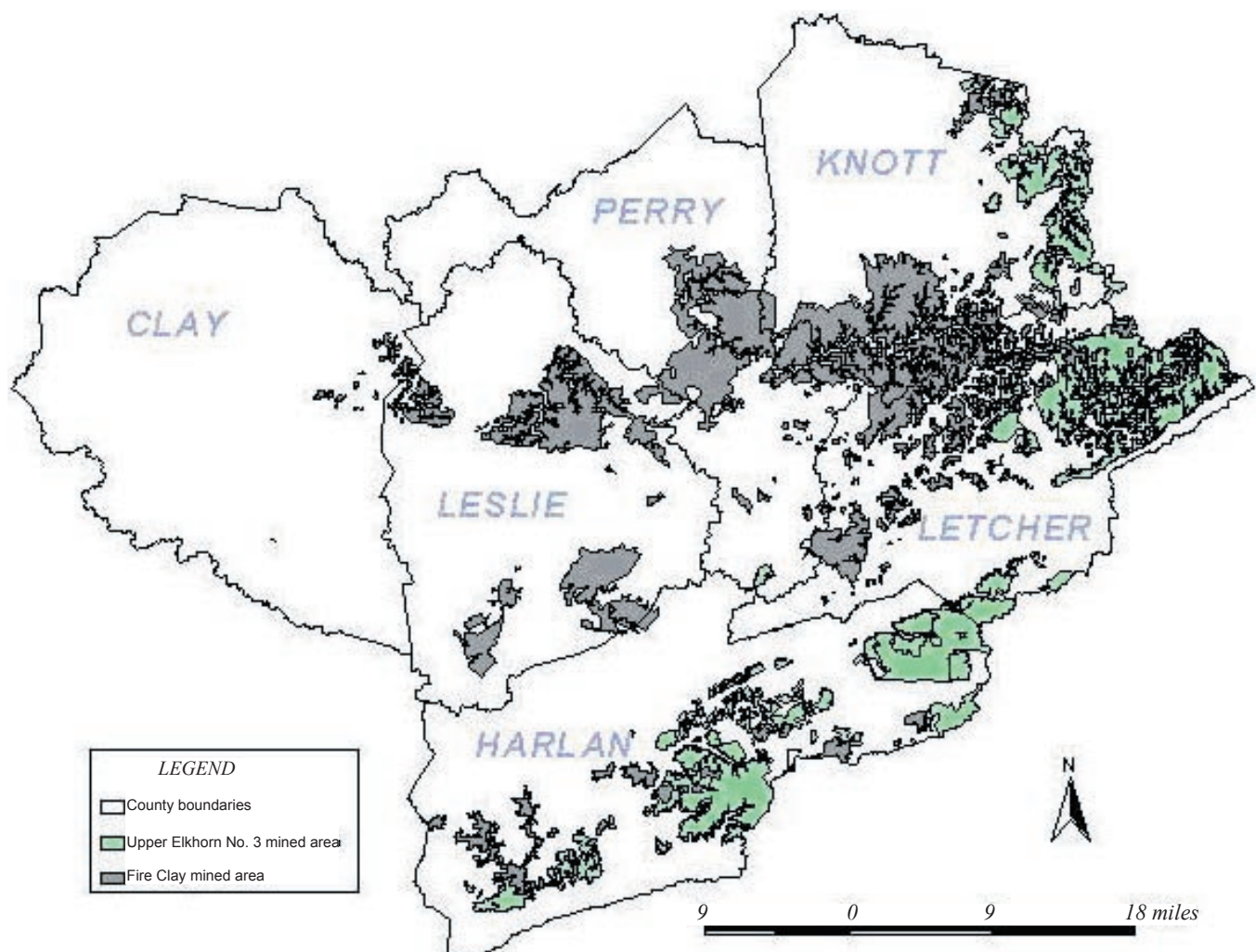


Figure 5. Approximate extent of mined-out areas in the Fire Clay (Hazard No. 4) and Upper Elkhorn No. 3 coal seams in Knott, Perry, Letcher, Clay, Leslie, and Harlan Counties.

rate of groundwater recharge to the mine. To determine the volume of the void space, mine maps were used to estimate the areal extent of the mined-out area, the coal-seam thickness, and the percentage of coal removal. The volume of the abandoned-mine void space could then be estimated using the equation:

$$V = AdC_r$$

where V =void volume (ft^3), A =areal extent of mining (ft^2), d =coal seam thickness (ft), and C_r =percentage of coal removed (decimal equivalent). For example, the areal extent of the South East Coal Company's Polly No. 4 Mine at Cow Branch in Letcher County is approximately 250 acres (10.9 million ft^2), and an estimated 80 percent of the coal has been removed (10.9 million $\text{ft}^2 \times 0.80 = 8.7$ million ft^2). Therefore, if the coal thickness is 4 ft, then the estimated mine volume is 34.8 million ft^3 (8.7 million $\text{ft}^2 \times 4$ ft), or 260 Mgal.

Because measured water levels were higher than coal roof elevations, the data indicated that the entire volume of the Cow Branch mine was flooded. This is not true for all mines, however. For example, the Polly No. 4 Mine at the Sand Lick site in Letcher County has a total mined area well over 200 acres. The flooded portion of the mined area is only 109 acres, however, as determined by water-level elevation within the mine (see Table 2). Hence, the flooded mine volume at this site is 109 acres $\times$ 4 ft coal thickness $\times$ 80 percent coal removed = 15.2 million ft^3 , or 114 Mgal. This example demonstrates the importance of measuring water levels in flooded mines. Water-level information from existing wells or drilling new wells penetrating the flooded mine is therefore essential for adequately characterizing a mine's ability to supply water. When possible, water-level recorders were installed into available wells in order to record changes in water levels, and therefore, water storage in the mines.

Above-drainage mines are rarely fully flooded since water is able to freely drain under gravity. The amount of storage in these mines is more dependent on the size of the mine, the basal structure of the coal seam, and the location of outflows with respect to basal structural lows.

The more important water-quantity attribute is a mine's rate of groundwater recharge. Recharge to flooded mines may come from several sources. Figure 6 is a diagram of the theoretical model of how deep mines receive groundwater recharge. Flooded mines receive recharge as direct infiltration of precipitation, mostly in zones of regional fracturing and near-surface fracture zones. Water also recharges from saturated overburden, and occasionally from saturated rocks below the coal seam. Mines located near surface-water streams may

also receive recharge (or provide discharge) through fracture zones associated with valley bottoms.

Recharge rate in below-drainage mines is measured through pumping tests. During these tests, a large volume of water is removed, and the rate of recharge is measured by monitoring water levels after pumping has stopped. Recharge rates can vary seasonally; therefore, in some cases pumping tests were performed during dry and wet seasons.

For above-drainage mines, recharge can be determined by monitoring the volume of water discharging from the mine. Assuming no change in storage, the volume of water exiting the mine at any given time will be equal to the water entering the mine. This approach requires long-term discharge monitoring to allow for seasonal changes in recharge and discharge, and to determine effects from unusually wet or dry periods. In order to more accurately measure the mine outflow, all outflows should be located (although this is not always possible). In this study, the largest outflows were fitted with H-type flumes or V-notch weirs, allowing for real-time continuous monitoring of mine-water discharge.

Rainfall data were gathered near each study site, either through on-site rain gages or by retrieving data from the National Weather Service's Integrated Flood Observing and Warning System data collection system. In most cases, IFLOWS rain gages were found within 5 mi of the study sites. If no IFLOWS gage was available, KGS rain gages were installed.

Water-Quality Sampling

Water-quality samples were collected from each study site at various times between 1997 and 2002 (Webb and others, 2006). Samples were analyzed at KGS laboratories for a suite of dissolved and total metals, major anions (sulfate, bicarbonate, nitrate, chloride, and fluoride), total dissolved solids, and alkalinity. These samples were collected using standard water-quality methods (U.S. Geological Survey, 1980) and analyzed using U.S. Environmental Protection Agency-approved methods. Field measurements were recorded at the time of sampling for pH, specific conductance, water temperature, and dissolved oxygen. These samples were collected either shortly after each site was located, during pumping tests (for below-drainage mines), or during varying seasonal conditions. A total of 49 water-quality samples were collected from the study locations during the project. This number includes samples collected from the two water sources used by the Evarts Water System. Those samples were collected from mines in the Upper Elkhorn No. 2 and No. 3 coal seams, locally called the Harlan, Darby, and Kellioka seams, respectively.

In addition to data collected by KGS, water-quality data were also obtained from other State agencies (Di-

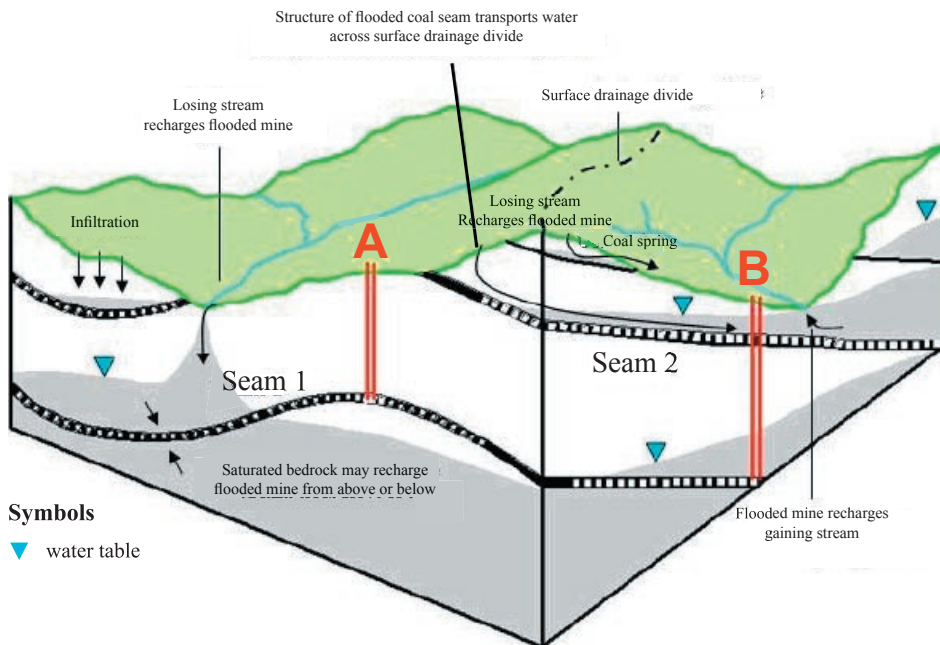


Figure 6. Conceptual model of how flooded mines are recharged (adapted from Lessing and Hobba, 1981).

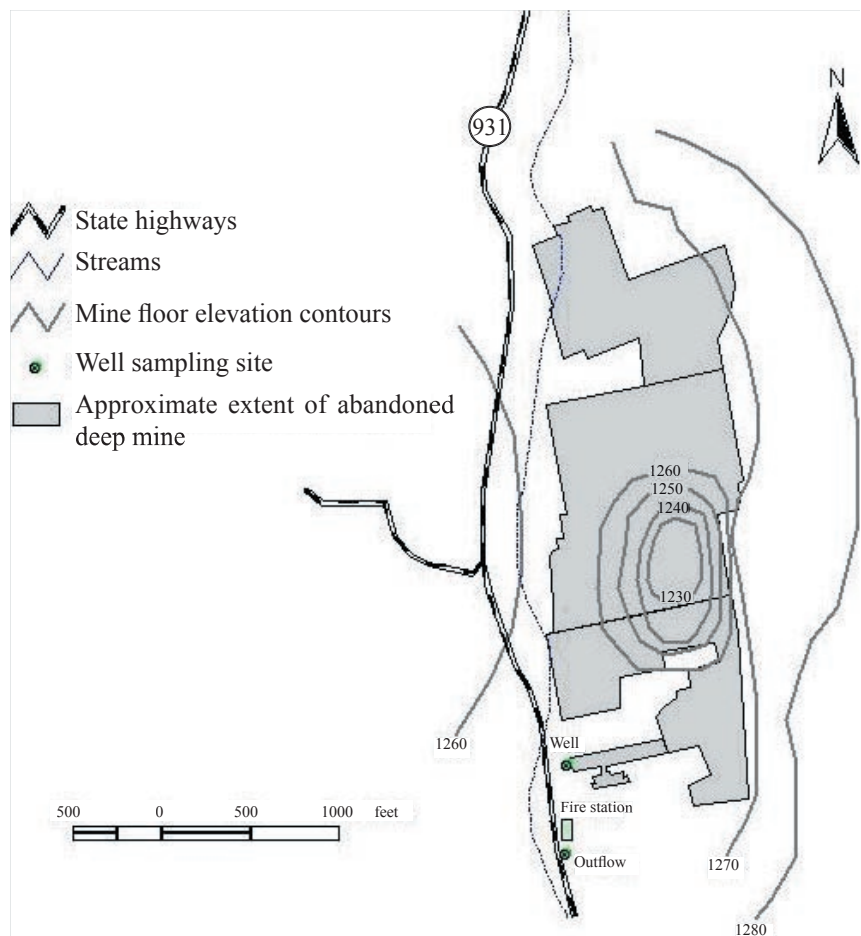
vision of Water and the Department of Surface Mining Reclamation and Enforcement) and from water-utility operators during the study period. All samples collected by other agencies were analyzed by laboratories certified by the Commonwealth for drinking-water analysis (Webb and others, 2006).

Results

Detailed Study Sites

Sand Lick. The detailed study at the Sand Lick site in Letcher County (Fig. 7) focused on part of the abandoned South East Coal Co. Polly No. 4 Mine in the Upper Elkhorn No. 3 coal seam. Recharge rates were determined by both pumping tests and natural discharge measurement. The only known local discharge from the mine is a spring that emerges about 100 ft south of the Sand Lick Fire Station. Discharge from this spring was gaged several times from September 1997 to November 1997, yielding an average value of 110 gal/min (range: 105 to 117 gal/min).

Figure 7. Diagram of Polly No. 4 Mine at Sand Lick site in Letcher County, showing sample sites. SNDL samples were collected at the well and SLFS samples were collected at the outflow.



This average value may be considered the baseline discharge rate for the spring during that time of year.

From November 5–8, 1997, a pumping test was performed at this site using an existing 18-in.-diameter well constructed into the backfilled drift entrance approximately 500 ft north of the Sand Lick Fire Station. Figure 8 shows the elevation (feet above mean sea level) of measured water levels in the pumping well over time. Water was pumped for 3 days at an average rate of 800 gal/min, for a total withdrawal of 2.97 Mgal and a draw-down of 2.7 ft. After pumping stopped, water-level recovery was monitored, and average recharge rate was determined to be 120 gal/min. The similarity of the pumping test recharge rate and

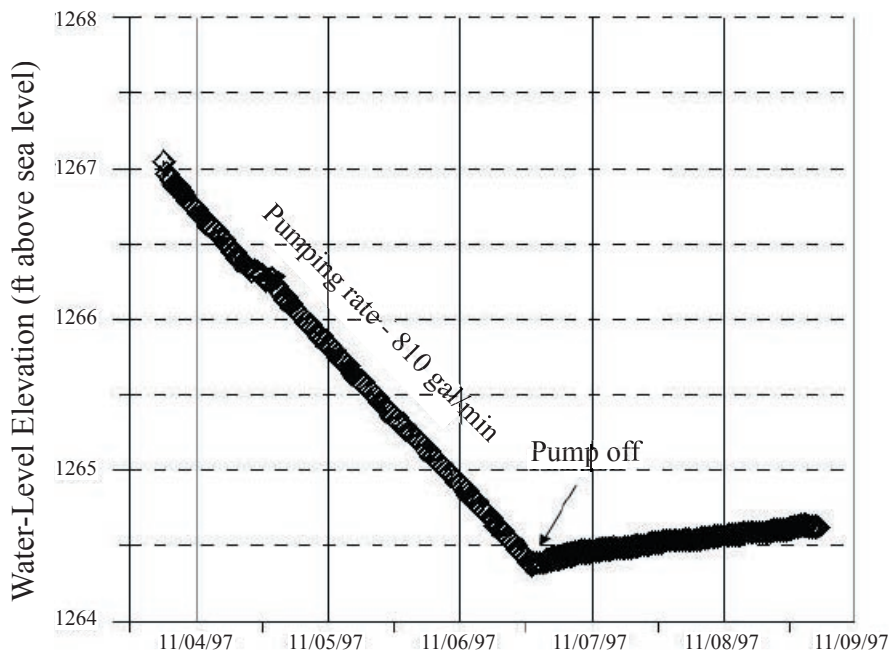


Figure 8. Water-level elevations in production well during pumping test at the Sand Lick site.

the spring discharge rate indicates that outflow from the mine does, in this case, reflect the recharge rate.

During the November 1997 pumping test at the Sand Lick site, five water-quality samples were collected from the discharge. Analysis of these samples (Webb and others, 2006) shows a maximum TDS concentration of

1,134 mg/L. Maximum concentrations of sulfate and sodium were elevated (569 and 205 mg/L, respectively) and bicarbonate concentrations ranged from 122 to 349 mg/L. Maximum concentrations of iron and manganese were 28 and 1.24 mg/L, respectively, and pH ranged from 6.43 to 6.81. The Sand Lick site was tested for PCB's, volatile organics, pesticides, fecal coliform, and orthophosphates, with no detectable concentrations of each constituent. An additional water-quality sample (SLFST001) was collected from the outcrop spring located behind the nearby Sand Lick Fire Station. Results from this sample were very similar to results from the samples collected during the pumping test, indicating that the spring water is most likely derived from the same source.

Cow Branch. This study focused on another part of the South East Coal Co.

Polly No. 4 Mine in Letcher County (Fig. 9). This part of the mine is below drainage and completely flooded. A pumping test was performed at this site from February 23–27, 1998. A submersible pump was installed in the void space of the abandoned mine at a depth of 146 ft

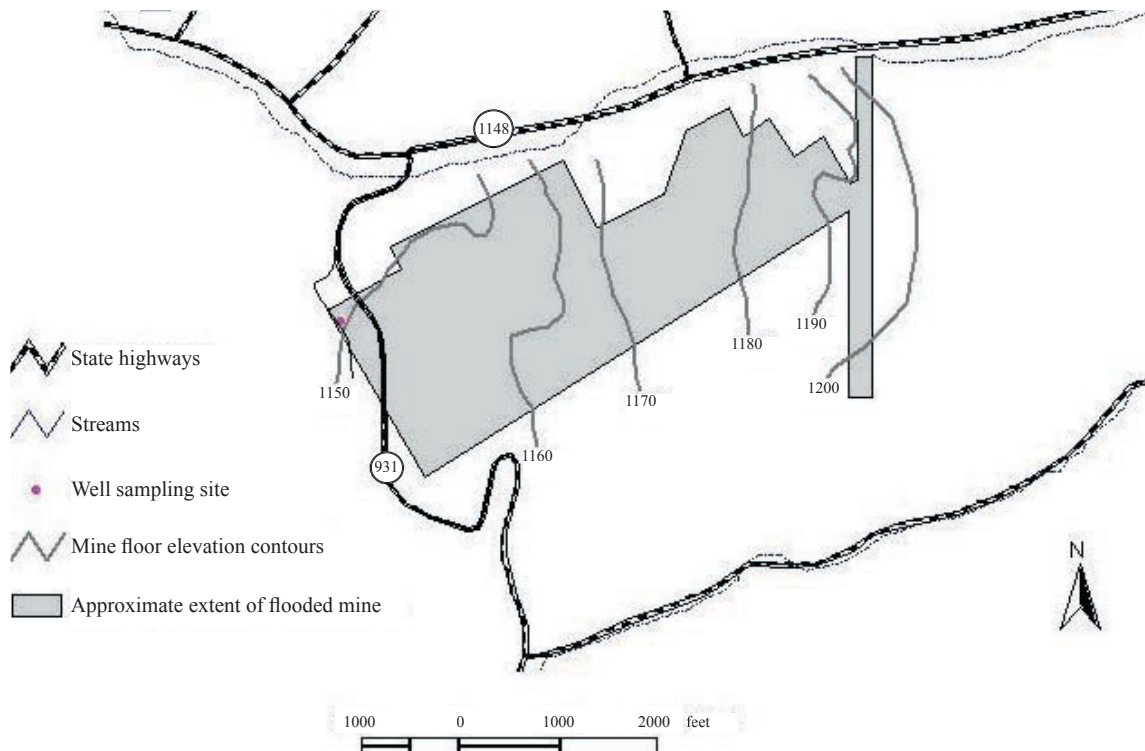


Figure 9. Location of sample site at Polly No. 4 Mine at Cow Branch in Letcher County.

below ground surface. Water was pumped at an average rate of 408 gal/min for 5 days, resulting in the removal of 2.9 Mgal. Water levels were recorded by pressure transducers installed in two monitoring wells; one well tapped the void space of the abandoned mine, and the other was drilled into a coal pillar adjacent to the mined area. Figure 10a shows measured water levels in both wells over time, along with recorded daily rainfall. Static water level in the coal-pillar well (seam well) stands over 13 ft above static water level in the monitoring well (surface elevations are identical for both wells). The pillar well responded more dramatically to rain in both timing and intensity. The monitoring well showed little response to rain at the scale of Figure 10a. Figure 10b is a plot of recorded water levels in the monitoring well over time, along with daily rainfall for the same period. The y-axis scale has been adjusted to show subtle changes in water level in response to rain, and to more

clearly show response to pumping during the February 23–27 pumping test. Water levels in the coal-pillar well showed no response to pumping, whereas the well tapping the void space showed a drawdown of 0.32 ft.

After pumping ceased, recovery was monitored to determine recharge rates to the mine. Full recovery occurred within 5 days after pumping stopped. Recharge rates were calculated to be between 320 and 420 gal/min, or approximately 500,000 gal/day.

Water-quality samples were collected at this site prior to and during the winter 1998 pumping test. The samples were drawn from the pumping-well discharge. Analytical results (Webb and others, 2006) from this sample show high TDS (1,942 mg/L); dissolved species were dominated by sulfate, bicarbonate, and sodium (692, 1,013, and 523 mg/L, respectively). Field-measured pH ranged from 6.81 to 7.77, and maximum iron and manganese concentrations were 8.33 and 0.529 mg/L, respectively.

No significant concentrations of pesticides, nitrates, fecal coliform, orthophosphates, PCB's, or volatile organics were detected.

Crafts Colly. This study site focused on part of the abandoned BethEnergy No. 22 Mine in the Upper Elkhorn No. 3 seam in Letcher County (Fig. 11). This part of the mine is below drainage and not completely flooded. A submersible pump installed into a well drilled 176 ft below the ground surface was used for water removal. The pumping rate was held steady at 57 gal/min for 5 days (March 11–16, 1999) for a total withdrawal of 0.41 Mgal. Water levels were monitored in both the pumping well and an existing domestic well 117 ft away; no drawdown was recorded in either well. Water levels in the domestic well had been monitored since July 1998 (Fig. 12), and were rising prior to the pumping test. The effect of the pumping test was to only slow the rate of water-level rise. The estimated recharge rate, based on the volume of the mine and the change in water levels during the periods before, during, and after the pumping test, was 180,000 to 220,000 gal/day.

Samples from this site were collected from two different wells penetrating the coal mine. Sample ADAM-002 (Webb and others, 2006) was collected from an unused private well, whereas samples ADAM-201 through ADAM-205 were

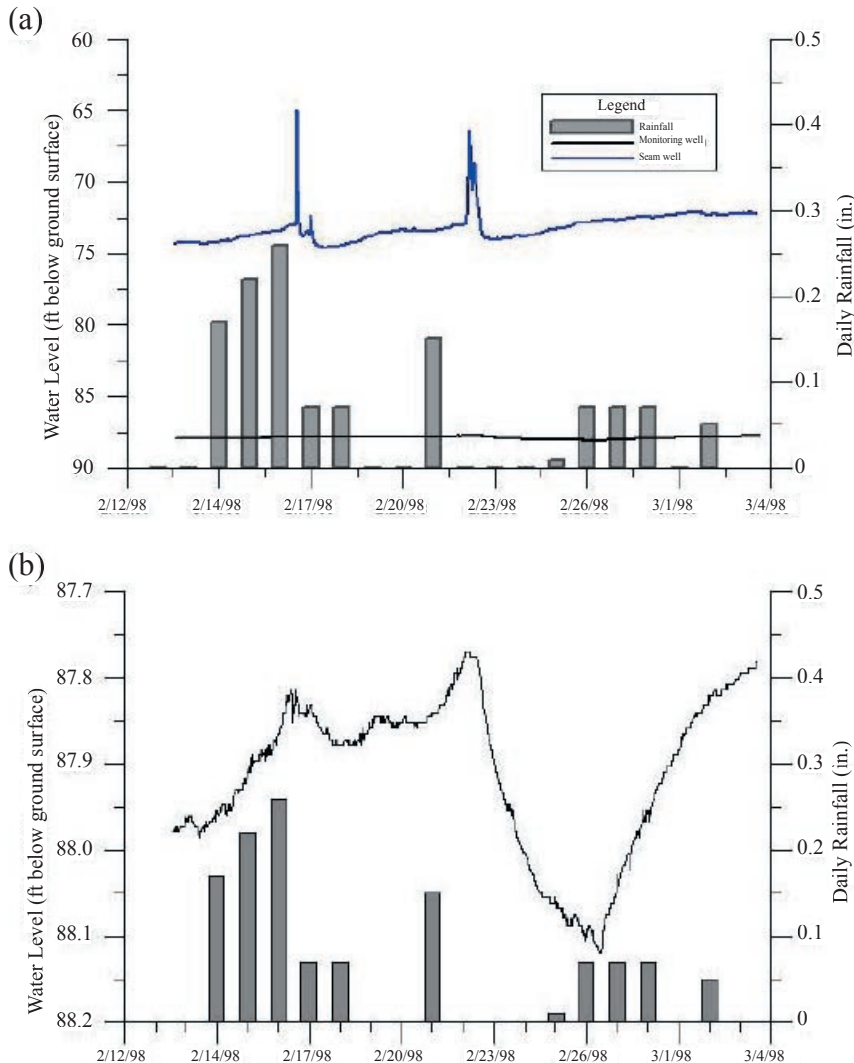


Figure 10. Daily rainfall and water levels in (a) monitoring well and seam well and (b) monitoring well only at Cow Branch site.

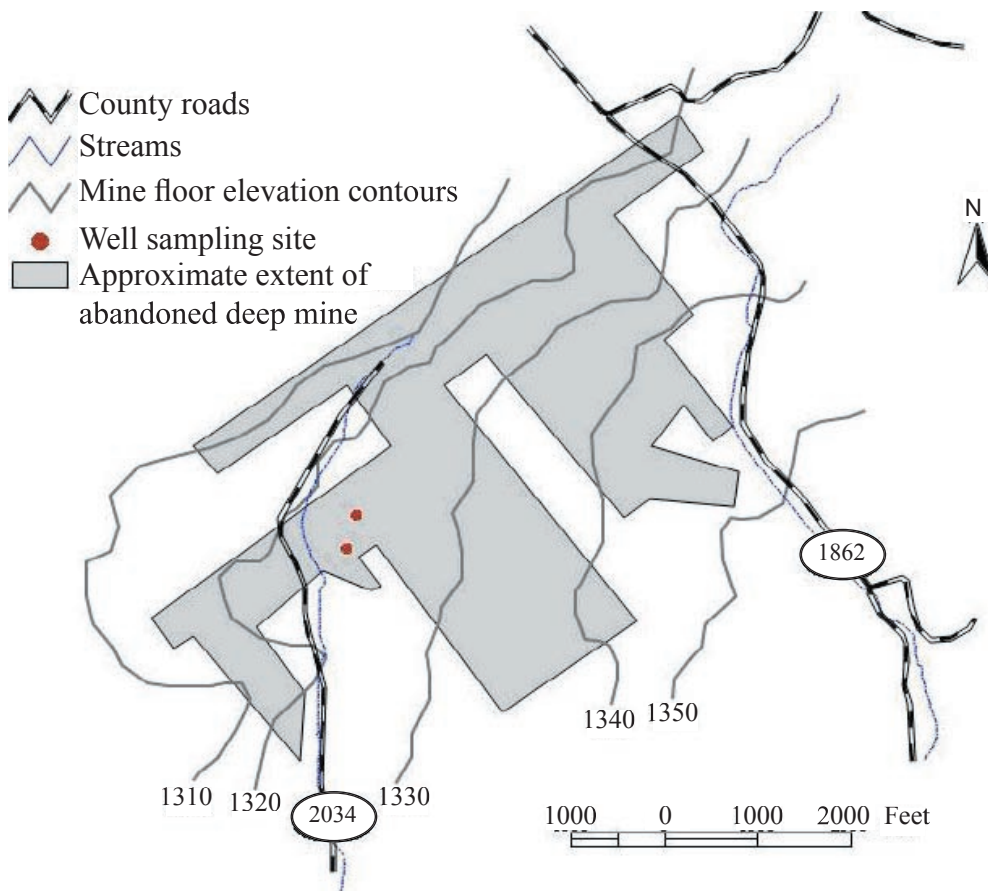


Figure 11. Locations of sample sites in BethEnergy No. 22 Mine at Crafts Colly in Letcher County.

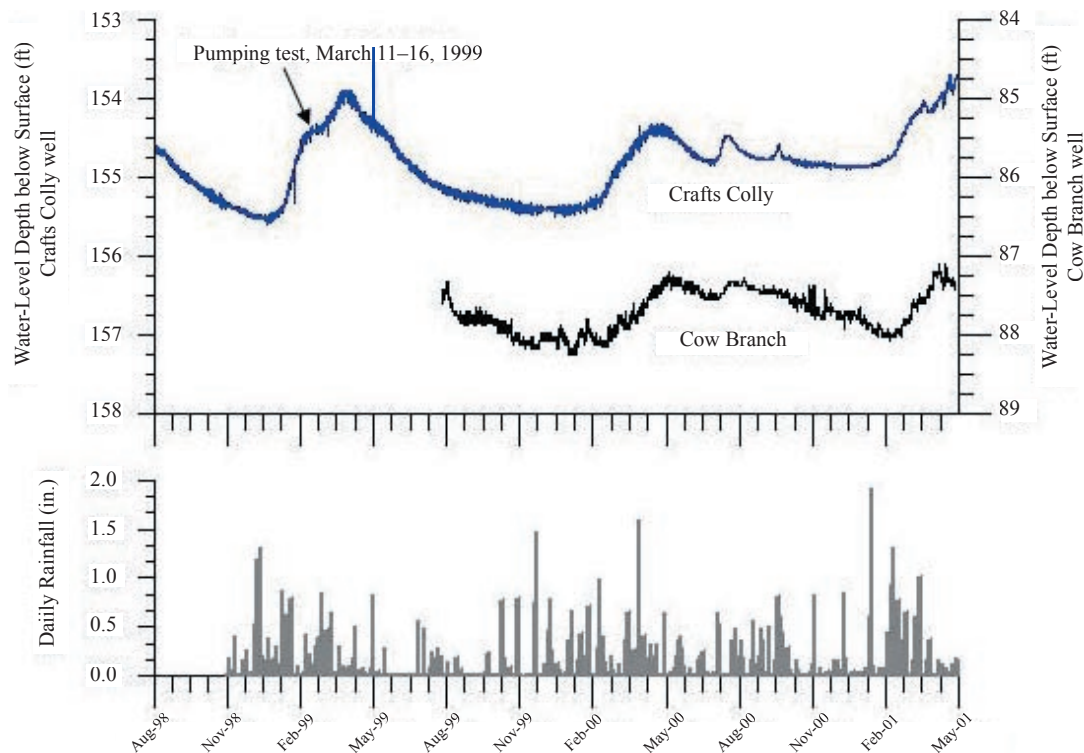


Figure 12. Daily rainfall and hydrographs for Crafts Colly monitoring well and Cow Branch monitoring well.

collected from a production well drilled into the coal void approximately 110 ft northeast of the private well. The private-well sample was dominated by sodium, bicarbonate, and sulfate (612, 990, and 786 mg/L, respectively), along with high concentrations of iron (15.1 mg/L), magnesium (19.3 mg/L), and manganese (0.201 mg/L). During the spring 1999 pumping test, three samples were collected from the production well (Webb and others, 2006). Although still dominated by sodium, bicarbonate, and sulfate, maximum concentrations were considerably lower in these samples compared to samples from the private well (247, 510, and 355 mg/L, respectively). Maximum iron (6.97 mg/L) and magnesium (17.8 mg/L) concentrations were also lower, whereas maximum manganese concentrations doubled (0.432 mg/L). The abandoned private well is less likely to represent the true water quality of the mine because of the generally poor condition of the well (less than 8 ft of surface casing, below-grade top of casing with no well cap, and a broken pump lodged at the base).

Manchester. The abandoned mine studied at this site (LeeCo No. 47 Mine in the Manchester coal seam) was used by the city of Manchester during the drought of 1999 to help replenish the system's water-supply reservoir. Prior to that usage, little information was available about the mine's supply capacity. The 1999 withdrawals were made from a boxcut pond at the flooded mine entrance. Water was pumped from the pond into Little Goose Creek, some 3 mi upstream of the city's water intake (Fig. 13).

Storage volume of the LeeCo No. 47 Mine was determined through use of mine maps supplied by the James River Coal Corp. The areal extent of the mine was calculated to be approximately 790 acres, the average thickness of the coal seam is 36 in., and the estimated coal removal is 60 percent. Multiplying these quantities yields an estimated storage volume of 62 million ft³, or roughly 460 Mgal.

A production well was drilled into the LeeCo No. 47 Mine void on January 6, 2000. This well is located near the southeastern edge of the mine works near the mine's topographic low. Upon penetrating the mine void, water rose in the well to an elevation of 847 ft above sea level. This was 56 ft above the elevation of the coal floor at that point,

and over 30 ft above the highest elevation in the mine, indicating that the mine was completely flooded.

Two pumping tests were performed at this site in order to determine seasonal recharge rates. The first was in March 2000 (wet season) and the second in late September 2000 (dry season) (Fig. 14).

The wet-season pumping test began at 17:00 on March 6 and continued through 19:06 on March 7, when the high-volume pump failed. The pumping rate was steady at 425 gal/min, for a total withdrawal of 665,000 gal. Water levels were monitored in the production well and in the boxcut pond. The total drawdown in the production well was slightly over 1 ft. Figure 14a is a graph showing the water levels in the pumping well and the boxcut pond. After pumping ceased, water levels continued to fall slightly before rising at approximately the same rate as before pumping began. The continuing decrease was because of pumping by Cobra Coal Co., which uses water from the pond at its nearby processing plant. The recharge rate before and after the pumping test was calculated to be 210,000 gal/day. During the pumping test there was a connection between the pumping well and the boxcut pond: the two curves on the graph are almost identical, indicating a direct connection between the well and the pond. The difference in elevation between the two sites, however, is such that the water level in the well would have to be dropped nearly 25 ft before drawing pond water into the well would be possible.

The second pumping test began September 26 at 15:15 and ended September 29 at 08:15. Pumping rate

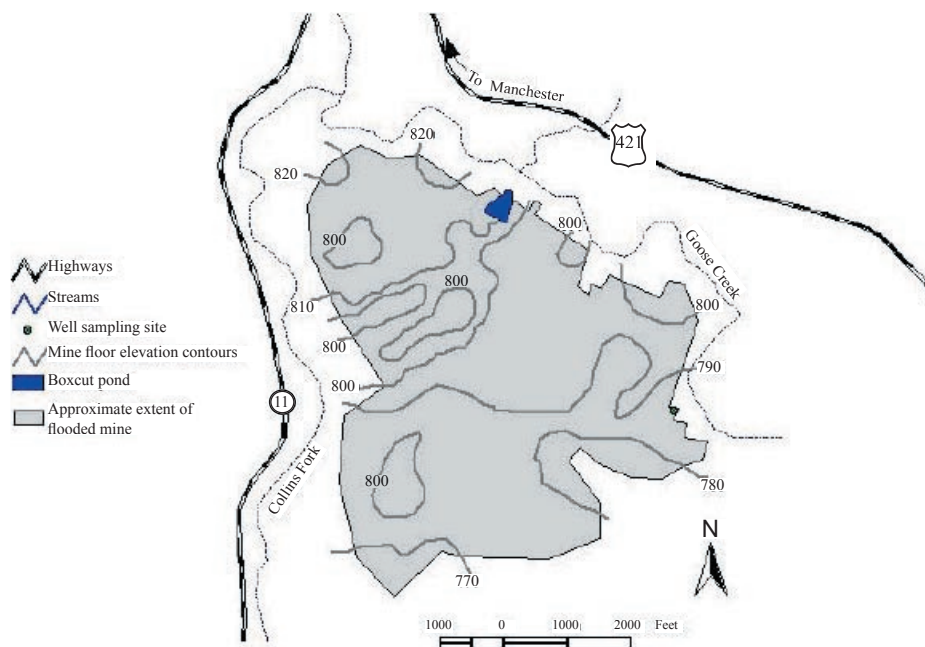


Figure 13. Locations of sample site at LeeCo No. 47 Mine at Manchester in Clay County.

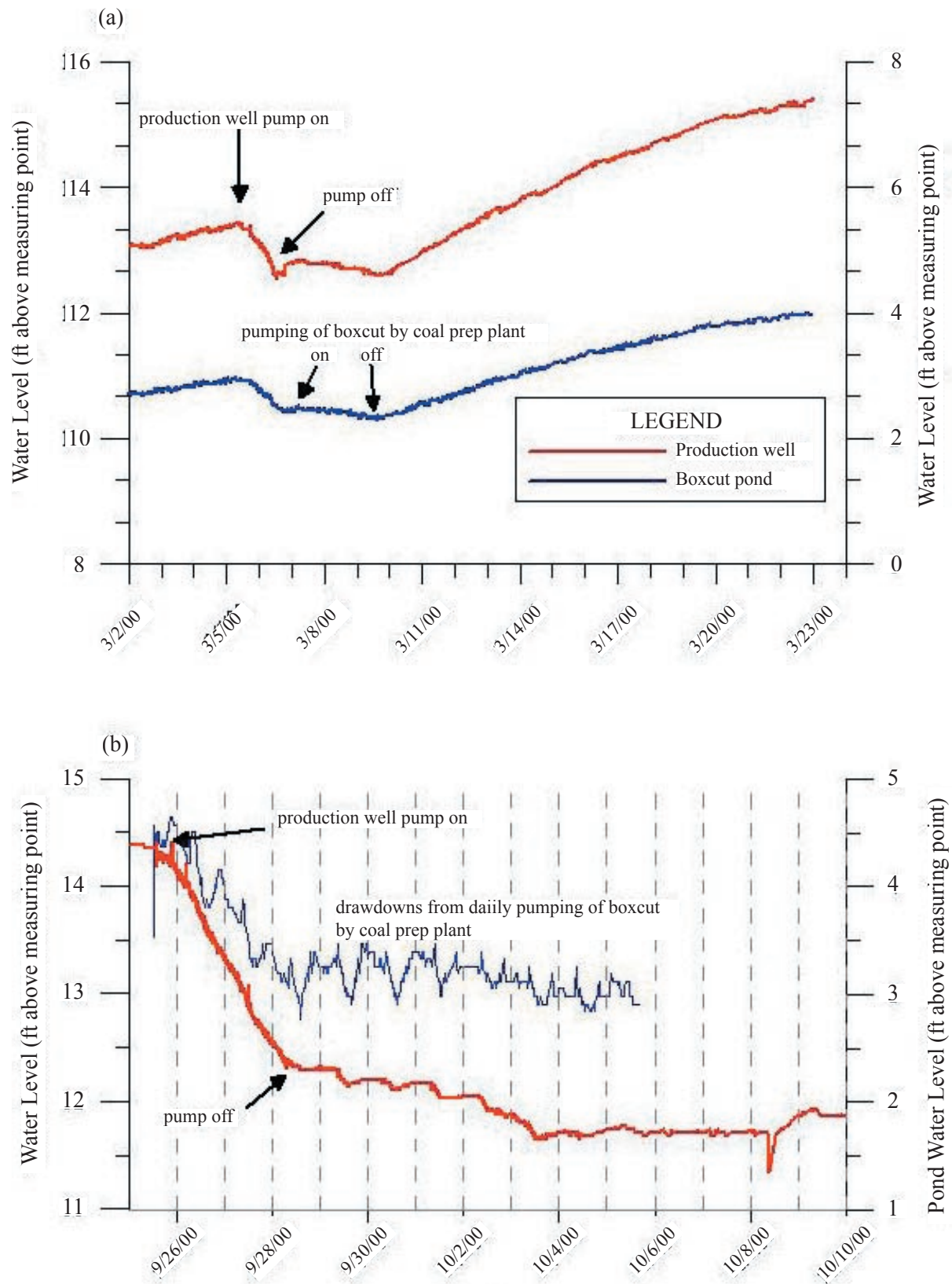


Figure 14. Drawdowns in monitoring points from (a) wet-season and (b) dry-season pumping tests at the Manchester site.

was steady at 475 gal/min for a total discharge during the test of 1.85 Mgal. Measured drawdown for the test was 1.9 ft in the production well and 1.1 ft at the boxcut pond (Fig. 14b). After pumping stopped, water levels in the production well continued to decline at a slower rate, similar to the rate of decline before the test began. Additional drawdown or recovery features can be seen in the water levels from the boxcut pond. These smaller water-level declines are caused by daily water usage by the Cobra Coal processing plant. The lack of recovery from drawdown caused by this pumping test demonstrates that there was no recharge to the mine during this time. Typically, late summer through mid-fall in eastern Kentucky can be characterized as the dry season. If an unusually wet September were occurring, the net recharge would resume.

All samples collected at this site were drawn from the production well drilled into the coal void. An initial sample was collected in January 2000 (CLAY-001; Webb and others, 2006). Two more samples were collected at the beginning and end of the spring 2000 pumping test (CLAY-002, CLAY-003) and three additional samples were collected during the fall 2000 pumping test (CLAY-021, CLAY-022, CLAY-023). The January 2000 sample and the two early pumping-test samples (CLAY-002, CLAY-021) were similar in water quality. All three had high specific conductance (2,788, 3,020, and 2,225 mg/L), bicarbonate (755, 830, and 850 mg/L), chloride (567, 590, and 307 mg/L), and sodium (518, 530, and 464 mg/L). Water quality changed during the course of both pumping tests, however. During the March test, specific conductance decreased from 3,020 to 1,680 mg/L, sodium concentrations decreased from 530 to 329 mg/L, and chloride concentrations decreased from 590 to 194 mg/L. During the September test, specific conductance dropped from 2,225 to 1,535 mg/L, sodium decreased from 464 to 334 mg/L, and chloride dropped from 307 to 158 mg/L. Both pumping tests also showed increases in sulfate. The shift in water-quality type can be explained by the early influence of salty water upwelling into the nearby Goose Creek Valley (the

area once produced over 200,000 bushels of salt per year), changing with time to a water type more typical of mine water derived from coal-bearing strata.

Leatherwood/Delphia. The abandoned mine at this site is an extremely large (6,800 acres) above-drainage mine in the Hazard No. 5A (Leatherwood) coal seam in southern Perry County (Fig. 15). Six large outflows from this mine were located and monitored for water quality and quantity. There are also numerous smaller flows that would be impractical to monitor. One of the six large outflows is being used by approximately 17 nearby homes. The usage has been estimated at approximately 3,400 gal/day, while another 150,000 gal/day flows into local drainage. Discharge from two other large outflows (Blue Diamond and Old House Branch) was recorded continuously using H-type flumes installed in January 2000. Flow from flume 1 (Fig. 16a; Old House Branch site) ranged from 45 gal/min up to 360 gal/min (65,000 to 520,000 gal/day). Flow from flume 2 (Fig. 16a; Blue Diamond site) ranged from 70 gal/min up to 320 gal/min (100,000 to 460,000 gal/day). These sites were monitored for a full year to record seasonal changes in water discharge, and thus, water supply.

As part of an effort to create a water district for the area, local officials notified KGS that additional sources may be necessary to meet anticipated system needs. During August of 2000, reconnaissance of the area resumed in order to locate additional supplies. Two large outflows from the Leatherwood mines were

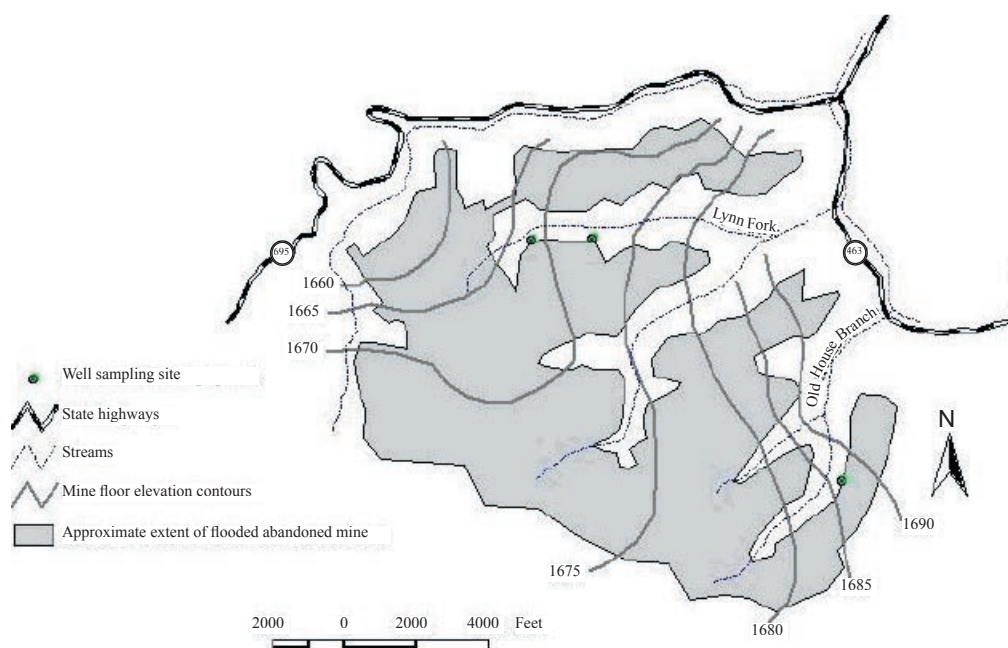


Figure 15. Locations of mine-water discharges and water-quality sampling sites at the Blue Diamond Mine at Leatherwood in Perry County: Old House Branch, Lynn Fork Upper, and Lynn Fork Lower.

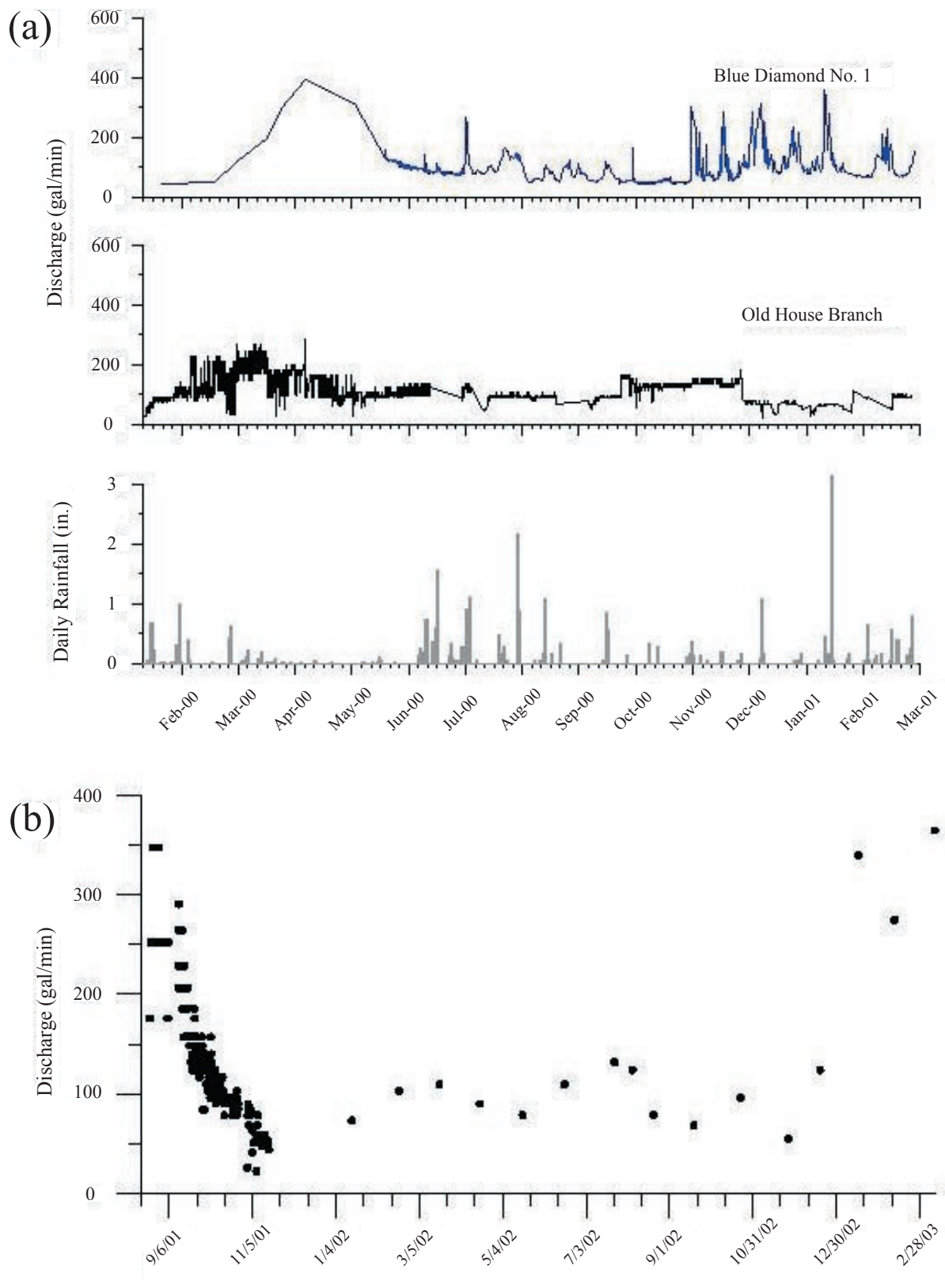


Figure 16. Rainfall and discharge measurements at Leatherwood sites for (a) Blue Diamond and Old House Branch sites and (b) Lynn Fork site.

located in the upper reaches of Lynn Fork. The two outflows exit the same section of mine, and supply almost all of the flow in Lynn Fork. Flumes were installed at the base of each outflow to record continuous discharge. The upper outflow (Lynn Fork Right) discharged diffusely through a section of drainage-control boulders emplaced by the surface-mining company to control runoff and sediment from the uppermost reaches of Lynn Fork that were buried with spoil during reining. The outflow deposited large amounts of iron oxide on the flume, requiring frequent cleaning. Difficult access to the site limited maintenance frequency, however, so most data collected from Lynn Fork Right are considered to be of limited value because of frequent flume failure. The lower discharge (Lynn Fork Left) did not pose data collection problems, and discharge was successfully recorded continuously for 4 months before the equipment failed because of vandalism. Monthly manual discharge measurements continued at Lynn Fork Left through March 2003 (Fig. 16b). The sum of the Lynn Fork outflows, along with those previously identified, has been determined to be sufficient to meet the district's needs, and the design of the collection and treatment system has been completed.

Two existing water production wells were located in the Leatherwood area near the abandoned coal camp. These wells were used by the coal company to supply water for the coal camp community (over 200 households) as well as for the coal processing plant. The estimated storage volume of the section of mine beneath the production well is near 115 Mgal. Former operators of the wells said that the storage volume ranged from 30 to 84 Mgal during usage. Well structures are still in place, and a 30-horsepower turbine pump is still installed in one of the wells. The other well is an open borehole measured to be 197.5 ft above the base of the coal void. The static water level is 194.5 ft below ground surface, with little change noted over time. Numerous groundwater seeps are found along the base of the surface-mining reclamation slopes surrounding the underground mine. At the time of this publication, refurbishment of the wells was considered uneconomical because of the cost of restoring electrical power and reconstructing the access road.

Water samples were collected from four large outflows in this area: the Blue Diamond site (samples BDMD-001, BDMD-002, BDMD-003), Old House Branch (OLDH-001, OLDH-002), Delphia Spring (DEL3-001), and Barkcamp Branch (CIST-001) (Webb and others, 2006). Results from analysis of these samples indicate that the mine produces water of good quality, with no constituents at levels above primary or secondary drinking-water standards set by the EPA. The only water-quality concern would be pH, which was slightly acidic (5.98 to 7.18; mean value of 6.7).

BenCo. This potential supply is the western part of the BenCo No. 4 Mine in the Hazard No. 4, or Fire Clay, coal seam. The mine is below local drainage, approximately 3 mi north of Hazard on the upper reaches of First Creek (Fig. 17). The estimated storage volume of the mine is near 100 Mgal.

In early October 2000, a production well was drilled into a downdip section of the mine to a depth of 79 ft below the ground surface. The coal void was encountered at 76 ft, and water rose into the well to 35 ft below the ground surface. Based on floor elevations of the mine and the elevation of the static water level, the entire southern section of the mine appears to be flooded. A second mine-water access point is located 2 mi east of the production well on Ky. 267. This access point is an abandoned boxcut that was formerly used to haul coal from the mine. The pit is approximately 100 ft deep. Most of the haulage infrastructure has been removed, and the pit is flooded to depths ranging from 10 to 35 ft.

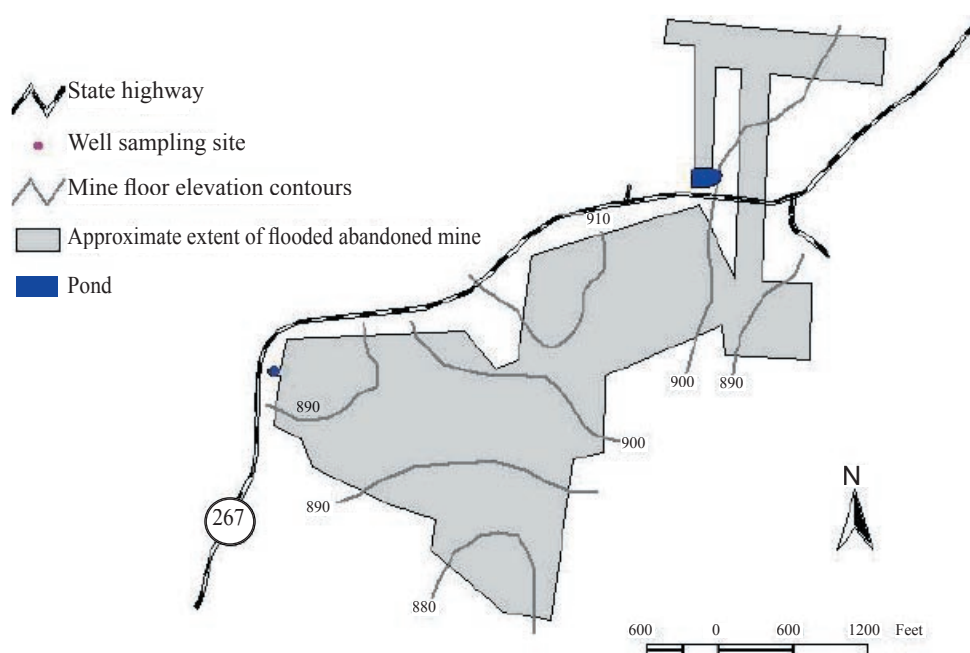


Figure 17. Locations of sample sites at BenCo No. 4 Mine at Hazard in Perry County.

In late November, a pumping test was performed at the BenCo production well to determine the rate of groundwater recharge to the mine. The pumping test duration was scheduled for 48 to 96 hrs, but because drawdown was significant, the test ceased at 2.5 hrs. The pumping rate was steady at 510 gal/min, for a total discharge of 77,000 gal. Just as drawdown was rapid, total water-level recovery was achieved within 6 hrs after pumping stopped. The average recharge rate was approximately 300,000 gal/day (approximately 210 gal/min), less than half the pumping rate, accounting for the rapid drawdown during the pumping test.

Water levels in the boxcut pond east of the production well were also monitored during the pumping test. There was no apparent change in water levels during the pumping period, indicating that there is no direct hydraulic connection between the boxcut pond and the production well. The boxcut pond and the production well are separated by an extensive section of unmined coal. This barrier is the result of the valley cut by First Creek, where coal-seam overburden is thin. During the summer of 2002, the boxcut pond was filled and capped as part of the post-mining reclamation process.

Four water-quality samples were collected from the BenCo site, one prior to and three during the fall 2000 pumping test. All samples were drawn from the production well. The results of these analyses are shown in Webb and others (2006). The only constituents above EPA drinking-water standards were iron (2.09 to 2.50 mg/L) and manganese (0.38 to 0.46 mg/L). The standards for both of these dissolved metals are aesthetic standards, and elevated levels do not pose health risks.

Discussion

Water Quantity

Temporal Variation. Monitoring of water-quantity changes may differ in technique, depending on whether the mine is above or below drainage. Most above-drainage mines are characterized by gravity-driven discharges at openings created by mining processes, or through seeps and springs that develop at weaknesses in outcrop barriers. Because these mines are free to drain, they maintain an approximate steady state, seldom substantially increasing or decreasing in storage. Therefore, temporal changes in above-drainage mines are best characterized as changes in discharge, or recharge, rates.

Conversely, monitoring of water-quantity variation in below-drainage mines is characterized by changes in storage volume, deduced from changes in water levels. Below-drainage mines will lose water via advection through coal-seam barriers, leakage into the

strata above and below, and often through discharges where the coal ultimately crops out. For example, seam 2 on Figure 6 is a below-drainage mine that crops out near the location of well A. If seam 2 fills to the point where the water-level elevation is higher in well B than the outcrop elevation, then discharge may occur as a spring or seep. A reduction in recharge rate will lower the water level in seam 2 and stop discharge from the coal outcrop. Water-level changes in partially flooded mines can translate into rather large changes in storage volume. For example, water levels measured in the wells in the mines underlying the Crafts Colly site indicated that the mines are not completely flooded. The hydrograph from the Crafts Colly well (Fig. 12) shows that water levels decreased steadily from March through mid-December of 1998, then began to rise sharply through late March of 1999. Based on mine geometry and water-level elevation change, this represents an estimated addition of 23 Mgal to storage in the mine.

Variations in storage volume of below-drainage mines are mostly related to seasonal variations in recharge rate. In addition to changes in the Crafts Colly well, Figure 12 also shows water levels recorded in the Cow Branch monitoring well from fall 1998 to spring 2001, along with daily rainfall in inches for the same period. Both wells monitor water levels in Upper Elkhorn No. 3 mines, located approximately 3 mi from each other. The y-axis measures water-level depth in feet below ground surface, and shows that the Crafts Colly mine is slightly deeper than the Cow Branch mine. These hydrographs show that water levels in both mines respond slowly to seasonal changes in rainfall, and to evaporation, transpiration, and recharge conditions that change with variations in leaf cover and ground litter.

Seasonal variations in mine-water levels in the wells shown in Figure 12 are almost identical in both timing and magnitude of change. There is significant lag time between the onset of the wet season and peaks in water level in both mines, and limited response to individual rainfalls. The Cow Branch mine shows more short-term response to rain, likely because of less overburden and closer proximity to the near-surface fracture zone, allowing for more direct recharge from surface water or precipitation (or both). Thus, the amount of lag time and response to rain for any individual mine is likely to decrease with depth below ground surface.

Water Quality

The broadest assessment of the quality of water produced by abandoned deep mines is a comparison of that water to generally accepted water-quality criteria. Tables 3 and 4 show the incidence of failure to meet EPA primary and secondary drinking-water standards, respectively, for all mine-water samples.

Table 3. Abandoned mine-water samples exceeding primary drinking-water standards.

	<i>Upper Elkhorn No. 3</i>		<i>Manchester</i>		<i>Hazard No. 4</i>		<i>Hazard No. 5A</i>		
	<i>Samples above MCL</i>	<i>% Samples above MCL</i>	<i>Samples above MCL</i>	<i>% Samples above MCL</i>	<i>Samples above MCL</i>	<i>% Samples above MCL</i>	<i>Samples above MCL</i>	<i>% Samples above MCL</i>	<i>MCL (mg/L)</i>
Arsenic	0	0	0	0	0	0	0	0	*0.05
Barium	0	0	0	0	0	0	0	0	2
Beryllium	0	0	0	0	0	0	0	0	0.004
Cadmium	1	5	0	0	0	0	0	0	0.005
Chromium	0	0	0	0	0	0	0	0	0.1
Nickel	1	5	0	0	0	0	0	0	0.1
Nitrate	0	0	0	0	0	0	0	0	10
Thallium	0	0	0	0	0	0	0	0	0.002

Table 4. Abandoned mine-water samples exceeding secondary drinking-water standards.

	<i>Upper Elkhorn No. 3</i>		<i>Manchester</i>		<i>Hazard No. 4</i>		<i>Hazard No. 5A</i>		
	<i>Samples above SMCL</i>	<i>% Samples above SMCL</i>	<i>Samples above SMCL</i>	<i>% Samples above SMCL</i>	<i>Samples above SMCL</i>	<i>% Samples above SMCL</i>	<i>Samples above SMCL</i>	<i>% Samples above SMCL</i>	<i>SMCL (mg/L)</i>
Aluminum	1	5	2	33.3	3	75	5	71.4	0.05
Iron	26	86.6	0	0	4	100	0	0	0.3
Manganese	27	90	1	16.6	4	100	1	14.3	0.005
Sulfate	25	89.3	0	0	0	0	0	0	250

The samples are organized by the coal seam mined. Table 3 shows that water-quality analyses resulted in only two samples, both from the Upper Elkhorn No. 3 coal seam, having individual analytes above the EPA primary drinking-water MCL's: one sample from the Polly Portal had elevated nickel concentrations and one sample from Evarts had cadmium above the MCL. The Evarts sample was collected at the water plant, and the cadmium could have leached from galvanized piping and fittings used in the delivery system between the source and the water plant.

Table 4 shows results from mine-water analyses compared to secondary EPA drinking-water MCL's. Mine pools in the Upper Elkhorn No. 3 coal seam show high incidences of iron, manganese, and sulfate concentrations above SMCL's; only one sample had high aluminum concentration. The Hazard No. 4 samples were predominantly high in aluminum, iron, and manganese, but no samples had high sulfate. The Manchester and Hazard No. 5A mines had no high iron or sulfate, but occasionally high manganese and frequently had high aluminum. Variation in incidences of substandard water quality among the coal seams shows that public water-supply treatment requirements may differ from site to site.

Water quality from abandoned deep mines was also compared to the overall groundwater quality of the study area. Quality analyses from all water well records in Knott, Letcher, Leslie, Perry, Clay, and Harlan Counties were retrieved from the Kentucky Groundwater Data Repository. These data were then compared to data collected during this study in order to identify differences (or similarities) between deep-mine water and ambient groundwater.

Figures 18 through 21 are a series of probability plots showing distributions of recorded pH, dissolved iron, TDS, and sulfate, respectively, for historical water-well records and mine-water samples. Figure 18 shows that the distribution of measured pH in mine water is quite similar to pH distribution in all water wells (Fig. 18b). Figure 18a includes more samples derived from fresher-water shallow wells; therefore, more variability is evident in pH values below 6 and above 8. This indicates that the buffering capacity of Eastern Kentucky Coal Field geology controls pool pH better in deep mines than in all groundwater in the region. Likewise, dissolved iron distribution in deep-mine water (Fig. 19b) is also similar to its distribution in ambient groundwater (Fig. 19a). Figures 20 and 21 show that there are differences in distributions of TDS and sulfate, however,

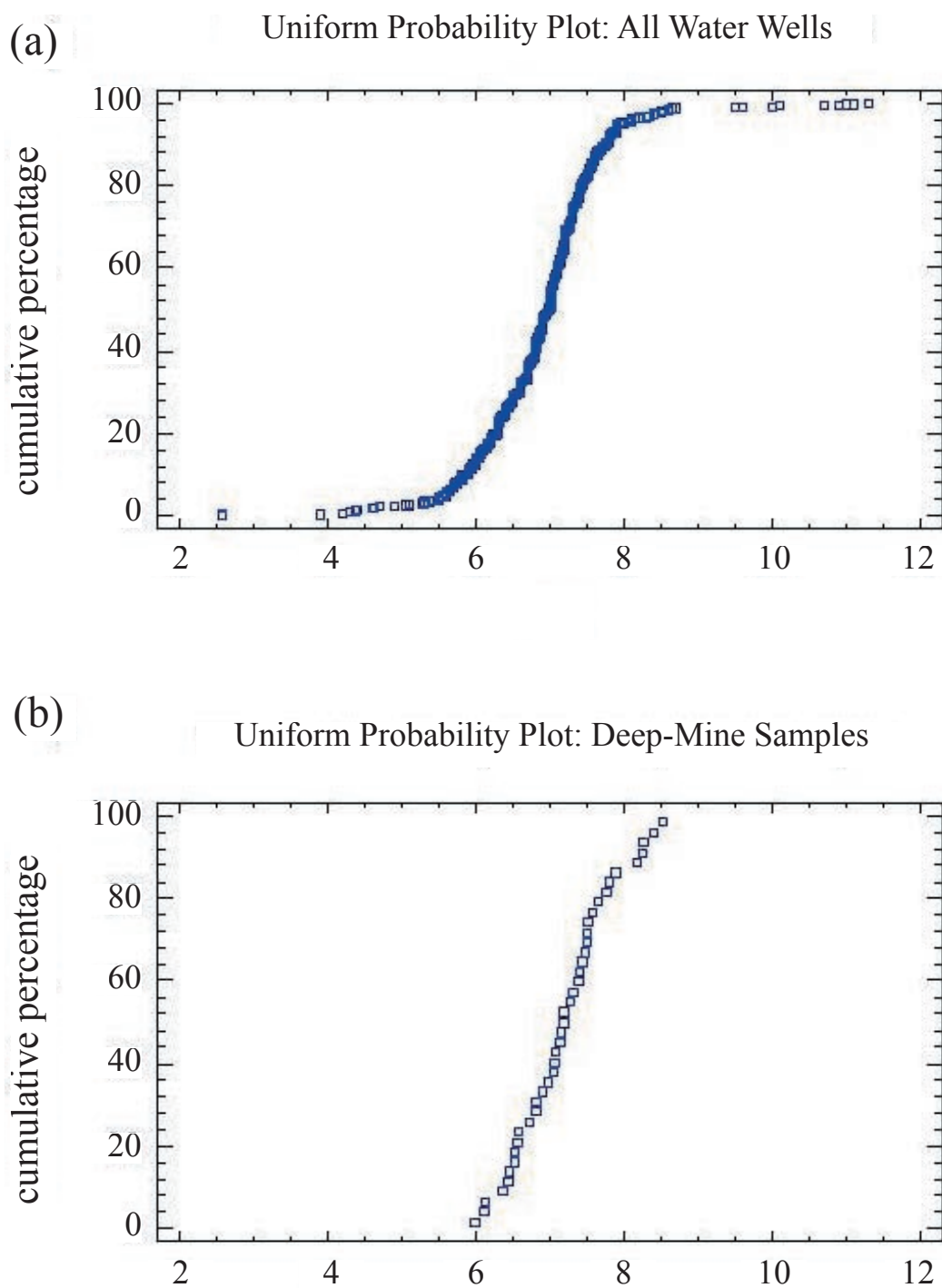


Figure 18. Distribution of pH values in (a) water-well records from within the study area and (b) samples collected from abandoned deep mines.

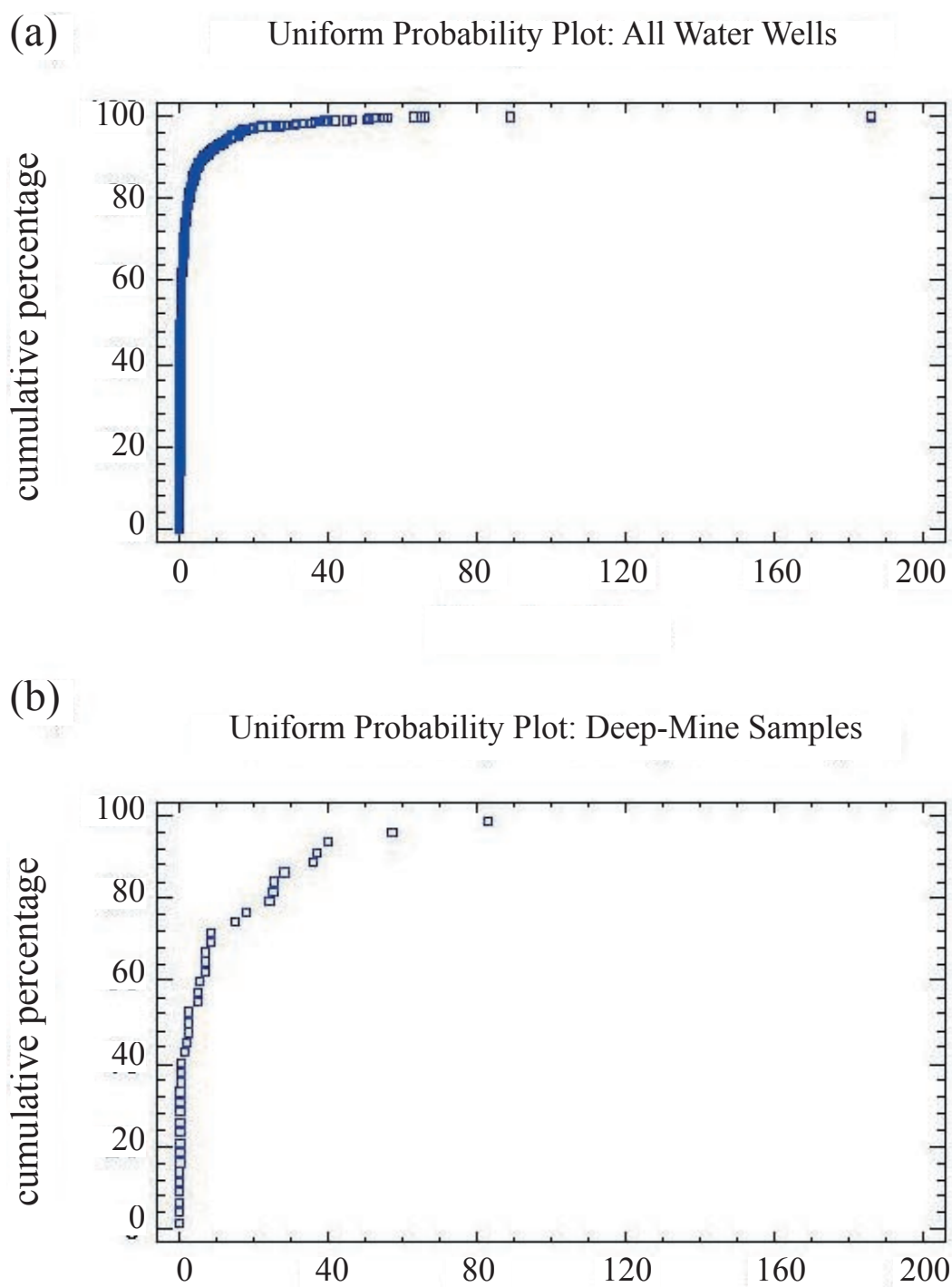


Figure 19. Distribution of iron values in (a) water-well records from within the study area and (b) samples collected from abandoned deep mines.

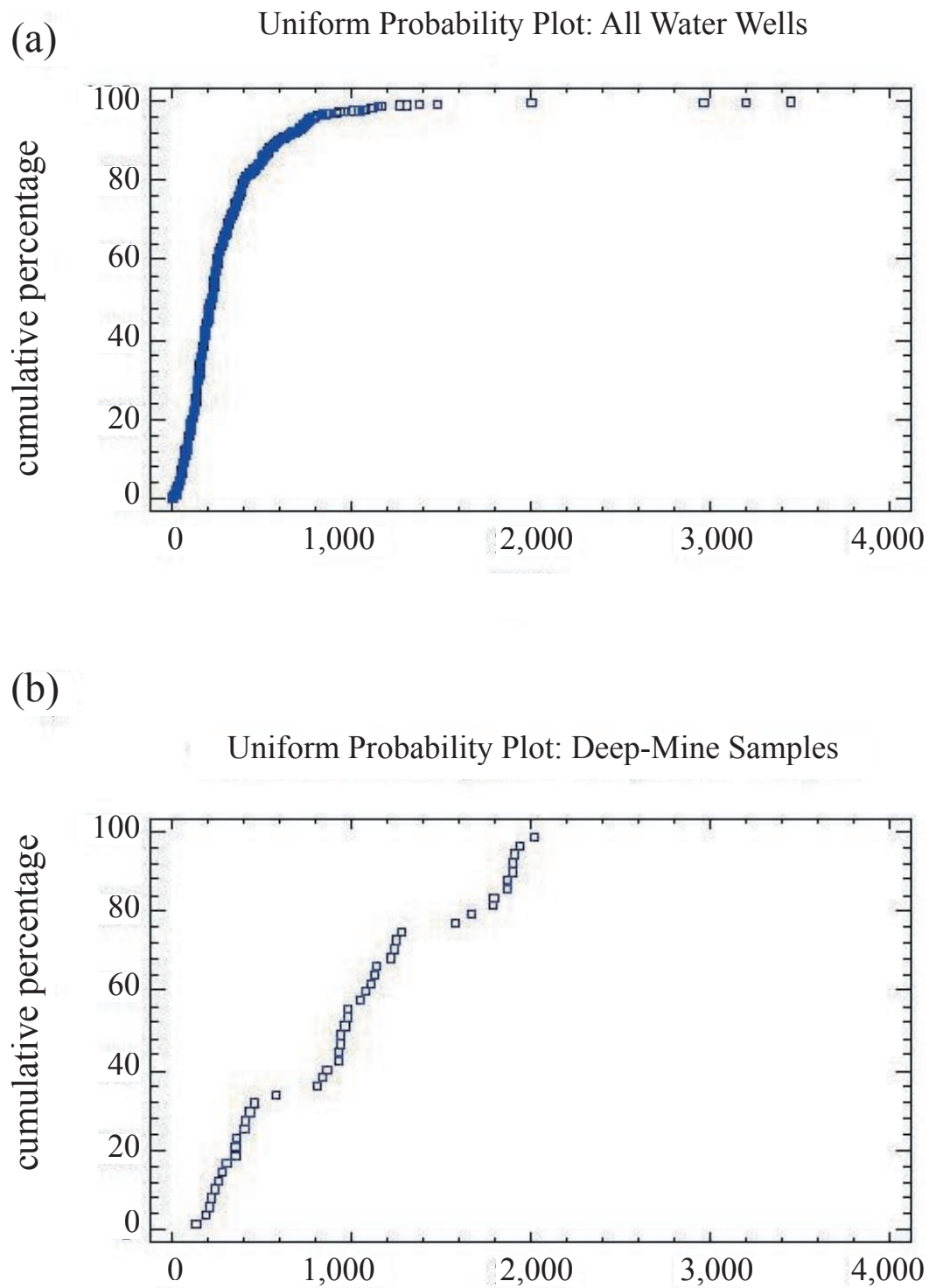


Figure 20. Distribution of TDS values in (a) water-well records from within the study area and (b) samples collected from abandoned deep mines.

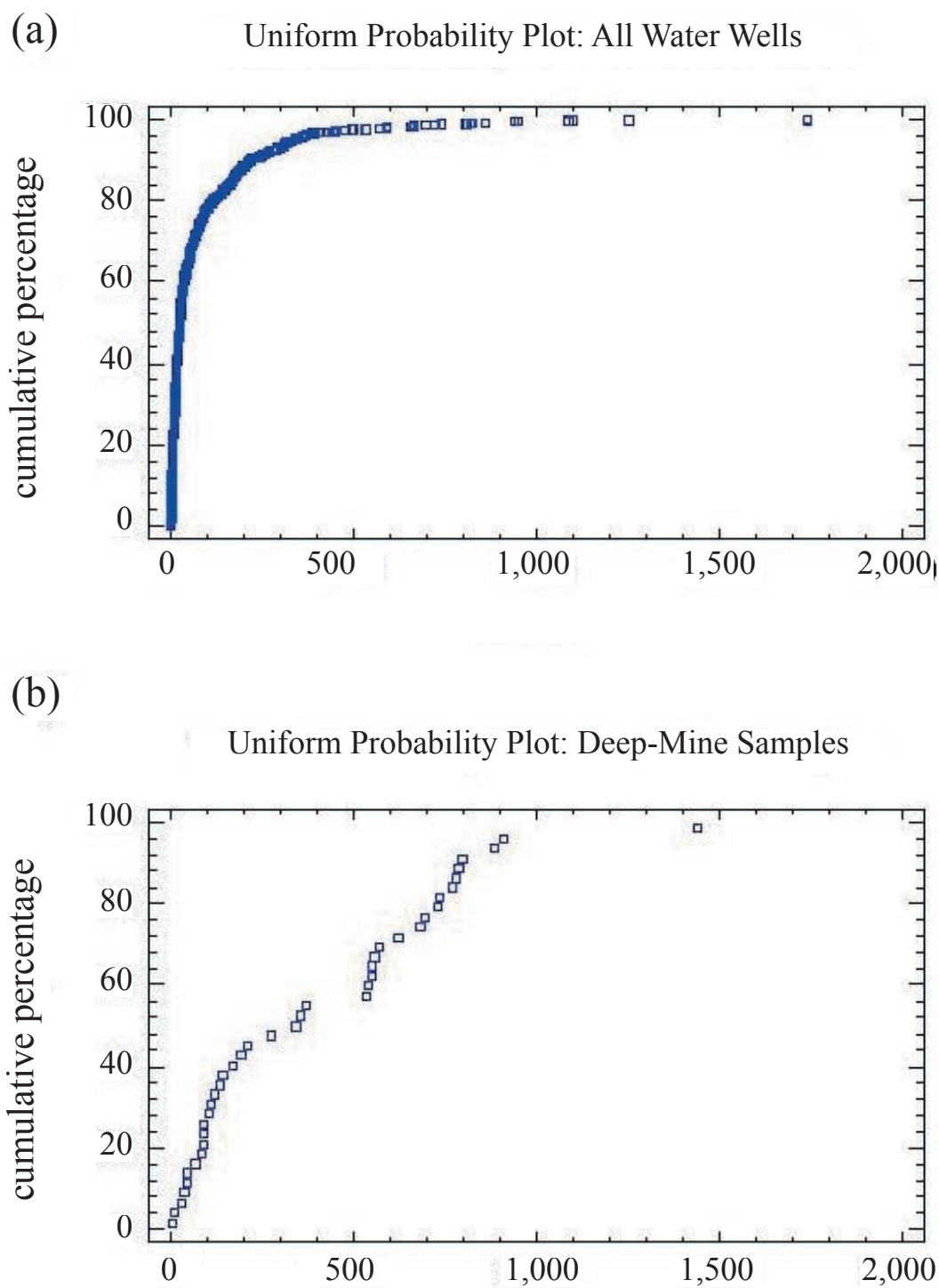


Figure 21. Distribution of sulfate values in (a) water-well records from within the study area and (b) samples collected from abandoned deep mines.

between ambient groundwater and deep-mine sources. These differences are made more evident by Figure 22, a series of box-and-whiskers plots (Tukey, 1977) graphically comparing mine-water and ambient-groundwater populations in terms of TDS (Fig. 22a), sulfate (Fig. 22b), and bicarbonate (Fig. 22c). The box represents the interquartile range (the difference between the 75th and 25th percentiles) of values for that group; the solid, horizontal line within the box is the median value; the whiskers are drawn to include those samples that fall within 1.5 times the interquartile range; and the sample mean is indicated by a "+" within the box. The boxes are also notched to represent the variance of the samples. The notches provide a quick visual comparison between the populations: boxes with overlapping notches indicate populations that are similar within a described confidence level (in this case, 95 percent). Figure 22 illustrates that the deep-mine water does not belong to the same population as the water quality of all wells in the study area. Median values of TDS, and the two anionic components that make up the majority of TDS, sulfate and bicarbonate, are noticeably higher in the mine water. Water-quality variability within the interquartile range for the three measured variables is likewise larger for mine water than for all wells. These conditions are most likely the result of groundwater in the mines being in direct contact with fresh mineral surfaces created during the mining process, and the ability of that water to readily mix in the underground mine. The occurrence of the high-concentration outliers in the all-well category may be because this category includes wells in the database that are completed in and withdrawing water from deep mines. The occasional very high outliers most likely attest to the variability in groundwater quality in the Eastern Kentucky Coal Field (Minns, 1993; Wunsch, 1993).

Figure 23 is a trilinear Piper diagram (Piper, 1944) showing the normalized weight percentages of major ions sampled through the duration of the study. Samples grouped by mine-water study site reveal different water

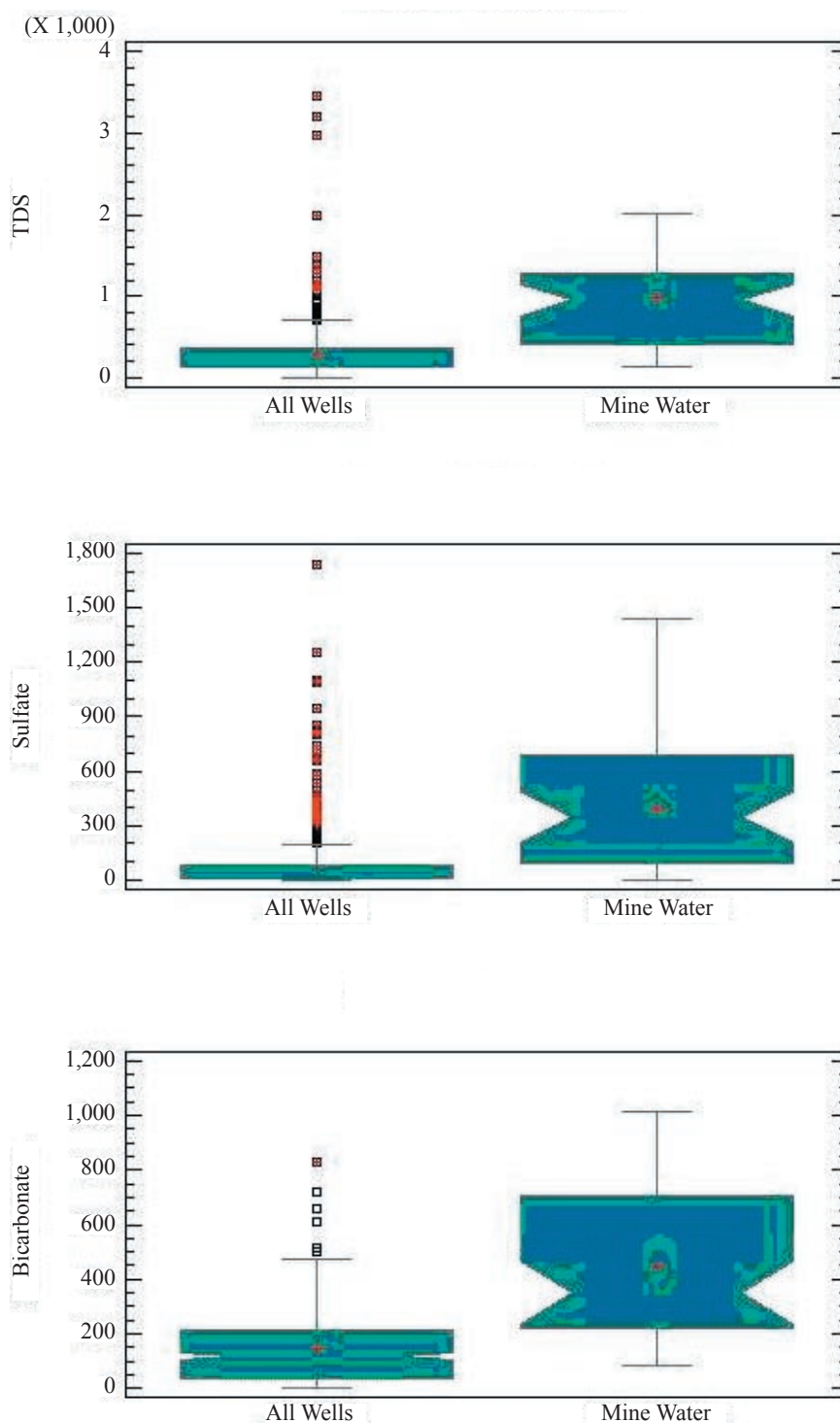


Figure 22. Box-and-whisker plots of TDS, sulfate, and bicarbonate data from existing water-well records and deep-mine water samples.

types with great variability in water chemistry. In general, the mine waters reflect the general chemical signatures presented by Wunsch (1993) concerning groundwater quality with respect to topographic position of the

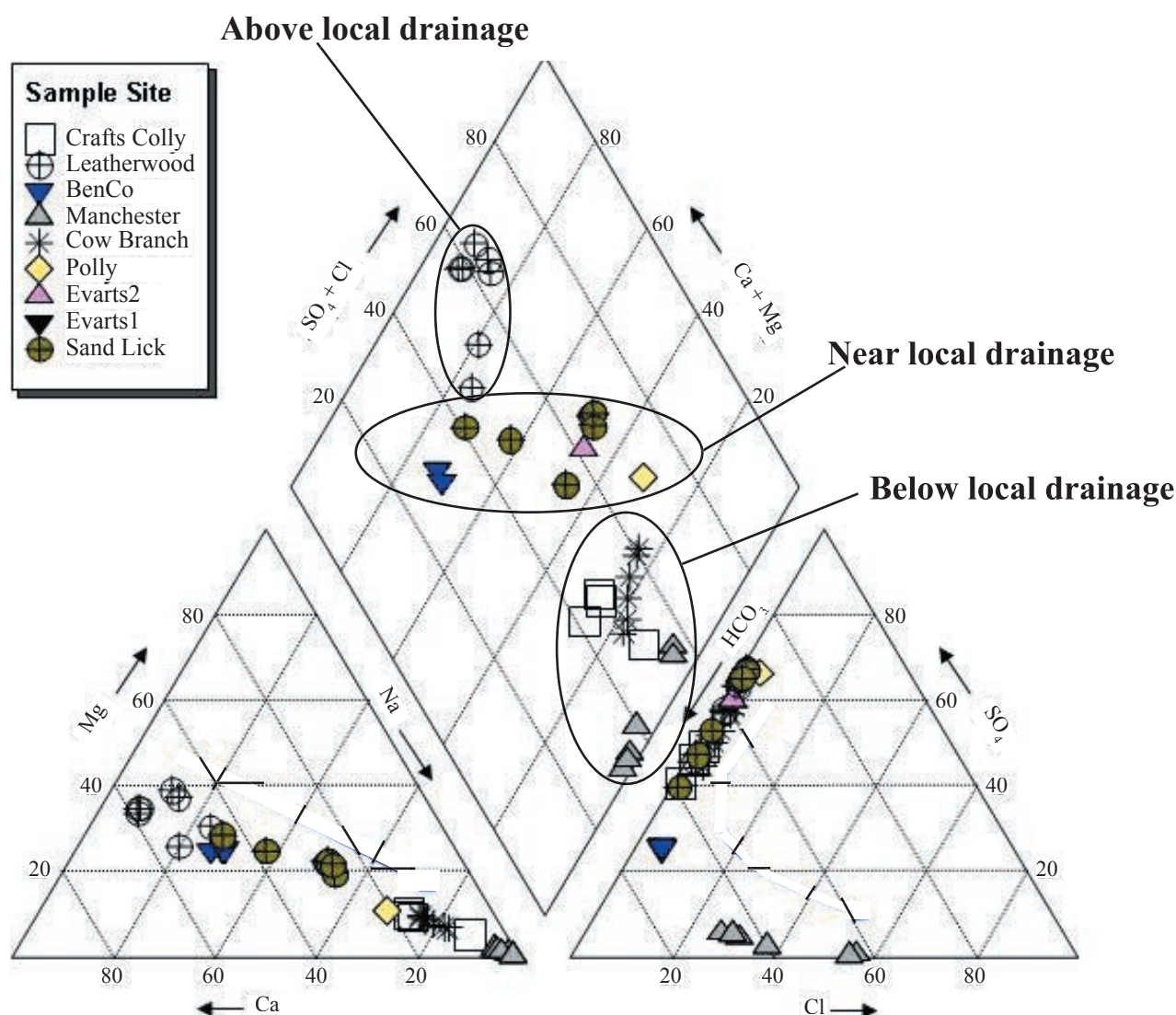


Figure 23. Normalized weight percentages of major ions from all samples collected during the study.

groundwater system. Mines above local drainage can be characterized as having a calcium, sulfate-bicarbonate composition, whereas mines near the elevation of local drainage contain a calcium-sodium, sulfate-bicarbonate water. Groundwater in mines below local drainage have a noticeable replacement of calcium with sodium, and the Manchester site contains a sodium-chloride water indicative of a distal end of a groundwater flow system (Wunsch, 1993). Groundwater in the Manchester area was produced for its salt content as far back as the early 1800's (White, 2005).

Table 5 shows descriptive statistics for the major water-quality analytes from all mine-water samples collected during this study. The wide range of variability displayed in Table 5 is not surprising because all samples are included without differentiation as to

coal seam, sample site, or physical setting. Included in Table 5 are calculations of standardized skewness and standardized kurtosis. Together these two parameters are indicators of the normality of sample distribution. Those analytes with skewness or kurtosis values outside the range from -2 to +2 are considered to have distributions with significant departure from normality (Snedecor and Cochran, 1967). Based on these criteria, analytes that do not appear to be normally distributed are bromide, chloride, barium, aluminum, calcium, iron, and manganese (Table 5).

In order to determine those factors that contribute to water-quality variability as shown in Table 5, the data were grouped by different physical characteristics that may affect mine-water quality. Figure 24 is a box-and-whiskers plot of selected analytes from mine-

Table 5. Descriptive statistics for mine-water analytes (mg/L).

Analyte	N	Maximum	Minimum	Mean	Median	Skewness	Kurtosis
Alkalinity	44	831	80	362.8	285.5	0.599	-0.890
Bicarbonate	36	1,013	100	471.8	349.5	0.391	-1.278
Conductivity*	45	3,021	278	1,449	1,500	0.239	-1.141
Hardness	38	448	20	222.1	221	0.065	-0.447
Dissolved solids	46	2,016	132	981	956	0.287	-1.119
pH**	47	8.53	5.98	7.13	7.09	0.247	-0.490
Nitrate	41	1.8	0.01	0.429	0.32	1.517	1.966
Sulfate	46	1,440	5.2	380.14	349.5	0.925	0.818
Fluoride	38	0.63	0.07	0.307	0.28	0.330	-1.277
Bromide	35	3.8	0.5	0.757	0.5	3.448	11.616
Chloride	45	590	1.4	57.7	12.3	3.365	11.343
Aluminum	36	0.98	0.0095	0.115	0.023	2.872	7.502
Arsenic	38	0.0255	0.005	0.0137	0.006	0.153	-1.983
Barium	40	0.93	0.019	0.122	0.039	2.986	8.315
Calcium	46	214	3.76	60.7	59.22	1.836	5.870
Iron	48	83	0.0045	10.57	2.25	2.345	6.624
Magnesium	46	58	0.89	22.3	19.46	0.765	0.315
Manganese	48	4.5	0.004	0.53	0.381	3.359	12.766
Potassium	46	14	2.55	6.41	6.185	0.810	0.619
Sodium	48	612	6.93	224	203.5	0.524	-0.924

* $\mu\text{S/cm}$

**standard units

water samples, separated by individual coal seams. In addition to samples collected during this study, these statistical analyses also include 12 samples collected by the Kentucky Division of Abandoned Mine Lands from mine pools near the current study sites.

Figure 24a shows similarities in sample populations from the Hazard Nos. 4, 5A, and 7 seams, but significant differences between those seams and the Manchester and Upper Elkhorn No. 3 seams. The latter two seams are similar in TDS, but are significantly higher than the other seams. Figure 24b shows that the Upper Elkhorn No. 3 samples are significantly higher in sulfate than the other seams, helping to explain the higher Upper Elkhorn No. 3 TDS shown in Figure 24a. The Manchester seam is lower in sulfate than the other seams. Figure 24c shows that the Manchester samples have significantly higher sodium concentrations than the other seams, which may account for the higher TDS values for the Manchester seam shown in Figure 24a.

Figure 25 is a series of box-and-whiskers plots for mine-water samples, separated by the sample sites' position with respect to local drainage. Figure 25a shows results for TDS for above- and below-drainage mines, and indicates that below-drainage mines tend to be slightly higher in TDS concentration. This is likely because below-drainage mines are more stagnant than above-drainage mines, leading to longer residence times

and more rock-water interactions, and less flushing by fresher recharge water. Figure 25b is a box-and-whiskers plot for sulfate with respect to drainage position. This plot shows that above- and below-drainage samples show no statistically significant differences between the populations. Sulfate concentrations for both settings have a median value near 300 mg/L, indicating that regardless of position with respect to drainage, dissolution of pyritic minerals is a dominant reaction.

Figure 25c is a box-and-whiskers plot for pH with respect to drainage position. This plot shows a statistically significant difference between the two populations: below-drainage pH values are higher than for those above drainage. The lower pH in above-drainage samples is because of increased reactions with carbon dioxide. Carbonate speciation and pH are interdependent; carbonic acid (H_2CO_3) activity produces lower-pH waters, whereas bicarbonate activity drives pH into the 7 to 9 range (Morel, 1983). In the above-drainage settings, recharge water reacts with soil and atmospheric CO_2 to increase carbonic acid concentration, which lowers pH values. As this shallow groundwater flows deeper, water-rock interaction consumes the acid and produces a water higher in bicarbonate content, raising pH values. This natural evolution of groundwater is supported by comparing Figure 25c with Figure 25d, a box-and-whisker plot of bicarbonate relative to drain-

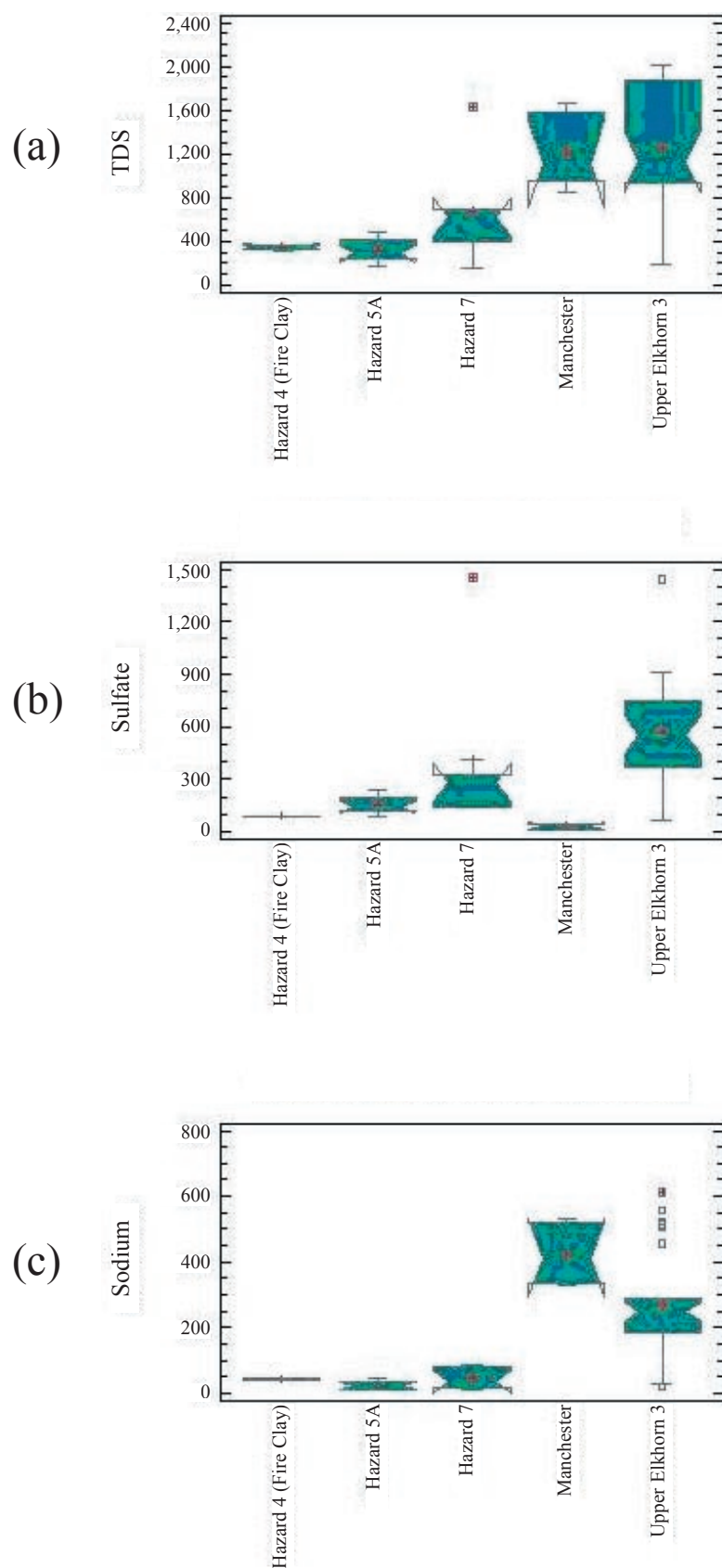


Figure 24. Distribution of TDS, sulfate, and sodium values separated by coal seam.

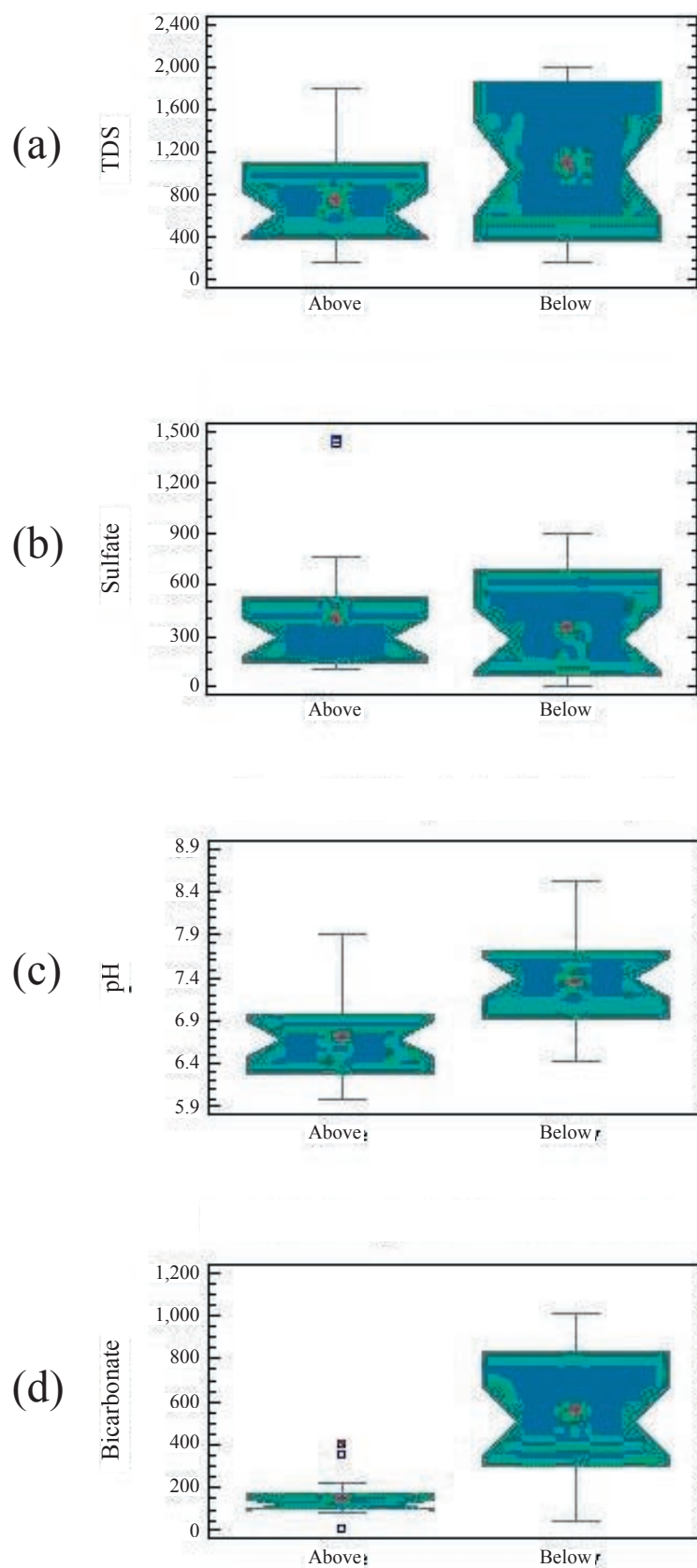


Figure 25. Distribution of mine-water analyses of TDS, sulfate, pH, and bicarbonate relative to being above or below local drainage.

age position. Comparison reveals that below-drainage samples generally contain higher concentrations of bicarbonate and, concomitantly, higher pH values than above-drainage samples.

Temporal Variation. Samples collected from abandoned deep mines during this study were generally not collected with adequate frequency or duration to allow for significant discussion of temporal water-quality trends. Quality of water produced by coal mines has been mostly predicted using various acid-base accounting methods based on evaluation of overburden strata (Caruccio, 1967; Caruccio and Ferm, 1974; diPretoro and Rauch, 1988; Brady and Cravotta, 1992). Younger (2000) presented a predictive empirical model for mine-water quality using data from 81 mine-water discharges in the Westphalian (i.e., Pennsylvanian) coal measures of central Scotland, northern England, and southern Wales. Much of Younger's model concerns the formation and subsequent flushing of acid-generating salts described by Bayless and Olyphant (1993). Acid-generating salts are formed during underground mining when pyrite oxidation in water-sparse areas forms intermediate solid phases (Cravotta, 1994), mostly ferrous/ferric hydroxyl-sulfate evaporites (Bayless and Olyphant, 1993; Younger, 2000) such as melanterite ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$). After mining has ceased, and dewatering of the mine has stopped, mines below drainage will eventually flood. As water inundates the mine voids, the readily soluble acid-generating salts release dissolved iron, sulfate, and acidity. As water continues to move through the mine voids, the ions and acidity released by the acid-generating salts will be flushed out, there-

fore decreasing with time from the point of inundation (Younger, 2000).

Figure 26 is a pair of time-series graphs depicting TDS values over time. In these graphs, time refers to the estimated time since the closure and subsequent flooding of the sampled mines. Figure 26a plots a linear-regression model describing the relationship between TDS and time. The resultant P-value from the analysis of variance is 0.0019, indicating a statistically significant relationship at the 99 percent confidence level. The resulting R^2 value of 19.82 indicates that the model explains less than 20 percent of the displayed variability. The low R^2 value is likely because TDS data are not normally distributed. Distribution normality can

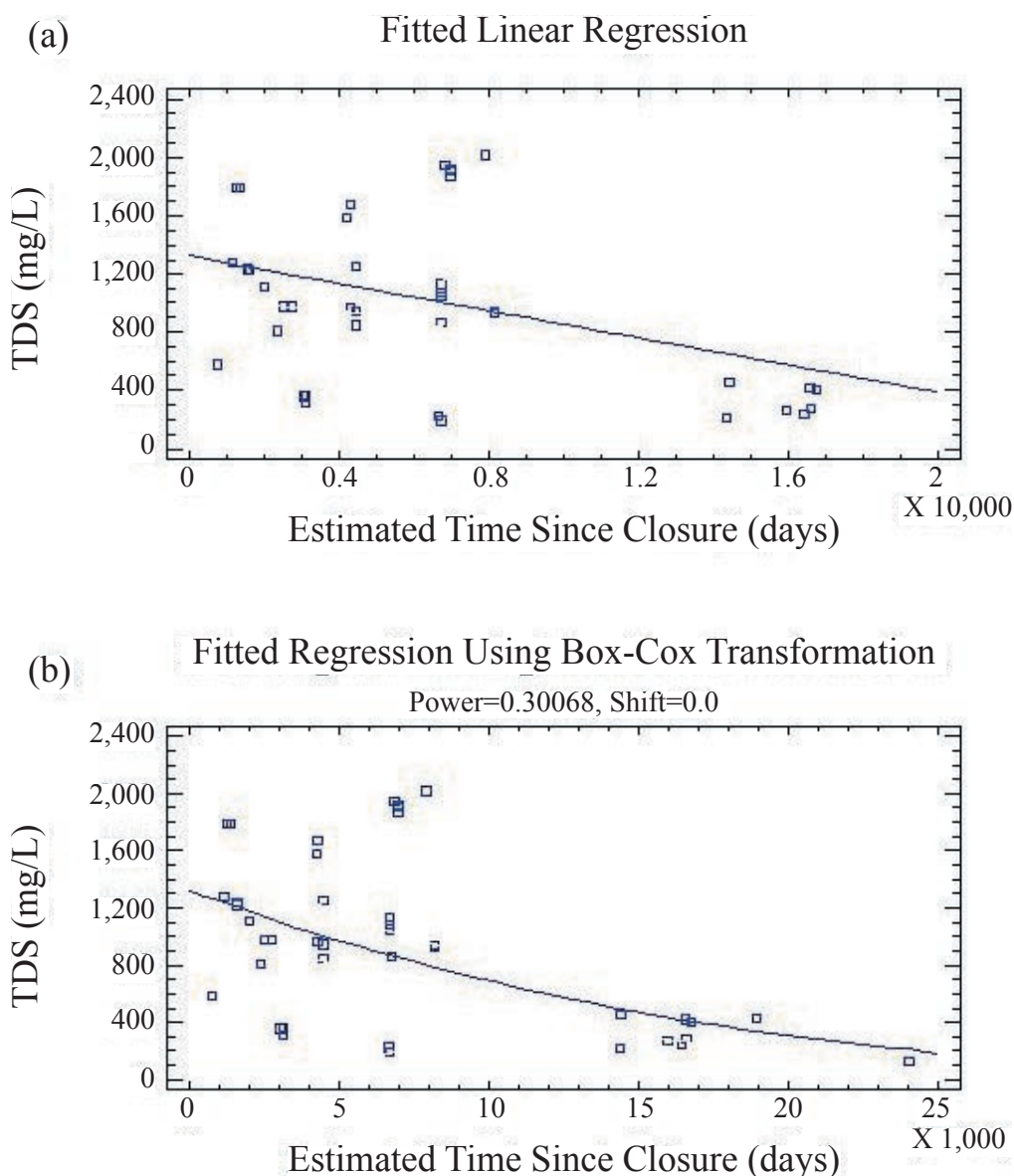


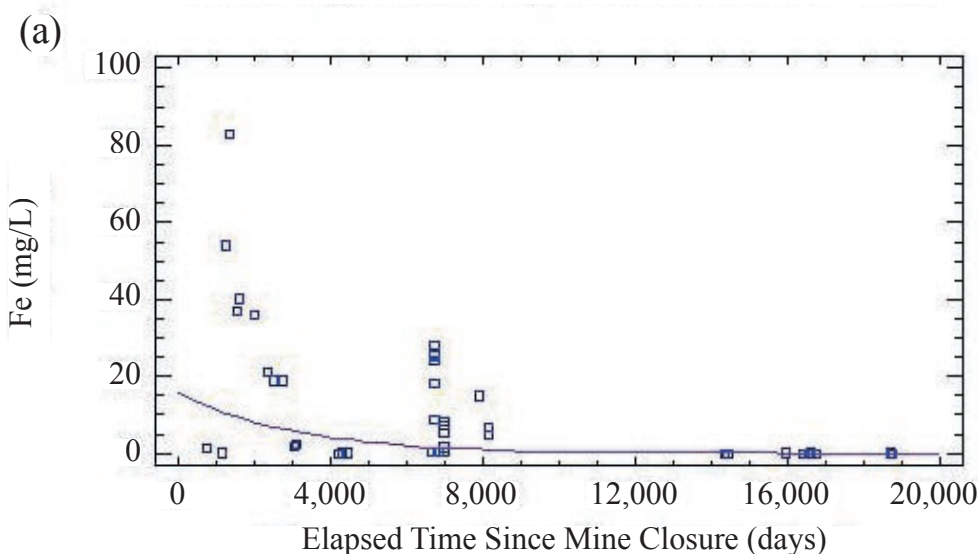
Figure 26. TDS concentrations versus. estimated time since mine closure showing (a) linear regression model and (b) Box-Cox transformation model.

be approximated by applying a Box-Cox transformation (Box and Cox, 1964) to the data. Figure 26b is a plot of the transformed TDS data over time, along with a fitted-regression model. In this case, the R^2 value is increased to 27.68, indicating that the model explains 28 percent of the variation. Although the transformed data still do not produce a regression with a high R^2 value, there is a statistically significant decreasing relationship between TDS and time at the 99 percent confidence level. The decrease in TDS over time is likely related to the flushing of acid-generating salts after inundation of the mine works.

Younger (2000) demonstrated the flushing of acid-generating salts using dissolved iron concentrations as an indicator of dissolution of acid-generating salts. Figure 27a is a time-series plot of Box-Cox-transformed iron data and a fitted-regression model. The resultant P-value is less than 0.01, indicating a statistically significant relationship (confidence level=99 percent). The R^2 value of 43.87 indicates the model explains 43.9 percent of the variation. Figure 27a uses all data collected during this study, and therefore may be skewed by the wide variation of iron concentrations between study sites, all of which were sampled at a wide range of times relative to mine closure. One sample location, the Polly Portal in Letcher County, was first sampled after mine closure, but prior to complete flooding of the mine. Figure 27b is a time-series plot of the Box-Cox-transformed data from the Polly site. The P-value calculated for the fitted regression indicates a significant relationship (confidence level=99 percent), and the R^2 value indicates that the model explains 91.7 percent of the variation. Figure 27b illustrates the dissolution and subsequent flushing of acid-generating salts after mine

inundation. The peak concentrations are controlled by the availability of acid-generating salts, the volume of the mined area, and the rate of recharge or flushing (Younger, 1997). As iron concentrations decrease with time, they asymptotically approach a lower, long-term level that is no longer controlled by acid-generating salts, but by water-rock reactions and the ongoing production of acidity next to the water table (Younger, 2000).

Fitted Regression Using Box-Cox Transformation



Fitted Regression Using Box-Cox Transformation

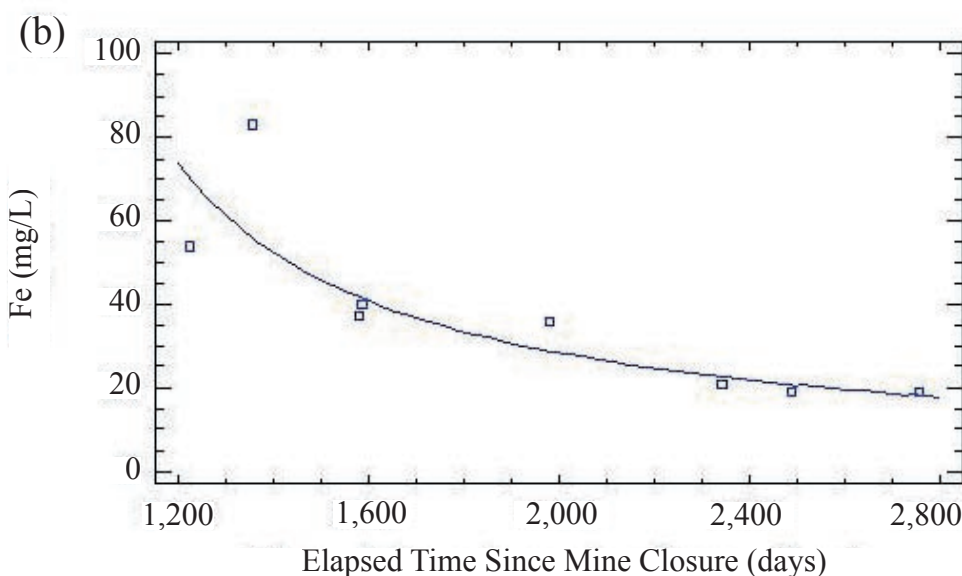


Figure 27. Time-series graphs of dissolved iron concentrations versus estimated time since mine closure for (a) all samples collected and (b) samples from Polly location.

Variations observed in the above analysis are expected, because of the lack of available data concerning flooding rates of closed mines. Mine closure dates are officially documented; however, mine flooding dates are not documented, and are certainly not the same as closure dates. Because most modern below-drainage mining is done downdip, normally the last area to be mined is the lowest. Thus, when mining is completed and dewatering stops, the first area to be flooded is also the last to be mined. Therefore, there may be several to many years' difference between the date of mining for an updip section of a mine and the date that section becomes flooded. There may also be a significant lag time between when dewatering stops and flooding occurs.

Summary

Potential use of abandoned underground coal mines as water supplies for municipal, industrial, agricultural, or domestic purposes depends on the volume of groundwater in storage, recharge rate, and water quality. To evaluate these factors, the user must consider the intended use of the water, water-quality requirements, and water availability. For example, a mine that produces a sustainable quantity of 1.5 Mgal/day but with elevated sulfate and iron concentrations may not be deemed suitable for a municipal water system. Even though the quantity may more than satisfy the design needs of the municipality, the costs of water treatment may be too great. That same source may be suitable for industrial cooling purposes, however, regardless of drinking-water quality issues.

Abandoned deep mines can often give municipalities the ability to draw water out of storage during periods when peak demand may be greater than sustainable supply from a primary source. There may be cases, however, where during dry seasons, deep mines show net losses in storage because of overwithdrawal or lack of recharge. A comprehensive understanding of seasonal changes in recharge, discharge, and storage volume is necessary before committing to a flooded deep mine as a primary or secondary source.

This study demonstrates that water quality in abandoned deep mines can be quite variable. Water-quality characteristics vary from mine to mine because of the position of the mine within the groundwater flow system, the mineralogy of the coal seam mined and the surrounding bedrock, and the time elapsed since the mine was flooded. Based on TDS, which ranged from 194 to 2,016 $\mu\text{S}/\text{cm}$, coal mines in the Manchester and Upper Elkhorn No. 3 coals produced the poorest water quality. In the study area, these seams were mined below the elevation of local drainage. The increase in TDS

is a result of increased mineralization of groundwater caused by relatively slow movement and increased age of the water in the distal ends of the groundwater flow system.

Other factors to consider regarding water quality of below-drainage mines is the length of time since closure and subsequent flooding of the mine. These factors are important because the reduction of acid-generating salts depends on the amount of time available for flushing. Similarly, the extent of flushing also depends on the rate of freshwater recharge through the mine.

For the above reasons, quality should be analyzed for each potential water source, even within a given mine. Water-quality monitoring must include sampling and analysis during water withdrawal to identify any changes in quality associated with induced mobility of otherwise slow-moving to stagnant water within a mine.

Water quantity from abandoned deep mines varies greatly, depending on many variables that control flooded volume of and recharge to the mine. Major variables controlling groundwater discharge from a mine are the surface area overlying the mine, the position of the mine within the local and regional groundwater systems, and the structural geology of the site, which determines how readily groundwater is able to drain from the mine, if at all. Recharge rates range from 120,000 to 1,230,000 gal/day; however, some deep mines show net losses in storage because of lack of recharge during drought periods.

This study demonstrates that water quality and quantity in abandoned deep mines is suitable for water supplies. Both quantity and quality are variable between mines, however. Variations can be attributed to geologic controls, physical setting, the age of the mine, and the rate of flushing. Therefore, quality and quantity must be analyzed for each potential water source. Measurements must include sampling water quality during water extraction to identify any changes in quality associated with induced mobility of otherwise slow-moving or stagnant water, and measuring groundwater fluctuation in mines during production tests to determine rate of groundwater recharge to the mine system.

Water-quality analyses used for this report can be found in Webb and others (2006).

Acknowledgments

Partial funding for this study was provided by the Kentucky Infrastructure Authority. Cooperation from local and county governments, mine owners, landowners, and the Kentucky Rural Water Association was essential and appreciated.

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Appendix A: Water-Quality Analyses from the Sand Lick Site (mg/L).

Parameter (mg/L)	SNDLK001 (9/11/97)	SNDLK002 11/5/97, 19:00	SNDLK003 11/6/97, 09:00	SNDLK004 11/6/97, 18:00	SNDLK005 11/7/97, 12:00	SNDLK006 11/8/97, 12:00	SLFST001 11/14/97, 9:00
Acidity as CaCO ₃	—	22	72	75	52	81	64
Alkalinity as CaCO ₃	100	120	273	280	280	286	332
HCO ₃	122	146	333	341	342	349	405
Cond.*	320	478	1,638	1,626	1,567	1,528	1,311
Hardness	117	160	448	442	420	394	330
Temp (°F)	62.4	57.7	55.4	55.8	55.6	56.8	58.3
TSS	16	17	28	24	18	5	13
TDS	220	194	1,134	1,130	1,076	1,048	866
PCB's	—	—	—	—	—	< MDL†	—
Pesticides	—	—	—	—	—	< MDL†	—
pH**	6.81	6.45	6.53	6.53	6.43	6.58	6.37
NO ₃	0.2	0.9	0.3	0.1	0.1	< 0.1	< 0.1
SO ₄	65.2	106	557	549	569	535	370
Fl	0.12	0.14	0.31	0.3	0.3	0.29	0.26
Br	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0
Cl	1.5	1.9	6.1	6	6	5.9	5.3
PO ₄	—	—	—	—	—	—	—
	Dissolved Total	Dissolved Total	Dissolved Total	Dissolved Total	Dissolved Total	Dissolved Total	Dissolved Total
Al	< 0.019 < 0.019	< 0.019 < 0.019	< 0.019 < 0.004	< 0.019 < 0.004	< 0.019 < 0.019	< 0.019 < 0.004	< 0.019 < 0.004
Sb	< 0.051 < 0.051	< 0.051 < 0.051	< 0.051 < 0.051	< 0.051 < 0.051	< 0.051 < 0.051	< 0.051 < 0.051	< 0.051 < 0.051
As	< 0.050 < 0.050	< 0.050 < 0.050	< 0.050 < 0.050	< 0.050 < 0.050	< 0.050 < 0.050	< 0.050 < 0.050	< 0.050 < 0.050
Ba	0.0508 0.0458	0.0634 0.0574	0.0269 0.0242	0.0220 0.0236	0.0264 0.0235	0.0256 0.023	0.0942 0.0376
Be	< 0.0024 < 0.0024	< 0.0024 < 0.0024	< 0.0024 < 0.0024	< 0.0024 < 0.0024	< 0.0024 < 0.0024	< 0.0024 < 0.0024	< 0.0024 < 0.0024
B	< 0.023 < 0.023	< 0.023 < 0.023	0.063 < 0.023	< 0.023 0.07	< 0.023 0.059	< 0.023 0.05	< 0.023 < 0.023
Cd	< 0.006 < 0.006	< 0.006 < 0.006	< 0.006 < 0.006	< 0.006 < 0.006	< 0.006 0.007	< 0.006 < 0.006	< 0.006 < 0.006
Ca	28 27.7	42.5 38.5	84.8 115	81.4 111	91 103	89.4 95	75.2 77.2
Cr	< 0.008 < 0.008	< 0.008 < 0.008	< 0.008 < 0.008	< 0.008 < 0.008	< 0.008 < 0.008	< 0.008 < 0.008	< 0.008 < 0.008
Co	< 0.012 < 0.012	< 0.012 < 0.012	< 0.012 < 0.012	< 0.012 < 0.012	< 0.012 < 0.012	< 0.012 < 0.012	< 0.012 0.017
Cu	< 0.007 < 0.007	< 0.007 < 0.007	< 0.007 < 0.007	0.012 < 0.007	< 0.007 < 0.007	< 0.007 < 0.007	< 0.007 < 0.007
Au	< 0.012 < 0.012	< 0.012 < 0.012	< 0.012 < 0.012	< 0.012 < 0.012	< 0.012 0.013	< 0.012 < 0.012	< 0.012 < 0.012
Fe	0.686 4.73	18.2 16.8	28 32.1	25.2 30.5	25.7 26.5	24.3 23.2	8.64 10.1
Pb	< 0.071 < 0.071	< 0.071 < 0.071	< 0.071 < 0.071	< 0.071 < 0.071	< 0.071 < 0.071	< 0.071 < 0.071	< 0.071 < 0.071
Li	< 0.003 < 0.003	0.011 0.009	0.074 0.085	0.069 0.083	0.082 0.079	0.085 0.078	0.072 0.072
Mg	10.9 10.8	17 16.1	41.9 48.2	40.4 48.2	46.4 46.6	45.3 43.1	33.2 34.4
Mn	0.382 0.414	0.708 0.656	1.11 1.29	1.06 1.29	1.24 1.27	1.22 1.16	1.15 1.21
Ni	< 0.049 < 0.049	< 0.049 < 0.049	< 0.049 < 0.049	< 0.049 < 0.049	< 0.049 < 0.049	< 0.049 < 0.049	< 0.049 < 0.049
P	< 0.121 0.213	0.16 < 0.121	0.065 < 0.121	< 0.121 < 0.121	< 0.121 < 0.121	< 0.121 < 0.121	< 0.121 < 0.121

Parameter (mg/L)	SNDLK001 (9/11/97)	SNDLK002 11/5/97, 19:00	SNDLK003 11/6/97, 09:00	SNDLK004 11/6/97, 18:00	SNDLK005 11/7/97, 12:00	SNDLK006 11/8/97, 12:00	SLFST001 11/14/97, 9:00
	Dissolved Total	Dissolved Total	Dissolved Total	DissolvedTotal	DissolvedTotal	Dissolved Total	Dissolved Total
K	3.53 3.54	4.1 3.94	6.62 7.3	6.33 7.46	6.82 6.85	6.96 6.6	5.12 5.03
Se	< 0.129 < 0.129	< 0.129 < 0.129	< 0.129 < 0.129	< 0.129 < 0.129	< 0.129 0.03	< 0.129 < 0.129	< 0.129 < 0.129
Si	3.97 < 0.034	6.78 6.41	9.09 10.2	8.78 10.1	9.52 9.64	9.55 9.1	7.58 7.81
Ag	< 0.006 < 0.006	< 0.006 < 0.006	< 0.006 < 0.006	< 0.006 < 0.006	< 0.006 < 0.006	< 0.006 < 0.006	< 0.006 < 0.006
Na	19.6 19.4	48.4 45.6	183 206	174 203	199 –	205 192	172 172
Sr	0.392 0.39	0.821 0.744	3.28 3.7	3.15 3.73	3.64 3.61	3.62 3.39	3.33 3.46
S	20.1 19.9	47.6 42.8	158 187	150 183	168 –	163 158	105 109
Tl	< 0.068 < 0.068	< 0.068 < 0.068	< 0.068 < 0.068	< 0.068 < 0.068	< 0.068 0.188	< 0.068 0.184	< 0.068 < 0.068
Sn	< 0.426 < 0.426	< 0.426 < 0.426	< 0.426 < 0.426	< 0.426 < 0.426	< 0.426 < 0.426	< 0.426 < 0.426	< 0.426 < 0.426
V	< 0.004 < 0.004	< 0.004 < 0.004	< 0.004 < 0.004	< 0.004 < 0.004	< 0.004 < 0.004	< 0.004 < 0.004	< 0.004 < 0.004
Zn	< 0.004 < 0.004	0.244 < 0.004	< 0.004 < 0.004	< 0.004 < 0.004	< 0.004 < 0.004	0.242 < 0.004	0.242 < 0.004

*µS/cm

**standard pH units

†method detection limit

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