# CHAPTER 7: MINE DRAINAGE PREDICTION, A SUMMARY OF CONCEPTS AND PROCESSES

**by**
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## INTRODUCTION

This chapter presents a summary of the key concepts and principles inherent in mine drainage prediction, and outlines a generalized approach to the assessment of coal mine drainage quality. Some issues that currently limit our ability to predict mine water quality and desired improvements are also discussed. The chapter is targeted mainly at water quality prediction from surface coal mines in humid climates. However, certain principles and practices can be applied to the analysis of underground coal mine water quality.

Mine drainage prediction is the integration of chemical, geologic, hydrologic, and biologic processes to arrive at an overall estimate of water quality after mining and reclamation are completed. Currently, the technology allows us to determine whether the water will be net alkaline or net acidic, where:

Net Alkalinity = Total alkalinity - Total acidity

The practical significance of selecting net alkalinity, rather than pH or metal concentration, lies in its fundamental control or influence on most other chemical properties of mine water. A net-alkaline water is capable of self-neutralizing inherent acid generating capacity, and buffering pH to circumneutral conditions, thereby limiting the activity of iron-oxidizing bacteria. In well aerated or oxidizing environments, the solubility of most metals is at a minimum at circumneutral pH. Treatment options are also controlled by the net alkalinity or net acidity of water. Extremely acidic waters may only be amenable to chemical treatment, while marginally acidic to alkaline water may be suited to various passive treatment technologies (Skousen et al., 1998). At the moment, prediction is qualitative, but as the science continues to advance, predictive capability should become progressively more refined and more quantitative.

Predicting the quality of mine drainage is not easy due to the amount and type of factors involved as well as the way the factors interact. In the simplest case, all components yield the same interpretation and the prediction can be made with a high degree of confidence. In marginal or complex sites, all components may not provide the same signals and the evaluator has to weigh certain factors more or less heavily to arrive at an assessment.

The evaluation process for mine drainage prediction includes analytical data and experiential information. Prediction of water quality is best achieved using a variety of tools. The classes of data and information evaluated directly or implicitly include:

- Qualitative and quantitative hydrologic data for surface and groundwater from mined and unmined areas;
- Geologic information, lithology, structure, and geochemistry;
- Results of past or equivalent mining; and
- Resource sensitivity.

Implicit in water quality and geochemical sampling is a requirement that the samples represent the system of interest. These data, collected at *representative* locations and times, are extrapolated to reach some final conclusion.

The remainder of this chapter is presented in three parts. First is a summary discussion of basic concepts that underlie the procedure of mine drainage prediction, taken in part, from other chapters of this report. Second is a generalized outline of the process of data analysis and interpretation to predict or estimate mine water quality. The chapter concludes with recommendations for improving our understanding and managing mine water impacts.

## GEOLOGIC PRINCIPLES

### Mineralogy

Mine drainage quality is influenced by the type, amount, and distribution of reactive minerals in contact with water. Two groups of minerals, sulfides and carbonates, largely control mine drainage quality even though they usually constitute only a few percent of the rock mass. Overburden analysis methods, discussed in previous chapters, are designed to quantify the amount of sulfide and carbonate present.

In coal mines, acid potential arises mostly from the sulfide mineral pyrite. In weathered rocks and soils, exchangeable acidity and metal sulfate minerals may also contribute to total acid production. Alkalinity is provided mostly by carbonate minerals. Of these, calcite and dolomite are the most important acid neutralizers. The mineral siderite is problematic for testing and interpretation. It initially provides neutralization, but subsequent iron hydrolysis produces acidity. The net neutralization from siderite is zero. Silicate minerals also provide some acid neutralization, but their rate of reaction is much slower than that of carbonates. Similarly, ion exchange reactions of acidic water with clays can also contribute alkalinity, but this only occurs when the strata are saturated. Small amounts of other elements are often contained in carbonates and can be released when the mineral dissolves. For example, a small percentage of manganese can substitute for iron in siderite.

### Paleoenvironment

The vertical and horizontal distribution of sulfides and carbonates in mine site overburden is a function of the paleoenvironment, or conditions under which the sediments were deposited and any alterations that occurred afterward. The sediments that formed these rocks were deposited in a variety of freshwater, brackish and marine environments, such as stream channels, bays, and shallow marine waters. In general, rocks formed in brackish water conditions contain higher levels of sulfides than marine or freshwater deposits. Paleoenvironment can result in large changes in rock type and chemistry over small horizontal distances. Brady et al. (1988) found both acid and alkaline water generated in five surface mines operating on the same seam in Fayette County, Pennsylvania. The mines were in close proximity to each other in the same watershed, but differed markedly in the amount of carbonate minerals and stratigraphy at each mine. The abrupt lateral changes were attributed to depositional history. The acid sites generally lacked calcareous

shales and contained a high percentage of sandstone overburden. Some concepts of paleoenvironment relevant to mine drainage prediction are reviewed in Chapter 2.

### Geologic Weathering

The Appalachian Plateau has been subjected to long term chemical and physical weathering. Chemical weathering in a humid climate removes the more soluble and reactive minerals, like carbonates and pyrite, from near-surface rocks and soils (Figure 2.7). The weathered zone, for mine drainage prediction purposes, is inert and has little capacity to either generate or neutralize acidity. Weathered materials are often weakly cemented or partially decomposed, and are often colored brown, yellow, or red. Weathering depth varies, but is often on the order of 20 feet in the Appalachians (Smith et al., 1974; 1976). Groundwater that circulates through the weathered zone contains low amounts of dissolved solids and alkalinity, reflecting the relative lack of soluble minerals in this zone.

Below the weathered zone, the rocks retain most of their original mineral assemblage, and may contain appreciable amounts of sulfides, carbonates or both. Groundwater circulating in this zone generally contains more dissolved solids. Example analyses of two ground waters from the weathered zone and deeper strata are shown in Table 7.1. The samples were taken from the Monongahela Group in northern West Virginia.

**Table 7.1.** Groundwater Quality from Overburden in the Weathered Zone and Deeper Strata (1)

| Sample Location | pH | Spec.Cond. | Alkalinity | Fe | Ca | Mg | Na | $SO_4$ | Cl |
|---|---|---|---|---|---|---|---|---|---|
| Weathered zone (15 feet deep) | 6.1 | 61 | 14.7 | 0.06 | 8.0 | 4.0 | 2.5 | 9.8 | 6.5 |
| Deep Strata (66 feet deep) | 7.1 | 431 | 124 | 0.08 | 55 | 27 | 7.8 | 78 | 10 |

(1) pH in standard units, specific conductance in umhos/cm, alkalinity in mg/L as CaCO3, all others in mg/L.

In this example, ground water from the weathered zone has low specific conductance, which indicates low dissolved solids content, and little alkalinity. Groundwater from deeper strata has much higher alkalinity and dissolved solids. The deeper water could add significant buffering to acidic water in surface mine backfills or as recharge to flooding underground mines. The weathered zone groundwater would have little impact on mine water chemistry.

## GEOCHEMICAL PRINCIPLES

The generation of acidity and alkalinity proceed at different rates and by different geochemical reactions. Pyrite oxidation involves the oxidation of both iron and sulfur and proceeds in four steps. The process is self-propagating, as shown in Figure 7.1, and as summarized in Rose and Cravotta (1998). It is catalyzed by iron-oxidizing bacteria and can proceed very rapidly.

Alkalinity production from carbonates is a dissolution reaction that depends on pH and the partial pressure of carbon dioxide ($pCO_2$). In general, lower pH and higher $pCO_2$ promote dissolution of carbonates and alkalinity production. Carbonate solubility is limited, however. Consequently, alkalinity concentrations

seldom exceed about 350 mg/L in surface mine waters, or more than about 600 mg/L in underground mine pool waters.

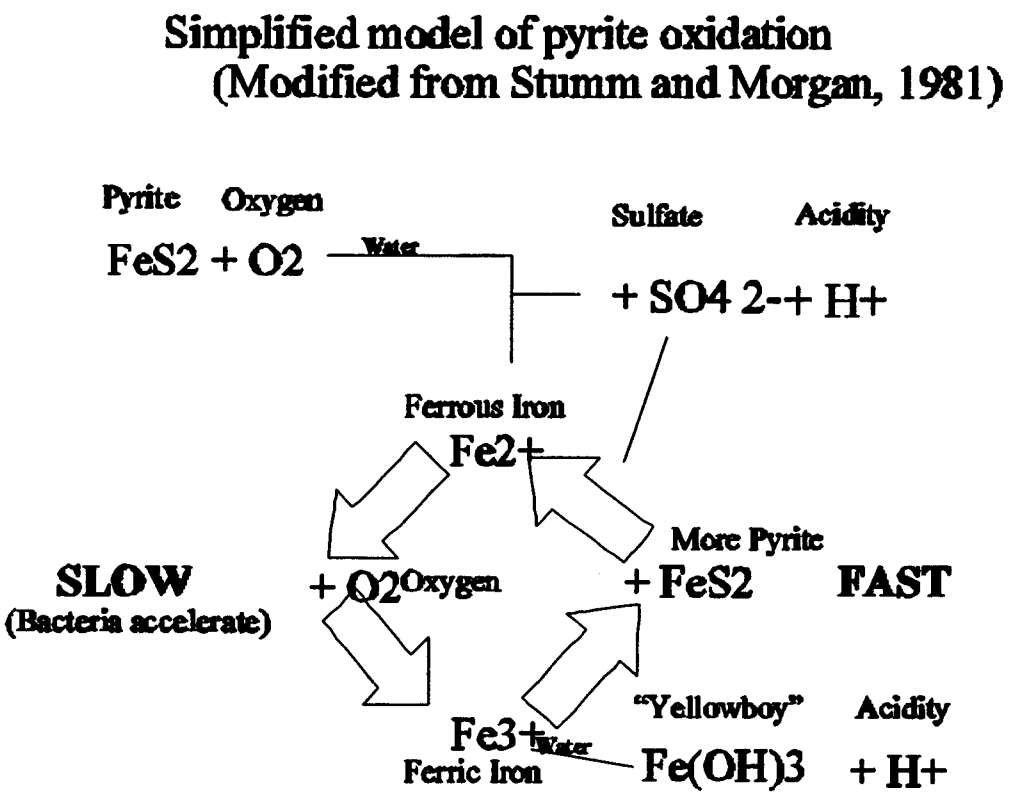



**Figure 7.1.** The fundamental mechanisms of pyrite oxidation.

Field validation studies of mine drainage and ABA have shown that an excess of neutralization potential compared to potential acidity is necessary to obtain alkaline drainage from surface mines (Chapters 2 and 4 of this book; Perry, 1998). How much pyrite or carbonate is needed to have significant capacity to generate acidity or alkalinity? In Pennsylvania, significant strata were defined by *threshold* values (Brady and Hornberger, 1990) for sulfur content and NP as: total sulfur content greater than 0.5%, and NP greater than 30 tons /1000 tons (3% $CaCO_3$ equivalent), with a fizz when treated with 10% hydrochloric acid. A later study of ABA and mine water quality in Pennsylvania (Brady et al., 1994; Perry and Brady, 1995) suggested that an average carbonate content of 1-3% (NP of 10-30 tons/1000 tons) can be sufficient to produce alkaline drainage. These criteria were developed based on experience with rocks in northern Appalachia in middle and Upper Pennsylvanian strata of the Allegheny, Conemaugh, Monongahela and Dunkard groups. These rocks generally contain higher levels of sulfides and carbonates than lower Pennsylvanian rocks. The lower Pennsylvanian rocks in central and southern Appalachians typically have low pyrite contents but also low carbonate contents. In the lower Pennsylvanian rocks, carbonate contents as little as 1% can be important sources of alkalinity and neutralization. The ADTI, after surveying the recent

literature and compiling our own field experience, recommend that one should assume that an NP of less than 10 tons/1000 tons will generate acid conditions and that an NP of greater than 21 tons/1000 tons will produce alkaline conditions. The modified ABA procedures recommended in Chapter 4 should, in the future, reduce that gray zone of 10-21 tons/1000 tons.

## HYDROLOGIC PRINCIPLES

### Net Recharge

The Appalachian and Midwestern coalfields lie in a humid continental climate with annual precipitation ranging from about 30 to 60 inches. Most of these coal-producing areas have at least 40 inches or more of precipitation. As a consequence, mine sites experience net recharge. The magnitude of recharge varies by location and topography; however, average or long-term recharge values have been developed. In the Appalachian region, recharge generally constitutes 20-30 % of annual precipitation. For example, Hobba (1984) estimates the average recharge within the Monongahela River basin of northern West Virginia is about 7 inches per year. This is equivalent to about 0.36 gallons per acre per minute (gpm/A) of infiltration. Callaghan et al. (1998) report somewhat higher recharge estimates for mining areas in Pennsylvania, ranging from 0.62 to 0.77 gpm/A.

Recharge rates for underground mines are controlled largely by overburden thickness with rates ranging from as much as 0.8gpm/A for mines under shallow cover (less than about 250 feet), to as low as 0.05 gpm/A or less under thick cover (Crichton, 1927; Stoner et al., 1987). In surface mine backfills, the infiltrating recharge is available to leach and mobilize soluble constituents. In underground mines, recharge eventually results in partial to complete flooding after closure.

### Groundwater Fracture Flow System

Appalachian surface mines are located within a groundwater flow system largely controlled by fractures and topography. In addition to tectonic fractures, fractures are naturally induced by geologic weathering and stress relief or unloading of overburden. An idealized section of ground water fracture flow in a hill that contains perched water bearing zones in dissected topography is shown in Figure 3.5. Most flow circulates within a few tens or hundreds of feet of the land surface. Overall, hilltops and slopes act as recharge areas, while foot slopes and valley floors are groundwater discharge areas. Surface mines intersect the fracture flow system. During mining, a mine usually acts as a groundwater sink, and groundwater flows into the mine from surrounding strata.

Larger regional aquifers underlie surface mines. These aquifers are slowly recharged by small amounts of deep infiltration. Ground water flow velocity is low and water usually has a very long residence time. A more detailed discussion of ground water flow and mining influences in the Appalachian Plateau is given by Callaghan et al. (1998) and chapter 3 of this report.

## Minespoil Aquifers

Mining and reclamation alters the hydrologic properties of rock strata. Mine spoil aquifers are usually 10 to 100 times more permeable than the intact bedrock from which they were derived (Hawkins, 1998a) and exhibit both porous media and conduit type flow. The dip of the pit floor or pavement often controls the direction of flow and buildup of a water table. In the Appalachian region, a thin perched aquifer typically develops in the spoil within about two years after backfilling is completed (Hawkins, 1998b; Razem, 1984). Water table thickness is usually less than ten feet and frequently discharges as *toe of spoil* seeps along the coal cropline. Most of the spoil mass is unsaturated. Nonetheless, ground water storage in spoil aquifers can be substantial. For example, one acre of mined land with a six foot thick saturated zone and a specific yield of 15% stores about 293,000 gallons of ground water.

Spoil recharge occurs from precipitation falling directly on the mined area and by lateral inflow from ground water in adjacent unmined rocks (Hawkins,1998a). Periodic infiltration leaches soluble materials into the aquifer. The spoil/highwall interface has been identified as an area where significant infiltration takes place. Consequently, special handling guidelines recommend placement of acid-forming material away from this interface. High infiltration zones can be used to add alkalinity to mine backfills (Carruccio and Geidel, 1984).

## Pre-mining Water Quality

Pre-mining ground water alkalinity concentrations are useful for confirming the presence of carbonates in mine site overburden. Chemical composition of groundwaters reflect the mineralogy of rocks and soils with which the water has been in contact. Brady (1998) suggests that alkalinity concentrations should exceed 50 mg/L from wells drilled in deeper strata if there are significant amounts of neutralizers present. On the other hand, alkalinity less than about 15 mg/l indicates a lack of neutralizers, or that the water sample represents flow through the weathered zone.

However, the presence or absence of significant amounts of pyrite cannot be determined from pre-mining water quality. Elevated sulfate concentrations should signify the presence of pyrite, since sulfate is a direct product of pyrite oxidation. In unmined ground water environments, pyrite is relatively stable and oxidizes only slowly. Data presented by Brady (1998) shows that sulfate concentrations are unrelated to the amount of pyrite in the overburden.

## Water Quality from Adjacent Mine Sites

Water quality from adjacent mines can be an excellent indicator of expected mine drainage with certain provisos, which include:

- Mining must be on the same seam with similar stratigraphy, topography, hydrology and mining methods;
- Material that could significantly change water chemistry has not been placed on the adjacent mine, unless the same treatment is proposed for the current mine; and
- The age of the adjacent mine site must be considered. Pollutant concentrations in surface mine discharges often peak within 5-10 years after mining and gradually decline thereafter, though at other

mines, the decline is much more gradual. Examination of an old mine site may not represent water quality that will be generated within the first few years of reclamation.

**Resource Sensitivity**

Mining can impact water and biota both on and off a mine site. Mine drainage prediction therefore includes an assessment of the resources that could be impacted and an evaluation of a margin of uncertainty in the prediction.

Sensitive resources include lightly buffered streams, waters that serve as sources for drinking water supply, waters with in-stream standards to protect sensitive biota, etc. Table 7.2 includes analyses from a lightly buffered stream sampled upstream and downstream of mine drainage entering the waterway. The upstream water has alkalinity of only 3 mg/L, showing virtually no capacity to neutralize any introduced acidity. Downstream of the mine water discharge, water quality is degraded and generally unsuited for most biota, recreational use or consumption due to acidity and metals concentrations. Even though the mine discharge was only a few percent of the total stream flow, it was sufficient to pollute a sensitive water resource. For such resources, the degree of uncertainty has to be small to prevent degradation.

At the other extreme are resources that are already degraded by past mining or other activities. Re-mining of old abandoned sites with current reclamation technology usually results in pollution abatement and water quality improvements (Hawkins, 1998b). In these instances, the risk to resources is low.

**Table 7.2**.(1) Water Quality of a Lightly Buffered Stream Upstream and Downstream of an Acidic Discharge

| Location | pH | Specific Conductance | Alkalinity | Total Acidity | Fe | Mn | Al | Sulfate |
|---|---|---|---|---|---|---|---|---|
| Upstream | 5.5 | 73 | 3 | 1.5 | 0.05 | 0.06 | 0.2 | 18 |
| Downstream | 3.7 | 449 | 0 | 97 | 9.4 | 2.8 | 9.4 | 151 |

(1)pH in standard units, specific conductance in umhos/cm@250C, alkalinity and acidity in mg/L $CaCO_3$ Eq, all others in mg/L.

## SAMPLING OVERBURDEN, SOILS, AND MINE SPOILS

The objectives of an overburden sampling program are to identify acid-and alkaline-forming materials present within the proposed mine area, show the vertical and horizontal distribution of these materials, and identify materials for special handling, alkaline addition, or topsoil substitutes. Exploratory drilling, by continuous core or cuttings from air rotary holes, is most commonly used to obtain samples. Sobek et al. (1978) provided an initial set of guidelines for sampling and characterizing overburden, spoils and minesoils. Most states have since refined their guidelines to reflect a minimum number of drillholes and sampling intervals. Different states follow different guidelines, though often there is a minimum of two drillholes recommended per site, with additional holes added as mine acreage increases. The state-by-state guidelines, based on experience with local geology, are reviewed in more detail in chapter 6. In most states,

a common approach is to add drillholes at a sampling density of about one per 40 acres. For areas known or suspected to exhibit variation in stratigraphy or geochemistry, tighter sampling patterns are necessary. However, Pennsylvania often doesn't require drillholes at all, relying more on information from adjacent mines. However, if no such information is available, or if for some reason it is not valid to use that information, they typically require 6 to 7 drillholes per 100 acres, which they find enables them to be quite accurate. ADTI participants agree with Pennsylvania that this is about the right number of drillholes when relevant adjacent site information is not available.

Drillholes for overburden sampling should intercept all the strata expected to be disturbed during surface mining. In hilly topography, this means placing some holes near the projected maximum highwall development. However, drillholes should also be spaced to provide distributed lateral coverage. Figure 7.2 is a plan of a 70 acre mine site which contained three overburden holes. Based on most guidelines, the number of drillholes was considered adequate for the mine size. All were located near maximum highwall height in one small area of the mine. Overburden analyses (ABA) of all three holes showed an abundance of calcareous shales with a weighted Net Neutralization Potential (NNP) of about 50 tons/1000 tons. On this basis, mine water was expected to be alkaline. Unfortunately, a major facies change occurred in the middle of the site, where the calcareous shales were replaced by sandstone containing some pyrite. The resulting mine water was acidic and is now routed to a passive treatment system. The lesson: it's not only how many sampling holes, but also where they are placed, which determines if one can use the data to accurately determine overburden properties.

Vertical sampling intervals are typically specified at three to five foot intervals in most state sampling recommendations (Chapter 6). Smaller intervals are useful for materials suspected of acid generating potential, such as rocks immediately above and below the coal, and "partings" within the seam. Thin rock units, with very high acid potential, can have a marked influence on mine water chemistry, especially if they are not recognized and are placed at random in the mine backfill. Inappropriate compositing can mask the potential effects of such units. See Table 6.6 and the accompanying discussion.

Another approach to overburden sampling uses the techniques of geostatistics. Geostatistics was originally developed to predict metal concentrations in ore bodies by examining the variation in analyses among spaced drillholes. The technique is not generally used by the coal mining industry, but could be useful for sites exhibiting complex lateral changes in geochemistry. From two such case studies, described in chapter 6, the reader can see that sampling programs need to be tailored to site geology and expected mining plans, and not driven by arbitrary fixed standards. Sites with complex geology, marginal or poor quality overburden quality or sensitive resources require close scrutiny. Conversely, sites with readily predictable geology and geochemistry and favorable overburden need not be sampled as intensively.

## OVERBURDEN TESTING AND INTRERPRETATION

Acid generation and neutralization of overburden samples are tested by one of two general methods: static or whole rock analysis, usually ABA, and kinetic or simulated weathering tests, including leaching tests in various column and chamber arrangements. These test methods, and some new techniques currently under development and evaluation, are described in detail in chapters 4 and 5 of this report.

**Acid/base Accounting**

Conventional ABA reports maximum values of potential acid generation and acid neutralization. These values probably represent the rock's behavior over a long period of chemical weathering. However, the test was not designed for, and gives no information about short term (a few years) chemical weathering rates. From extensive use of ABA on coal mines and base and precious metal mines over the last 20+ years, it has become apparent that an excess of neutralizers relative to acid potential is required to produce alkaline drainage. A summary of suggested criteria for interpreting ABA data for water quality prediction is shown in Table 7.3.

These criteria were developed over a variety of rock types and climates. It is not surprising that the criteria do not identify identical ranges or cutoff points for classifying samples. The reported values consistently show, however, that an excess of neutralizers over acid potential is needed to obtain alkaline drainage.

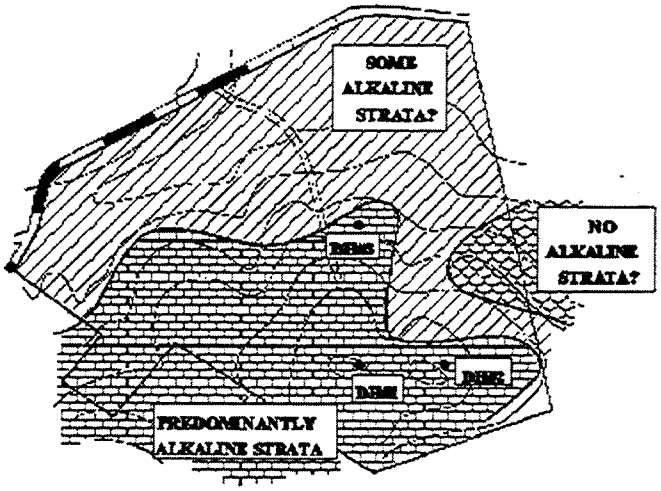
For the sake of completeness, Table 7.3 contains several criteria that were originally developed for soils and revegetation considerations, not water quality per se. These include pH less than 4.0 to define "acid-toxic" and NNP of less than -5.0 tons/1000 tons for "potentially toxic". The criteria are based on the lower limits of plant growth tolerance to acid conditions and liming requirements for native soils in the Appalachians. Experience with ABA has shown that the same criteria cannot be applied to assess both soils and water quality.

Perhaps the principal caveat to the principle *excess neutralization potential* are those mines where the rocks contain so little sulfur that they are incapable of generating significant acidity, regardless of their carbonate content. As already discussed, weathered strata is typically low in both pyrite and carbonates. Smith et al. (1974, 1976) noted that these conditions also exist for some strata in the central and southern Appalachians.

ABA has also been criticized for not predicting metals concentrations. Without additional detailed information on rock type and mineralogy, ABA cannot be used to predict specific metals concentrations. However, the suite of kinetic tests discussed in Chapter 5 can potentially be used to estimate the relative mobility of metals in acid-forming rocks.

ABA has also tended to overestimate the NP in rocks containing siderite. A modification to the lab test involving hydrogen peroxide addition, described in Chapter 4, should largely eliminate this problem. We recommend the use of this modified NP procedure because it more accurately reflects the NP of overburden materials, reduces analytical variability, and provides a better framework for predicting mine water quality. A new technique, also described in Chapter 4, definitely distinguishes siderite from the alkalinity-producing carbonate rocks, and may become an additional important tool.

**Figure 7.2.** A plan view of a 70 acre mine site showing the 3 boreholes drilled.




ABA remains the preferred static test for coal mine overburden because it is an established and recognized procedure, is relatively rapid and inexpensive, and has been field calibrated. Table 7.4 summarizes the findings of three studies comparing ABA data with post-mining water quality for surface coal mines in northern Appalachia and the midwest. In all cases, an excess of neutralizers over MPA was needed to obtain net alkaline water. In each of the three studies, there is a mixed zone of ABA values where water may be marginally net alkaline to net acid (range about +100 to -100 net alkalinity). For mines with these types of marginal overburden quality, evaluation of other data, such as adjacent mining, is very important.

An example of a detailed lithologic and ABA log is shown in Table 7.5. The log is from northern Appalachia for a sequence of rocks including the Middle and Upper Kittanning coals. For ABA interpretation, the overburden can be characterized as consisting of five main units:

- The upper 20 feet, which is oxidized and has little potential to generate significant acidity or to neutralize acid.
- The next 18 feet, which lacks appreciable neutralizers, and has some acid potential.
- A fractured but hard high-grade limestone unit, which is present from about 38-50 feet, with NP values as high as 800 tons/1000 tons (80% $CaCO_3$).
- The next 28 feet, which is essentially neutral.
- The interburden from about 78 feet to the top of the Middle Kittanning coal, which has moderate to high sulfur content and lacks significant neutralizers. These rocks are capable of producing moderate to strong acid drainage.

**Table 7.3.** Summary of Suggested Criteria for Interpreting Acid-Base Accounting (1)

| CRITERIA | APPLICATION | REFERENCE |
|---|---|---|
| Rocks with NNP less than -5 parts/1000 considered potentially toxic | Coal overburden rocks in northern Appalachian basin for root zone media in reclamation; mine drainage quality | Smith et. al., 1974, 1976; Surface Mine Drainage Task Force, 1979; Skousen et.al., 1987 |
| Rocks with paste pH less than 4.0 considered acid toxic | Coal overburden rocks in northern Appalachian basin for root zone media, mine drainage quality.<br>Base and precious metal mine waste rock in Australia and southeast Asia | Smith et. al., 1974, 1976; Surface Mine Drainage Task Force, 1979<br><br>Miller and Murray, 1988 |
| Rocks with greater than 0.5% sulfur may generate significant acidity | Coal overburden rocks in northern Appalachian basin, mine drainage quality.<br>Base and precious metal mine waste rock in Australia and southeast Asia | Brady and Hornberger, 1990<br><br>Miller and Murray, 1988 |
| Rocks with NP greater than 30 parts/1000 and "fizz" are significant sources of alkalinity. | Coal overburden rocks in northern Appalachian basin, mine drainage quality | Brady and Hornberger, 1990 |
| Rocks with NNP greater than 20 parts/1000 produce alkaline drainage | Coal overburden rocks in northern Appalachian basin. Base and precious metal mine waste rock and tailings in Canada. | Skousen et.al., 1987;<br>British Columbia Acid Mine Drainage Task Force, 1989;<br>Ferguson and Morin, 1991 |
| Rocks with NNP less than -20 parts/1000 produce AMD | Base and precious metal mine waste rock and tailings in Canada. | British Columbia Acid Mine Drainage Task Force, 1989;<br>Ferguson and Morin, 1991 |
| Rocks with NNP greater than 0 do not produce acid. Tailings with NNP less than 0 produce AMD. | Base and precious metal mine waste rock and tailings in Canada. | Patterson and Ferguson, 1994;<br>Ferguson and Morin, 1991 |
| NP/MPA ratio less than 1 likely results in AMD. | Base and precious metal mine waste rock and tailings in Canada. | Patterson and Ferguson, 1994;<br>Ferguson and Morin, 1991 |
| NP/MPA ratio classified as less than 1(likely AMD), between 1 and 2(possible AMD), and greater than 2(low probability of AMD). | Base and precious metal mine waste rock and tailings in Canada. | Ferguson and Robertson , 1994<br>Price et al, 1997 |
| Theoretical NP/MPA ratio of 2 needed for complete acid neutralization. | Coal overburden rocks in northern Appalachian basin, mine drainage quality. | Cravotta et.al., 1990 |
| NP/MPA ratio used with NP threshold to determine confidence levels for acid producing samples. 80% confidence of no acid production if NP/MPA ratio of 6.5 and NP threshold of 3.3%. | Coal overburden samples from 4 states: PA, WV, TN, and KY. | Bradham and Caruccio, 1995. |
| Use actual NP and MPA values as well as ratios to account for buffering capacity of the system. | Base metal mine waste rock, United States | Filipek et.al., 1991 |

**(1) Criteria in this table were developed for classification of <u>individual</u> rock samples**

Absent other information, what water quality will result from surface mining of both coals? The overburden data from Table 7.5 were put in a spreadsheet and volume-adjusted ABA parameters were calculated for each individual sample, as well as a summary numbers for the entire section. The basic procedures for performing these calculations have been described by Smith and Brady (1990) and are used in Pennsylvania and other states. The drillhole is located in hilly terrain. The mining area represented by this drillhole covers

about 10 acres at the top of the rock column and about 25.5 acres at the base of the middle Kittanning coal. The area of each sample interval between the top and bottom is interpolated.

Comparing these data to the criteria given in Table 7.4, the large excess of neutralizers should generate alkaline drainage. However, the most significant source of neutralization is the 11 foot thick limestone, located roughly in the middle of the overburden column. To work effectively, the limestone has to be broken or crushed during blasting and grading to relatively small pieces to dissolve and supply alkalinity. Large blocks of limestone will not be chemically active in the spoil pile. The limestone should also be mixed with in the spoil for maximum effect. Studies of alkaline addition have generally shown best results from incorporation of alkaline material and less effect if placement is all at the surface or the bottom of the spoil pile (Smith and Brady, 1998). Thus, mining and reclamation practices will have some influence on the final water quality.

By way of contrast, it is interesting to look at the expected water quality if the Middle Kittanning (lowest coal in the drill log) is extracted by underground mining. Lets assume that the mine is located above local drainage and is developed as a room-and-pillar down-dip mine with retreat mining. The mine would be expected to flood to the portal elevation after closure. The rocks immediately associated with the coal (i.e. roof, floor, and partings) will have the most obvious controls on water chemistry. The roof rock has a strong acid potential, and no significant NP is available at mine level. The mine pool will probably be strongly acidic. Unless the overburden is severely fractured and subsided to at least 40 feet above the mine, the limestone is unlikely to significantly affect mine pool chemistry. Prolonged flooding (decades) may ultimately improve water quality.

**Table 7.4.** Summary of water quality prediction from three studies of mine drainage and ABA.

| Overburden Quality | Water Quality | | | Study Source |
|---|---|---|---|---|
| | Net Acid | Variable | Net Alkaline | |
| Neutralization Potential (NP) | < 10 parts/1000 | 10 to 21 | >21 parts/1000 | PA (Brady et al., 1994; Perry &Brady, 1995) |
| NP with thresholds | < 1 parts/1000 | 1 to 10 | >10 parts/1000 | PA (Brady et al., 1994; Perry &Brady, 1995) |
| Net Neutralization Potential (NNP) | < 20 parts/1000 | 20 to 40 | >40 parts/1000 | WV (diPretoro & Rauch, 1988) |
| NNP | < 0 parts/1000 | 0 to 12 | >12 parts/1000 | PA (Brady et al., 1994; Perry &Brady, 1995) |
| NNP with thresholds | < -5 ton/1000 | -5 to +5 | >5 ton/1000 | PA (Brady et al., 1994; Perry &Brady, 1995) |
| NNP | < 10 parts/1000 | 10 to 30 | >30 parts/1000 | WV (diPretoro & Rauch, 1988) |
| NNP | < 10 parts/1000 | 10 to 20 | ? | USBM (Erickson & Hedin, 1988) |

(1) Overburden criteria in this table are developed from volume weighted summaries of overburden data.

**Table 7.5.** Example—ABA log of Middle and Upper Kittanning coals

| Sample Interval (ft) | Lithologic Description | %S | MPA tons/1000tons | Fizz Rating | NP tons/1000tons | NNP tons/1000tons |
|---|---|---|---|---|---|---|
| 0-2 | Soil | | | | | |
| 2-5 | Lt brown to lt gray sandy Siltstone | 0.15 | 4.69 | 0 | 3.72 | -0.97 |
| 5-8 | “ “ | 0.15 | 4.69 | 0 | 3.72 | -0.97 |
| 8-10 | “ “ | 0.15 | 4.69 | 0 | 4.49 | -0.20 |
| 10-12.3 | “ “ | 0.15 | 4.69 | 0 | 6.01 | 1.32 |
| 12.3-14 | “ “ | 0.15 | 4.69 | 0 | 10.99 | 6.30 |
| 14-17 | “ “ | 0.15 | 4.69 | 0 | 12.68 | 7.99 |
| 17-19.6 | “ “ | 0.15 | 4.69 | 0 | 9.52 | 4.83 |
| 19.6-22 | Black Shale, slightly weathered | 0.37 | 11.56 | 0 | 11.64 | 0.08 |
| 22-25 | “ “ | 0.65 | 20.31 | 0 | 6.93 | -13.38 |
| 25-25.7 | “ “ | 0.93 | 29.06 | 0 | 5.29 | -23.77 |
| 25.7-26.2 | Coal (Upper Kittanning) claystone binder @26.1-26.2 | 0.17 | 5.31 | 0 | 5.01 | -0.30 |
| 25.7-27.8 | Coal (Upper Kittanning) | 0.89 | 27.81 | 0 | 3.92 | -23.89 |
| 27.8-29.0 | Lt gray silty Claystone, soft | 0.15 | 4.69 | 0 | 4.89 | 0.20 |
| 29-31.7 | “ “ | 0.27 | 8.44 | 0 | 7.75 | -0.69 |
| 31.7-34 | Lt gray sandy Siltstone w\ fine gr Sandstone @ 37.2-37.8,medium | 0.17 | 5.31 | 0 | 7.01 | 1.70 |
| 34-37 | “ “ | 0.15 | 4.69 | 0 | 6.66 | 1.97 |
| 37-38.2 | “ “ | 0.28 | 8.75 | 0 | 18.94 | 10.19 |
| 38.2-40 | Lt brown to Lt gray Limestone, Fractured, hard | 0.15 | 4.69 | 3 | 679.00 | 674.31 |
| 40-41 | “ “ | 0.15 | 4.69 | 3 | 654.00 | 649.31 |
| 41-42 | “ “ | 0.15 | 4.69 | 3 | 519.00 | 514.31 |
| 42-43 | “ “ | 0.15 | 4.69 | 3 | 773.00 | 768.31 |
| 43-44 | “ “ | 0.15 | 4.69 | 3 | 736.00 | 731.31 |
| 44-45 | “ “ | 0.15 | 4.69 | 3 | 777.00 | 772.31 |
| 45-46 | “ “ | 0.15 | 4.69 | 3 | 814.00 | 809.31 |
| 46-47 | “ “ | 0.15 | 4.69 | 3 | 821.00 | 816.31 |
| 47-48 | “ “ | 0.15 | 4.69 | 3 | 765.00 | 760.31 |
| 48-49.9 | “ “ | 0.15 | 4.69 | 3 | 701.00 | 696.31 |
| 49.9-52.4 | Lt gray silty Claystone, vert fractures | 0.15 | 4.69 | 0 | 13.18 | 8.49 |
| 52.4-55 | Lt gray to brown Siltstone, Fe stains on fractures, medium | 0.15 | 4.69 | 0 | 10.94 | 6.25 |
| 55-58 | “ “ | 0.15 | 4.69 | 0 | 9.02 | 4.33 |
| 58-61 | “ “ | 0.15 | 4.69 | 0 | 10.57 | 5.88 |
| 61-63.7 | “ “ | 0.15 | 4.69 | 0 | 8.05 | 3.36 |
| 63.7-66.5 | Med to dark gray Shale, Fe stains on fractures, medium | 0.15 | 4.69 | 0 | 9.62 | 4.93 |
| 66.5-69 | “ “ | 0.51 | 15.94 | 0 | 10.17 | -5.77 |
| 69-72 | Dark gray to black shale, Fe stains | 0.56 | 17.50 | 0 | 14.08 | -3.42 |
| 72-75 | “ “ | 0.16 | 5.00 | 0 | 11.34 | 6.34 |
| 75-78 | “ “ | 0.52 | 16.25 | 0 | 18.41 | 2.16 |
| 78-81 | “ “ | 0.81 | 25.31 | 0 | 11.05 | -14.26 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 81-84 | “ “ | 0.94 | 29.38 | 0 | 15.22 | -14.16 |
| 84-85.5 | “ “ | 1.64 | 51.25 | 0 | 13.60 | -37.65 |
| 85.5-87 | Dark gray fine grained Sandstone w\black shale Intbeds, medium | 3.26 | 101.88 | 0 | 5.62 | -96.26 |
| 87-87.9 | “ “ | 4.20 | 131.25 | 0 | 2.62 | -128.63 |
| 87.9-89.5 | Coal (Middle Kittanning) | | 0.00 | | | 0.00 |
| 89.5-90 | Coal (Middle Kittanning) claystone binder @89.5-90.0, soft | 4.12 | 128.75 | 0 | 3.60 | -125.15 |
| 90-92.2 | Coal (Middle Kittanning) | | 0.00 | | | 0.00 |

Apparent water quality in underground mines is also a function of where it is measured. Mine pools tend to stratify chemically, with the best water quality usually found at the top of the water column. The worst or most mineralized water is usually at the bottom of the pool or appears as outcrop barrier seepage. Two samples collected from different elevations in the same well illustrate this phenomenon in Table 7.6. The 100 foot sample is taken at mine level, and contains substantially higher concentrations of all parameters. Significantly, iron, for which this water will require treatment, is over 35 time greater in the pool than in the stratified sample.

**Kinetic Tests**

Kinetic or simulated weathering tests are not used routinely for coal mine drainage prediction, only when additional information or specific characterizations are needed. However, they should probably be used much more frequently than is now the case, and should be considered whenever the ratio of the NP to S (or MPA) is near 1. They are widely used in the hard rock mining industry. The fundamental concept is to simulate the cyclic wetting, drying and flushing of spoil material. The chief advantages of kinetic tests are simulation of relative rates of acid generation and alkaline production, simulation of relative concentrations of net acidity, metals and sulfate, and simulation of amendments such as alkaline addition.

Unfortunately, no single kinetic test method has emerged as the best or standard technique, although weathering tests have been shown to be more accurate than other kinetic tests in predicting mine water quality (Bradham and Caruccio, 1990). However, since a variety of tests are in use, results must be interpreted on the basis of the specific test protocol used. Net acidity, metals, cations, or sulfate data can be plotted as daily production rates (mg of ion per g of sample per time interval) or as cumulative production rates with time. Although the data are sometimes plotted as concentrations, this defeats the purpose of the kinetic test evaluation and does not allow samples to be readily compared due to variations in rock weight and effluent volume. From the plots of production rates, samples are classified as alkaline or low, medium, or high acid producers or similar descriptive terms. The key aspect of kinetic tests are changes in the rates of production that develop over time, as carbonate minerals are consumed and sulfide minerals oxidize. However, at certain threshold levels of NP, the carbonate minerals inhibit oxidation of sulfide minerals, enhancing stability.

Few field calibration studies and screening criteria for kinetic tests are published. This stems from the application of kinetic tests on a case by case basis, rather than on a broad scale. Figure 5.6 shows an example of a plot of net cumulative acidity (as mg of acidity/gm of sample) in which two of the samples were

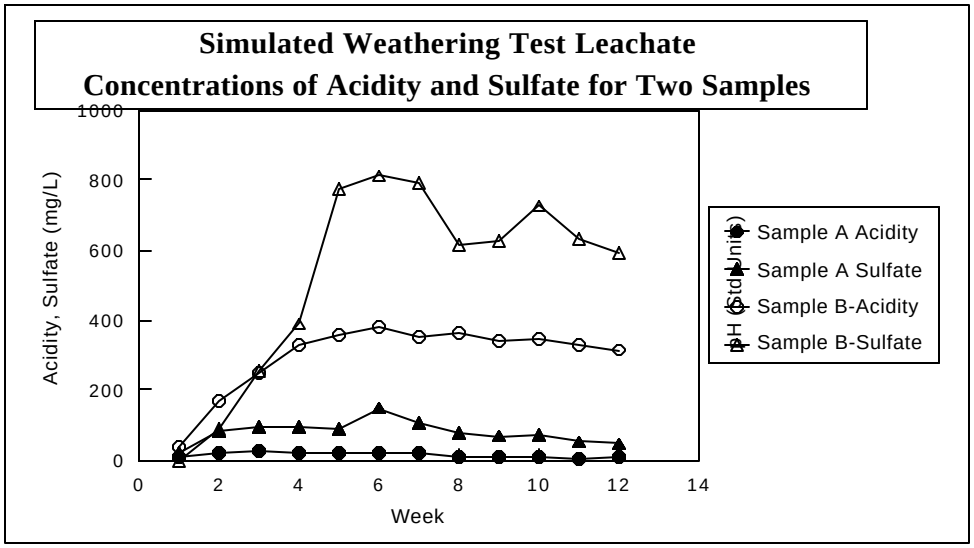
alkaline and one exhibited low acidity. Either daily or cumulative data can be plotted and the interpretation related to the differing slopes of the lines. With cumulative data, the chemical weathering attributes are usually defined by one of three trends. Figure 5.6 is an example of relatively straight slopes indicating that the acid and alkaline production potentials vary little with time and that few weathering products accumulated in the sample prior to leaching. This is common for all alkaline samples. A second common trend is a steep acid slope initially, followed by a much flatter slope for the remainder of the test, which suggests that accumulated acid weathering products are initially being flushed. A steep slope also indicates that the sample may weather quickly upon exposure. The third major trend in acid samples is that the sample may exhibit low acidity or sulfate values initially and after several weeks begin to produce significant acidity. These samples are normally high acid producers, as discussed in Chapter 5. Plots similar to those presented in Figures 5.6 and 5.7 can be constructed for metals or other parameters of interest. The interpretation has to be keyed to the specific test method, however. This stems from the use of kinetic tests on a case by case basis, and the variety of test protocols in use.

Figure 7.4a shows an example plot of sulfate and total acidity generated from a 12 week leaching test for two samples. A standard quantity of water was added to columns containing the crushed samples. Sample B produces much higher concentrations of both acidity and sulfate than sample A. Sulfate and acidity concentrations reach a peak after about 5 weeks and decline only slightly thereafter. This is interpreted to mean that sample could still generate additional acidity and sulfate beyond the 12 week test period. Sample A on the other hand, never produces much acidity or sulfate throughout the test, and both parameters are decreasing in the later weeks of the test. Sample A is not expected to be an acid source. Sample B could generate significant acidity.

Figure 7.4b is a cumulative plot of acidity and sulfate generation for two samples from a 70 day (10 week) weathering test. The cumulative production of acid and sulfate is expressed in mg/g of sample. This allows direct comparison of samples on a mass basis. Sample D produces a total of about 3.5 mg acidity/g sample for the test period compared to about 0.32 mg/g for sample C, a difference of about 10 fold. Thus D is expected to be a significant acid source relative to C. The slope of the cumulative acidity plots for both samples continue to increase at a constant rate at the end of the test period. This indicates that both rocks are likely to continue to produce acidity. A decrease in slope or flattening of the line would signify that the rate of acid production was declining.

**Table 7.6.** Stratification of water quality in an underground mine pool--pH in standard units, specific conductance in umhos/cm@25, alkalinity in mg/L $CaCO_3$ equivalent, all others in mg/L.

| Sample Depth | pH | Alkalinity | Specific Conductance | Fe | Mn | Sulfate |
|---|---|---|---|---|---|---|
| 100 feet (bottom) | 7.15 | 565 | 7000 | 202 | 2.8 | 3654 |
| 60 feet | 7.60 | 257 | 4240 | 5.6 | 0.38 | 1936 |



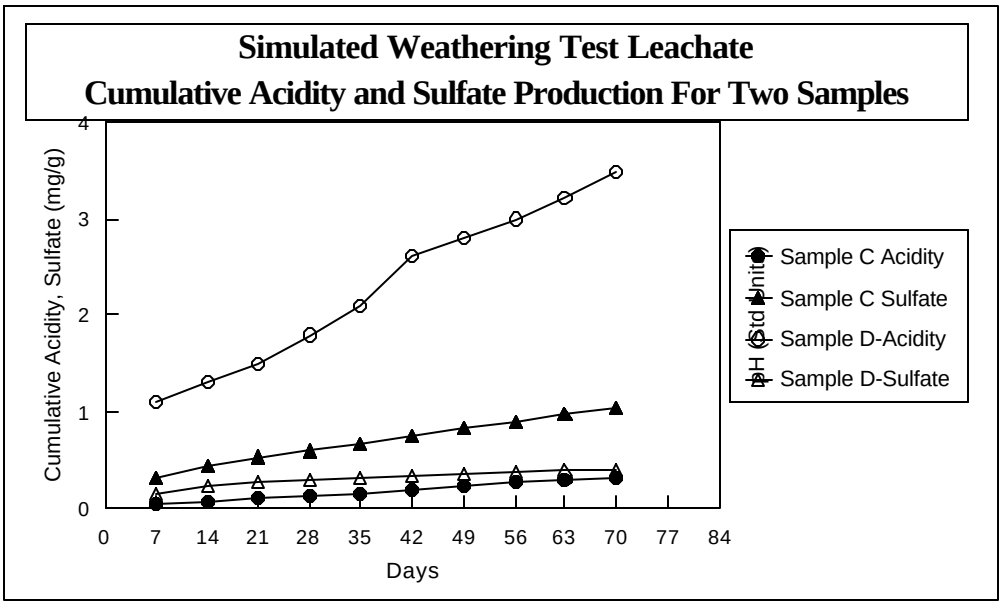




**Figure 7.4.** Two examples of cumulative acidity and sulfate production graphs.

## A GENERALIZED APPROACH TO THE ANALYSIS OF SITE DATA AND PREDICTION OF MINE DRAINAGE QUALITY

Mine drainage quality is largely controlled by three major variables: geologic conditions, hydrologic conditions, and the mining and reclamation plans. While these three factors control mine water chemistry, resource sensitivity determines what risk is assumed if the site is mined. Resource sensitivity is therefore part of the evaluation. Finally, adjacent mining, if suitable examples exist, show post-mining results that may be analogous to the site under development. Pennsylvania has demonstrated that properly used, such data can be extremely useful.

The unique character and condition of each mine site precludes a standardized cookbook approach to the evaluation process. Instead, the process can be seen as a series of questions to determine:

- Is site characterization adequate?
- What are site conditions?
- What effect will mining and reclamation have, i.e. what is the expected post-mining water quality?
- Does post-mining water quality produce unacceptable effects?

Whether one is preparing or reviewing a permit, one has to achieve some level of satisfaction that each of these issues has been adequately addressed. The process is conceptually illustrated in Figure 7.5. The proposed mining operation is analyzed for geologic, hydrologic and mining conditions to predict expected mine drainage characteristics. Projected water quality is then evaluated against on- and off-site resources to determine probable impacts. The risk of these impacts must then be classed as acceptable or not, based on legal or regulatory standards, technology limits, or other criteria.

Following is a generalized set of questions, arranged by topics to form a typical evaluation for a surface coal mine. An analogous process can be described for underground mines, with some common elements between the two as, well as features unique to each. The list is not intended to be an inflexible set of rules, but rather a guide that must be adjusted based on site specific issues.

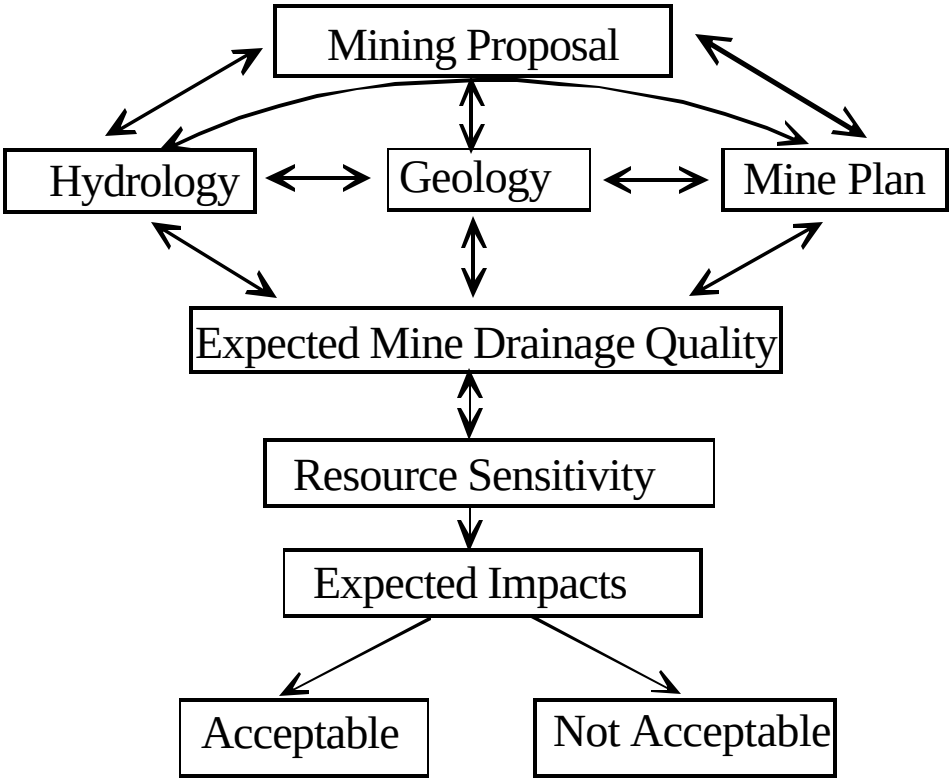



**Figure 7.5.** Diagram illustrating the major elements of mine drainage prediction and evaluation

General stratigraphy, lithology and structure

*Is the reported site geology consistent with published geologic reports that describe the general geology?* Large differences between general and site-specific geology indicate that local geology exhibits rapid changes over small distances, or that site characterization is inadequate or inaccurate.

*Are the rock types and vertical sequences of rocks laterally consistent across the area?* Variation in stratigraphy may signal changes in geochemistry of the rocks as well.

*Are there structural features (anticlines or synclines) present?* These may control or influence ground water flow direction after reclamation.

*What is the degree and direction of dip of the coal beds to be mined?* Ground water usually flows in the direction of dip in surface mine spoil aquifers. In underground mines, flooding typically begins at the downdip end of the mine.

*Are limestones or limey shales or mudstones present?* Limestones contain high percentages of acid neutralizers, but must be broken into small size fragments to be chemically active. Limey shales and mudstones may undergo rapid physical weathering and release alkalinity quickly.

*Is the coal bed laterally consistent in thickness and composition?* Coal beds can thicken, thin or pinch out entirely. Channel sandstones that replace coal in the latter case sometimes contain pyrite, and usually lack carbonates. Partings within a coal bed frequently form acid.

*How much sandstone is present in the overburden?* Some of the most severe acid drainage comes from sites with large percentages of sandstone and little carbonates. Hard sandstone that resists physical weathering creates large voids and helps circulate oxygen into the spoil pile. In underground mines, competent sandstones may resist breaking and subsiding.

Hydrogeologic Setting

*What is the topographic setting of the mine?* Surface mines located on hilltops and upper slopes are likely to be in ground-water recharge areas. Surface mines located on footslopes or valley floors are usually in ground-water discharge zones. These mines will receive flow from upgradient. The possibility of generating acid drainage is higher for mines in discharge zones compared to otherwise similar mines in a recharge area, unless the pyritic material will be permanently inundated after reclamation.

Underground mines located above drainage may flood only partially after closure and discharge by outcrop barrier leakage or at other points. Below drainage mines will usually flood completely after closure.

*Where are aquifers located?* Mines usually will intercept some ground water from the fracture flow system on hillsides. Mine drainage can move through the fracture flow system to discharge from or recharge aquifers at lower elevations. Underground mines may intercept larger regional aquifers.

*Are springs and seeps present on the mine*? Springs and seeps indicate local ground water discharge zones and infer that the underlying rock is of lower permeability.

*What are static water levels in drillholes and wells*? Static water levels indicate in a general manner, the amount of ground water that may be encountered during mining. Water table elevation in surface mine spoil is usually lower than pre-mining water levels.

*Where is the coal cropline?* The cropline, along with dip largely determines the location of post-mining discharges. For underground mines, the cropline indicates a potential seepage after flooding.

Drillhole Information

*Are exploratory holes distributed across the mine site?* Distributed drillholes are needed to determine whether stratigraphy is consistent or variable.

*Are drill logs and cross-sections plotted in the correct locations with all units described and identified?* Accurate locations are necessary to determine structure and to correlate strata.

*Are there directional trends in the stratigraphy?* Thickening or thinning beds or facies changes within the mine site can affect the distribution of acid forming and acid neutralizing minerals.

*Are all of the strata to be disturbed during mining represented in the drillhole data?* It is necessary to identify all rocks that may contribute to mine drainage quality.

*Do the number and distribution of drillholes provide a clear interpretation of site stratigraphy?* If stratigraphic units cannot be correlated or facies changes identified, additional exploratory drilling may be needed.

Geochemical Data

*Have the samples been collected, stored and analyzed following generally accepted and documented procedures?* Analytical results can vary widely if a quality assurance/quality control plan is not followed, making interpretation difficult or impossible.

*Do the geochemical data represent the rocks both vertically and horizontally?* Samples must represent the different rock types identified. Subsamples within individual stratigraphic units are needed to identify changes in geochemistry that are not obvious based on visual inspection. Typical subsample units are 3 to5 feet, maybe less when significant acid forming potential is suspected.

For ABA data, reports should include calculated MPA, NP and NNP. Color and fizz rating are useful supplemental information to identify the weathered zone and the presence of carbonates.

For simulated weathering tests, the data report should include tabular summaries and/or plots and graphs of the leachate quality data, and a description of the specific test method used.

*Where are the significant acid forming and acid neutralizing materials?* Each drillhole is examined by individual sample analyses to identify which rocks are contributing to acid generation or neutralization. Some numeric criteria for characterizing rocks from ABA analysis as significant sources of acidity or alkalinity are shown in Table 8.4.

*Are there directional trends in geochemistry?* Compare chemical data among drillholes to determine lateral consistency. Both sulfur and carbonate content can increase or decrease across a mine, and the unit may thicken, thin, or pinch out.

*Is a weathered zone of low sulfur and low neutralizer content present?* These materials will not generate much acidity or alkalinity.

*Is old minespoil or coal refuse present?* These materials have undergone chemical weathering and can contain metal sulfate minerals such as copiapite, halotrichite and others. The metal sulfate minerals are a source of stored acidity and metals. For these kinds of materials, include sulfate sulfur in the calculation of potential acidity. Weathered samples show spoil quality that could develop on the new mine.

*Are there individual samples or strata with high acid generating potential?* These rocks may require preventive measures including but not limited to alkaline addition, special handling and water management.

*Are there individual samples or strata with high neutralizing potential?* These rocks are principal source of alkalinity in the spoil. They should be mixed with acid forming material or otherwise redistributed to offset acid generation.

*Are ABA data combined or plotted by a method that simulates the geometry of the mine site?* Several criteria for interpreting ABA data from NP, NNP and as ratio of NP to MPA were discussed earlier in this chapter. The criteria were developed from ABA data that were combined into a summary value for the entire mine site.

*Does weighted ABA data and interpretive criteria suggest drainage is likely to be alkaline, acidic or marginal quality?* In general, an excess of neutralizers are needed to preclude acid drainage. Sites lacking neutralizers are probable acid formers, unless the rocks are also essentially without pyrite. The strength or severity of acid drainage depends on sulfur content, amount of neutralizers present and rock types. Conclusions drawn from ABA data should be compared with other tools like adjacent mining and baseline water quality to strengthen conclusions.

Hydrology

*Were water quality samples collected, preserved stored and analyzed using generally accepted and documented methods?* Analytical results can vary widely if a quality assurance/quality control plan is not followed, making interpretation difficult or impossible.

*How much alkalinity is present in "deep"ground-water (below the weathered zone)?* These waters should have appreciable alkalinity (>50 mg/L) if significant NP is present in the rocks.

*How much alkalinity and dissolved solids are in springs and seeps?* These waters usually circulate in the weathered zone and are generally low in dissolved solids (less than a few hundred mg/L) and alkalinity (often less than 20 mg/L).

*Are multiple samples available to characterize seasonal variation in quality?* In the Appalachian region, samples collected in late winter to early spring and late summer to fall will display the range in water quality likely to encountered.

*Do samples reflect the different aquifer systems that will be encountered or affected by mining?* Mixing mine drainage with aquifers of different chemistry will have impacts that differ in type and severity.

*Does ground water quality show influence of past mining?* Ground waters within a few hundred feet of land surface in Appalachia usually have less than 100mg/L of sulfate as background. Elevated sulfate concentrations can indicate that mine drainage has migrated on site from other surface or underground mines. Mine waters that have been neutralized by carbonate reactions in surface mine spoil often produce water with the cation fraction dominated by calcium and magnesium.

*Are there samples from previous or adjacent mining in the same coal bed?* Adjacent mining can show the general character of expected water quality from the proposed mine if the sites have similar geology, hydrology and mining techniques.

*Are there others sources of ground-water recharge to the site and if so, what is its quality?* Drainage from mines on other seams etc. can influence water quality

*Are stream sampling sites perennial, intermittent or ephemeral?* Water quality is some composite of ground discharge and surface runoff. Concentrations of some parameters like sulfate and alkalinity are sensitive to flow conditions and the contributions of different sources.

*Are multiple samples provided to estimate the range in seasonal variation of water quality?* In the Appalachian region, samples collected in late winter to early spring and late summer to fall will display the range in water quality likely to encountered. Mine drainage impacts to streams are often most pronounced during low flow conditions, when mine water is a larger percentage of stream flow.

*Are measured flow data reported with water quality?* These data are needed to perform loading, mass balance, or mixing calculations for projecting the impacts of mine drainage on a receiving stream.

*Are streams lightly buffered?* Lightly buffered waters have little capacity to neutralize an influx of acid drainage.

*Does flow increase or decrease downstream?* In most Appalachian drainage basins, flow increases downstream (gaining streams). If flow decreases downstream, the loss could be infiltrating underground mines or karst.

*Does surface water quality show influence of mine drainage from past or current mining?* Many surface waters in the Appalachian region have background concentrations of less than 50 mg/L of sulfate. Elevated sulfate concentrations often indicate mine drainage effects. Mine waters that have been neutralized by carbonate reactions in surface mine spoil often produce water with the cation fraction dominated by calcium and magnesium.

Mining and Reclamation Plan

*What surface mining method and spoil handling/spreading equipment will be used?* The mining method and equipment determines pit size, exposure time before reclamation, and the ability to segregate or special handle acid-forming material. In general, area mining by dragline provides the longest exposure time before reclamation, and the least flexibility in handling acid material or installing other preventive measures. Contour haulback or block cut with trucks and loaders usually have the most flexibility to incorporate special handling, water management and alkaline addition.

*What materials, if any, are proposed for special handling?* In the Appalachian region, special handling involves placement of acid forming material above the expected post-mining water table. Ten to twenty feet above the pit floor is a common target zone for placement. In the mid-continent and rarely in Appalachia, flooding or placing acid forming material below the water table is used.

*Are materials to be specially handled easily recognized in the field?* They can usually be distinguished by color or rock type

*Is alkaline addition proposed? If yes, what quantity and where will it be placed in the backfill?* Alkaline addition can be beneficial on marginal sites and as a "best management practice." The common practice is to add alkaline material based on the deficiency expressed by negative NNP for a single strata or an entire overburden section. Adding more alkaline material to raise the NNP above zero seems to increase the chances for success. Placing all the alkaline material at the top or bottom of the backfill is less effective than mixing or incorporating the alkaline material into the spoil pile.

Adjacent Mining

*Were mining and reclamation methods including special handling, alkaline addition and water management methods similar on the existing and proposed mine?* No mines are identical but the overall mining and reclamation techniques should be similar for a valid comparison.

*Do the sites have similar overburden stratigraphy and geochemistry?* Even adjacent sites can be geologically dissimilar, due to facies changes, topography, etc. If the sites are not stratigraphically and geochemically similar, using data from the adjacent site will be misleading.

*What is the post-mining water quality and quantity from the adjacent site?* Assuming the comparison is valid, this information is extremely useful in predicting future water quality at the unmined site.

Resource Sensitivity

*Are there lightly buffered surface or ground waters that could be affected? Are there public or private water supplies (intakes, reservoirs, and wells) that could be impacted? Are there sensitive biota that could be affected?* Quality could be damaged by small amounts of acid drainage.

*Is water quality already degraded by past mining or other activities?* This might mean that the watershed cannot withstand any additional degradation or, alternatively, may indicate that the watershed is less vulnerable.

The questions posed in the preceding sections are not all-encompassing. They do, however, flag the major data needs for an analysis and prediction of mine drainage quality and can serve as a starting point for specific case reviews.

## DEVELOPING MINE DRAINAGE SCIENCE: ISSUES, OPPORTUNITIES AND NEEDS

An enormous body of scientific research and practical experience in mine drainage has developed over the last century. Nonetheless, our ability to correctly anticipate, prevent, or manage mine drainage and its effects is still limited. Additional effort is needed to:

1. Enhance quantitative prediction of mine drainage chemistry. Currently, assessments are often confined to a determination of net acid or net alkaline. Establishing expected ranges of alkalinity, acidity or other key parameters would reduce levels of uncertainty on marginal or sensitive sites.

2. Establish a consensus on kinetic test methodology. Currently a large number of test protocols are available, and each may produce different results. The lack of consensus has made wide spread application and interpretation of kinetic tests quite difficult.

3. Conduct field calibration studies of mine water quality and analytical/predictive methods. The most comprehensive field calibration studies that exist are for ABA in northern Appalachia and a few mid-continent sites. Analogous studies are needed in central and southern Appalachia and the mid-continent. Few published studies relate kinetic tests and field performance.

4. Develop improved predictive technology for underground mine water quality. Prediction work on underground mines has received less attention compared to surface mines. However, most of the existing mine drainage pollution in Appalachia comes from abandoned underground mines.

5. Pursue the development and testing of new and revised analytical techniques, such as downhole wireline logging, evolved gas analysis, and other methods.

6. Learn from past mistakes and accumulated data. Baseline and monitoring data are available from completed and ongoing mining from companies, consultants and government agencies. Careful examination of quality would help refine predictive techniques.

7. Examine the application of mineralogical data and geochemical modeling techniques to mine drainage prediction. These methods are being applied in the hard rock mining industry to mine drainage prediction.

8. Pursue the use of analytical tools, such as three dimensional modeling software packages that can perform overburden volumetric analysis and statistical analysis procedures, including, where appropriate for detailed sampling and analysis, variography and kriging.

The science of mine drainage prediction has benefited from new and improved testing methods, many field studies and experiments, and practical experience. The need for and possibility of continued improvements and refinements still remains a major challenge.

Acknowledgments: The author thanks Robert Evans, Hydrologist, Office of Surface Mining, for several productive brainstorming sessions that contributed to the development of this chapter. A chapter discussing mine drainage prediction (Kania, 1998), written by Tim Kania, Hydrologist, Pennsylvania DEP, also provided much guidance and insight in this effort.

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