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Technical Communication

The Influence of Coal Quality Variation on Utilization of Water from Abandoned Coal Mines as a Municipal Water Source

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Abstract. As population increases and high quality water becomes more difficult to obtain, many communities will seek alternative water supply sources. Some municipalities have realized that they have a reservoir of unexploited water readily available in abandoned underground coal mines. Analysis of the mine's history, the quality of the coal and water that reside within the mine, and knowledge of local hydrology, geology, and mine chemistry will provide communities with the information they need to determine the best mine sites to use.

Key words: Arsenic; lead; mercury; pyrite; water supply

Introduction

Population growth, industrial development, urbanization, and increased water consumption have contributed to an increasing scarcity of potable water. Traditional methods of providing water are sometimes inadequate, leaving many municipalities searching for alternative sources.

There are over 22,000 abandoned coal mines sites in the U.S. Many of these abandoned mines contain water of sufficient quality and quantity to be considered as sources for municipal supplies. Examples of successful use of flooded mines as public water supplies come from the states of West Virginia, Washington, Kentucky, Pennsylvania, and Virginia in the U.S., and internationally from the UK and Slovakia (Cicmanova et al. 1999).

Seventy communities in West Virginia use mine water for public supply, providing water for over 81,600 people (Hobba 1987; Pack 1992). For example, the city of Buckhannon, in northern Upshur County, WV, found that they could not provide enough water from the Buckhannon River during drought periods. The city investigated local mines and identified three that had the greatest potential for water production. During testing, it was discovered that these mines simply acted as conduits that drained and stored good quality groundwater. Subsequently, the decision was made to utilize the water (Hobba 1987). Similarly, Kentucky has several communities obtaining water from coal mines (Cumbie 2001) and Greenwood, Arkansas is currently testing water from local mines to determine the feasibility of pumping it for municipal use (Brahana and Varnell 2003).

Using abandoned coal mines as a water source can have many benefits. The mine is a ready-made reservoir and requires minimal infrastructure construction. Most of the utilities that use water from mines simply pump the water from wells drilled into the pooled water and then run it through their current treatment plant. Since it is covered, it is easier to protect the well from contamination from surface sources and is not affected by algae blooms, overturn, or other problems associated with climatic changes. Most important though is the low cost. Greenwood, Arkansas expects savings in the next decade to exceed $20 million if they can utilize mine water (Brahana and Varnell 2003).

The composition of coal is highly variable, a product of the chemistry, the biota, the geology, and the conditions under which it was formed and modified. Of special concern are a small number of trace elements that have the potential to pose serious health hazards if the existing water treatment facilities are not prepared to test for and treat water containing these contaminants. This communication provides an overview of how and why trace metal concentrations vary in mine water, and some suggestions on choosing mines that may be appropriate as water supply reservoirs.

Methodology

An analysis of coal variation within the United States was conducted using a coal quality data base available from the U.S. Geological Survey (Bragg et al. 2003). This information was cross-referenced to a list of hazardous chemicals in the U.S. Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as the Superfund list, U.S. Environmental Protection Agency (EPA) water quality standards, data collected on coal mine water utilization in Greenwood, Arkansas, and to geochemical reactions known to occur in abandoned coal mines. These data were used to extrapolate the type of information that could be used by communities to make wise decisions concerning the use of mine water.

Results and Discussion

Sources of Variation

Trace elements occur within coal in very small amounts, generally <100 g/kg. These elements make up only a very small percentage of the coal yet can adversely impact the environment and pose a health hazard. The presence of trace elements is determined by many different factors, so that their concentrations in the coal and surrounding rock layers can vary greatly, even within a single coal seam.

Coal is formed from plant debris that has undergone chemical and physical changes induced by heat and pressure. It is composed of 60% to over 90% carbon (by volume) and a vast number of other elements. In addition to mineral matter associated with the plant tissue, inorganic material buried along with the plant mass and components that infiltrated into the mineral mass subsequently (during or after diagenesis) add to the trace metal components (Speight 1983).

Coal constituents vary according to the dominant type of vegetation from which they were formed (Valkovic 1983). Gymnosperms dominated the Jurassic and Cretaceous period; the coal formed from them is quite different in character and mineral constituents from coals that formed later from angiosperms. Within the same seam, coal formed from leaves differ greatly from that composed of more woody stem debris. Tables of mineral constituents within various plants can be obtained from Bouska (1981) and elsewhere.

The absorption of an element by a plant depends not only on the concentration of the element within the local soil but also on the associated elements present. Some toxic substances, such as lead, enter a plant by ionic substitution and are incorporated into the plant structure. These materials tend to accumulate in the leaves, wood, and bark and are subsequently found in the coal.

Factors other than the organic composition of the precursor plants also affect the coal. Weathered materials from the surrounding area were deposited in coal-forming swamps along with wind-blown contaminants from volcanic activity and other cataclysmic events. Ions were added by exchange with the clays and organic materials and additional elements were introduced into the coal by infiltrating groundwater (Valkovic 1983).

Elements are classified by their affinities to occur in minerals of a single group. Chalcophile elements (As, Cd, Cu, Hg, Pb, Sb, Se, and Zn) are found in combination with sulfur and are commonly found in pyrite and marcasite. Notably, arsenopyrite, or its amorphous phase (FeAsS) can form in sediments and be a sink for arsenic (Wood 1999). Lithophile elements occur along with silicon and include Al, Be, K, Na, Ti, Y, and Zr. These occur frequently in coal in clay minerals, and quartz. , Calcium, Fe, Mg, and Mn can often be found as carbonate minerals.

Trace Elements

CERCLA provides a priority list of hazardous substances, based on a combination of frequency, toxicity, and the potential for human exposure. This algorithm utilizes data compiled by the U.S. Agency for Toxic Substances and Disease Registry (ATSDR), (ATSDR Information Center 2001). The top three elements on the CERCLA list occur in coal mines: arsenic, lead, and mercury. The maximum permissible contaminant level allowable in public drinking water after treatment is 10 µg (ppb) for arsenic, 2 µg (ppb) for mercury, and 0 (zero) µg (ppb) for lead (EPA 2003)

A public drinking water supply (raw water) must have minimal concentrations of any harmful or toxic element to ensure the safety of the population. Treatment procedures can remove varying amounts of these trace elements but must ensure that they meet the requirements set forth by the U.S. Safe Drinking Water Act. This entails a great responsibility on the municipalities in selecting a water source.

Bragg et al. (2003) provides site by site analyses of the constituents found in coal formations throughout the U.S. The data base provides a sample number, sample location, and major constituents in ppm, minor constituents in ppm, oxide concentration, sulfur concentration, as well as a quality evaluation of the coal found in each location. Accessing this site can provide valuable information about local sites and also allows comparison between regions. For example, 27 data points from six seams within the Hartshorne formation in the Arkansas River Valley were plotted in Figure 1, and demonstrate the variability of arsenic within the region. Arsenic content ranged from <5 ppm to >60 ppm. Similar variability exists in WV coal, where reported arsenic concentrations varied from .080 to more than 727 ppm, with a standard deviation of 38.52 ppm.

Representative samples from three geographical regions demonstrate regional differences in concentration of all three of the trace elements selected (Figure 2). Coal fields in WV had higher concentrations of each of the selected elements but all three coal fields demonstrated marked variability. As expected (Kresse 2003), there appears to be a correlation between arsenic and pyrite content.

Pyrite oxidizes relatively rapidly, releasing acidity into the waters draining through the mine. As the pyrite breaks down, other minerals that were present in the pyrite matrix are released. Arsenic, with its affinity for sulfur, is often released in this manner; trace amounts of mercury and lead are sometimes released this way also. Arsenic concentrations have been linked in several studies to the oxidation of sulfide minerals and examples of widespread areas of elevated As in ground water are often correlated to the degree to which the area was mined.

The acidic water, in turn, reacts with the other minerals present; some elements are dissolved, some materials that were absorbed into the clay matrix of shales are released, and some metals that are present in solution may be adsorbed by the clay minerals that remain. Of particular interest is what is occurring with the trace elements, especially arsenic. The arsenic ions exist most commonly as As^{+3} (arsenite) and As^{+5} (arsenate). Arsenite is generally more toxic to humans and is much more soluble in water than arsenate. Conditions that affect As valence includes pH, redox, presence of competing ions at sorption sites, microbial activity, and adsorption-desorption reactions. Arsenate generally predominates under oxidizing conditions, arsenite under reducing conditions. Between pH 3-7, negatively charged ions of $H_2AsO_4^-$ dominate; between pH 7-11, $HAsO_4^{2-}$ dominates and H_3AsO_3 is present as an uncharged ion.

Recent studies have shown that Mn oxides can cause rapid oxidation of both arsenite and arsenate ions (Kresse 2003). Both forms of arsenic adsorb strongly to iron-oxide surfaces but arsenate has a tendency to desorb as pH increases as the negative net charge of the iron oxide repels the negatively charged arsenate. Arsenite adsorption also tends to decrease as pH increases. Precipitation of sulfide minerals, which can occur through bacterial sulfate reduction, removes arsenic from water (Wood 1999).

Coal Mine Water

Water that initially fills a mine that contains pyrite is generally high in acidity and mineral content due to the first-time flushing of acid products (Demchak et al. 2001). The highest concentration of iron and other contaminants occurs as such water flows out from the mine. The amount of oxygen present, the distribution of pyrite, the recharge rate, and the activity of iron oxidizing bacteria control the subsequent rate of acid production. Pyrite oxidation will continue if the mine is only partially flooded but the amount of pyrite is finite and the iron content will eventually tend to decrease with the continued passage of water through the same strata (Robb 1994). If the mine is completely inundated, oxygen is limiting and the water quality will recover much quicker.

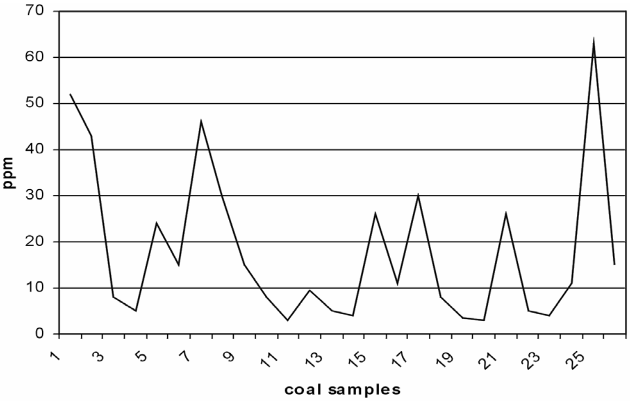

Figure 1. Variablity in arsenic content in coal samples from various seams of the Arkansas River Valley, plotted from west to east (data from Bragg et al. 2003)

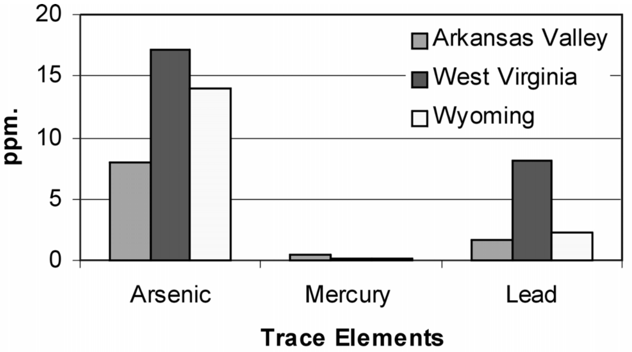

Figure 2. Trace elements in three U.S. coal fields, (data from Bragg et al. 2003)

The earliest model for the length of time required for mine water to return to near normal pH assumed that iron concentrations would decrease 50% each time the mine water was replenished. This is a generalization, but has some merit based on observation of coal mines in England. Water that replaces the original mine water has diminished concentrations of both acid and mineral content (Demchak et al. 2001)

Mining regions that contain calcium and magnesium carbonate benefit from the buffering action provided by these minerals. Derbyshire, England has experienced extensive mining of galena and associated minerals included pyrite, sphalerite, and fluoride. Water passing through these old mines is used for drinking water today. The high alkalinity suppresses the solubility of the metals and the calcite lowers the fluoride concentrations (Banks et al. 1997).

Research has been conducted in Greenwood, Arkansas over the past two years to determine the feasibility of using two abandoned coal mines near the city as an additional water source to augment water from the city reservoir. A total of 32 water quality tests were conducted at nine sites that had been identified as being connected to the water within the mines. Estimates place the amount of water within the void space of the two mines as close to 2 billion liters (over 500 million gallons). Analysis indicated elevated concentrations of several ions but none at levels that were deemed unhealthy with treatment. Lead (0.04 mg/L), Hg (<0.0002 mg/L), and As (<0.04 mg/L) were within the U.S. EPA guidelines, even without treatment (EPA 2003).

Concentrations of trace elements within the coal at Greenwood are shown in Figure 3. There are several explanations for the discrepancies noted between the concentrations in the coal and water samples. The most obvious explanation is that there is tremendous dilution from the volume of water that flooded into the void space left by coal extraction.

The coal mines located in Greenwood, Arkansas have been abandoned since flooding in 1928. The mines are completely filled with water, with outflow occurring at strip pits that were constructed at a later time and that crossed the main shafts of the underground mines. Water exits from the mine shafts into the open pits and eventually flows into a local stream. Outflow from the mines are variable but the mine pools must have been completely replaced several times over. The pH of the water exiting the mine is between 7 and 8. The bicarbonate levels indicate that calcium carbonate within the rock surrounding the mined area is buffering the water.

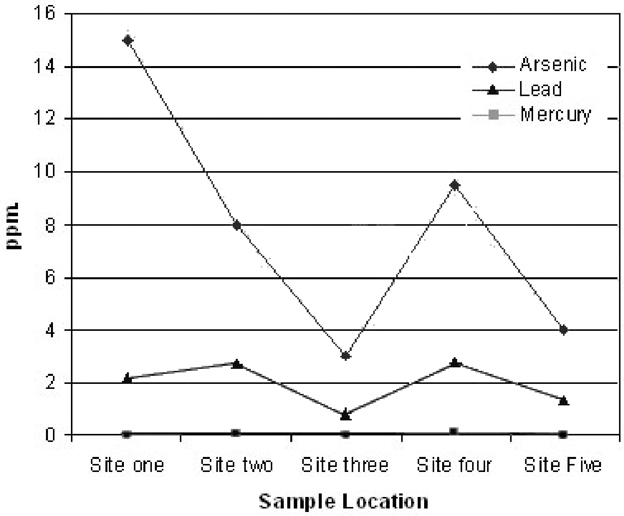

Figure 3. Trace elements from the Greenwood, Arkansas coal seam (data from Bragg et al. 2003)

Conclusions

Each coal mine, and the water within it, is a product of the local environment. Geology, precipitation, local land morphology, age of the mine, type of coal, and many other factors determine the quantity and quality of the water. Even though each coal mine is different, there are some general trends and practices that can be followed in making an informed choice concerning utilizing water from a coal mine.

1. If possible, choose mines that have been completely inundated for a long time. Extensive research conducted buffering action of indicates that in inundated mines, pH increases, conductivity decreases, and concentrations of sulfate, iron, manganese, etc. decrease with time (Demchak et al. 2001; Robb 1994) These same studies indicate that the decrease is exponential and that concentrations of contaminants, especially those from pyrite, typically decrease ≈50% during the time period required for the mine to recharge with "fresh" water.

2. Water quality will probably be better in mines that contain low pyrite concentrations (Robb 1994). Pyrite content of coal varies by location.

3. Mines that are completely or partially sealed from the atmosphere afford fewer problems. The presence of oxygen and the activity of iron-oxidizing bacteria accelerate acid generation and the dissolution of contaminants (Singer and Stumm 1970). In contrast, underground voids that are open to the atmosphere or that have been partially surface mined are more likely to be contaminated. Sealed mines are also much easier to protect from contamination by surface activities unrelated to mining, though the possibility of unauthorized waste disposal into mine pools must be carefully investigated.

1. Mines that are buffered by carbonate minerals are likely to be less contaminated (Banks et al 1997).

2. Water quality can change over time as coal pillars left from room and pillar mining degrade or collapse over time, exposing more pyrite to oxygen and water. This is not likely to be a problem in inundated mines.

6. Develop a system to monitor the raw water on a regular basis so that potential problems can be detected in advance. Because some trace elements are harmful to health in extremely small quantities and because they are found in variable concentrations within coal, it is necessary to monitor the raw water supplies often and on a regular basis. Arsenic ions tend to desorb from iron oxides at elevated pH levels (Kresse and Fazio 2003). As a result, even when pH concentrations are elevated, testing for arsenic should continue.

7. Expect to increase the amount of treatment required by the water treatment plant when mine water is being used. Most water from mines will have elevated concentrations of both major and minor constituents. This is especially true during the initial pumping and use of the water. However, often the water has stratified into layers of water of varying quality, with higher quality water lying above poorer quality water (Brahana and Varnell 2003); water treatment costs can thus be radically affected by the depth of the water that is being pumped.

8. Public perception and support is a major factor to consider in using water from a coal mine. Although adequate sources for public water are very difficult to find in many communities, the public perception of using "dirty water" from the mine must be dealt with. In many regions, abandoned coal mines offer a viable alternative to meeting the water needs of a community, if the community is willing to consider this alternative.

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