Acid–Base Accounting to Predict Post-Mining Drainage Quality on Surface Mines

J. Skousen,* J. Simmons, L. M. McDonald, and P. Ziemkiewicz

ABSTRACT

Acid–base accounting (ABA) is an analytical procedure that provides values to help assess the acid-producing and acid-neutralizing potential of overburden rocks prior to coal mining and other large-scale excavations. This procedure was developed by West Virginia University scientists during the 1960s. After the passage of laws requiring an assessment of surface mining on water quality, ABA became a preferred method to predict post-mining water quality, and permitting decisions for surface mines are largely based on the values determined by ABA. To predict the post-mining water quality, the amount of acid-producing rock is compared with the amount of acid-neutralizing rock, and a prediction of the water quality at the site (whether acid or alkaline) is obtained. We gathered geologic and geographic data for 56 mined sites in West Virginia, which allowed us to estimate total overburden amounts, and values were determined for maximum potential acidity (MPA), neutralization potential (NP), net neutralization potential (NNP), and NP to MPA ratios for each site based on ABA. These values were correlated to post-mining water quality from springs or seeps on the mined property. Overburden mass was determined by three methods, with the method used by Pennsylvania researchers showing the most accurate results for overburden mass. A poor relationship existed between MPA and post-mining water quality, NP was intermediate, and NNP and the NP to MPA ratio showed the best prediction accuracy. In this study, NNP and the NP to MPA ratio gave identical water quality prediction results. Therefore, with NP to MPA ratios, values were separated into categories: <1 should produce acid drainage, between 1 and 2 can produce either acid or alkaline water conditions, and >2 should produce alkaline water. On our 56 surface mined sites, NP to MPA ratios varied from 0.1 to 31, and six sites (11%) did not fit the expected pattern using this category approach. Two sites with ratios <1 did not produce acid drainage as predicted (the drainage was neutral), and four sites with a ratio >2 produced acid drainage when they should not have. These latter four sites were either mined very slowly, had nonrepresentative ABA data, received water from an adjacent underground mine, or had a surface mining practice that degraded the water. In general, an NP to MPA ratio of <1 produced mostly acid drainage sites, between 1 and 2 produced mostly alkaline drainage sites, while NP to MPA ratios >2 produced alkaline drainage with a few exceptions. Using these values, ABA is a good tool to assess overburden quality before surface mining and to predict post-mining drainage quality after mining. The interpretation from ABA values was correct in 50 out of 52 cases (96%), excluding the four anomalous sites, which had acid water for reasons other than overburden quality.

Most coal mining state regulatory agencies began requiring the prediction of acid-producing and acid-neutralizing materials in the overburden of surface mine operations in the early 1970s. For example, the West Virginia legislature passed a law in 1971 requiring mine operators to show in the permit "the presence of any acid-producing materials, which, when present, may cause minesoils with a pH of less than 3.5 and prevent effective revegetation" (West Virginia Department of Mines and Minerals, 1971). Dr. Richard M. Smith and his associates at West Virginia University, in conjunction with the existing West Virginia coal regulatory agency, began working on a procedure to identify acid-producing materials in 1965 (Perry, 1998). Throughout the late 1960s and 1970s, the procedure was refined and termed *acid–base accounting* (ABA) (Smith et al., 1976). Acid–base accounting was originally designed to distinguish layers in the overburden that could be used as topsoil substitutes or as hard durable rock for valley fills. Since the method identified both acid-producing and acid-neutralizing materials in the overburden, this method was one of the earliest technologies available to predict the quantity of acid-producing materials prior to mining (Grube et al., 1973; Skousen et al., 1990; West Virginia University, 1971). Since the late 1970s and the passage of the Surface Mining Control and Reclamation Act (1977), ABA has become widely adopted as a method of overburden characterization and prediction of post-mining drainage quality (Sobek et al., 2000). It was and is extensively used to help in surface mine planning and permitting decisions.

While ABA is the most commonly used method for predicting post-mining water quality, kinetic or leaching tests have also been used, especially within the past five years. These leaching tests are especially useful where the acid-producing and acid-neutralizing materials of a site are nearly balanced, where one does not overwhelm the other (Geidel et al., 2000). Therefore, leaching tests often provide additional information that supplements the ABA data, and as such provides an important assessment that is not available from static tests like ABA (Hornberger and Brady, 1998).

Acid–base accounting, as originally developed, is designed to measure neutralization potential (NP) and sulfur content of individual overburden strata. From these measurements, maximum potential acidity (MPA) and net neutralization potential (NNP) are calculated for each geologic layer from the surface of the land down to, including, and immediately underlying the coal seam. The NP is a measure of the amount of acid-neutralizing compounds (mostly carbonates, exchangeable alkali, and alkali earth cations) present in the coal and overburden. The NP is calculated from the amount of acid neutralized by the sample in $CaCO_3$ equivalents

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Abbreviations: ABA, acid–base accounting; MPA, maximum potential acidity; NNP, net neutralization potential; NP, neutralization potential; PADEP, Pennsylvania Department of Environmental Protection; S&S, Simmons and Skousen.

and is expressed in Mg/1000 Mg (or parts/1000 parts) of overburden (Kania, 1998). Refinements have been made recently to the NP method to discount artifacts from slower-reacting, nonacid-neutralizing carbonates, such as siderite (Skousen et al., 1997).

The MPA is the maximum amount of sulfuric acid that can be produced from the oxidation of sulfur minerals in the rocks or overburden material. Although acid production is associated with pyritic sulfur, the ABA procedure typically measures total sulfur because it is easier to measure than pyritic sulfur. Total sulfur is currently the most common value used to calculate MPA (Kania, 1998). The simplest and most frequently used method of total S determination is high-temperature furnace combustion (Skousen, 2000). This method gives a percent of sulfur present in the rock and is then multiplied by a constant to determine the MPA in Mg/1000 Mg, which is comparable with the NP determination. For the complete oxidation of pyrite and neutralization of all generated acidity:

$$FeS_2 + 2CaCO_3 + 3.75O_2 + 1.5H_2O \rightarrow Fe(OH)_3 + 2SO_4^{-2} + 2Ca^{+2} + 2CO_2 \quad [1]$$

where 1 mole of FeS_2 (64 g of sulfur) is neutralized by 2 moles of $CaCO_3$ (200 g of $CaCO_3$). Therefore, the constant is 31.25, which means that it takes 31.25 Mg of $CaCO_3$ to neutralize 1000 Mg of rock containing 1% pyritic sulfur. Cravotta et al. (1990) suggested that in a closed system (such as that of a surface mine backfill), CO_2 would not be driven off in the reaction, but would instead react with water to form carbonic acid as in the following reaction:

$$FeS_2 + 4CaCO_3 + 3.75O_2 + 3.5H_2O \rightarrow Fe(OH)_3 + 2SO_4^{-2} + 4Ca^{+2} + 4HCO_3^- \quad [2]$$

In this reaction, 1 mole of FeS_2 is neutralized by 4 moles of $CaCO_3$. Therefore, with this equation, 1000 Mg of rock containing 1% pyritic sulfur requires 62.5 Mg of $CaCO_3$ for neutralization. Studies analyzing ABA have used both methods. The results have been mixed (Brady and Cravotta, 1992; Brady et al., 1994). In general, the 31.25 factor for overburden MPA calculation is most commonly used.

After the NP and MPA are calculated with the above methods, total net neutralizing potential (NNP) is determined for each stratigraphic layer by subtracting the MPA from the NP. Conceptually, a positive number indicates more potentially acid-neutralizing strata in the overburden and a negative number indicates more potentially acid-producing strata in the overburden. The NP to MPA ratio is simply computed by dividing the NP by the MPA. A ratio of 1 is equivalent to an NNP of 0. These values for each rock unit can then be used to identify potentially acid-producing rock or overburden and can assist in planning overburden handling and placement (Skousen et al., 1987).

The use of ABA data to predict post-mining water quality involves numerous assumptions: (i) all sulfur in a sample will react to form acid, (ii) all material in the sample that consumes acid in the laboratory will generate alkalinity in the field, and (iii) the pyrite oxidation rate is less than or equal to the rate of carbonate mineral dissolution (Perry, 1985). In spite of these assumptions, researchers have used ABA values to predict post-mining drainage quality, and several studies described herein have shown that ABA is a valuable tool in predicting acid or alkaline post-mining water quality conditions.

In the initial usage of ABA as a predictor of post-mining water quality, overburden estimates were made only according to layer thickness (thickness-weighted), giving equal weight to layers at the top and bottom of the stratigraphic column. However, most surface mines of Appalachia have hilly to mountainous topography with horizontal strata. So, a 2-m-thick rock stratum high in the overburden contains much less volume of material than a 2-m-thick rock stratum low in the overburden. Therefore, this method of interpretation overestimated the amount of acid-neutralizing material high in the overburden column, and created a situation where insufficient carbonate materials were available for neutralization of acidity in high-sulfur rocks near the coal seam. Many sites were mined under this scenario and some subsequently generated severe, post-mining acid mine drainage due to inaccurate overburden interpretation (Surface Mine Drainage Task Force, 1979).

In the early 1980s, computer spreadsheets came into use for volume adjustment of ABA data. Once volumes of specific rock types were determined, total mass of acid-producing, inert, or acid-neutralizing rocks could be calculated for the entire site (mass-weighted), thereby providing one value for MPA and NP for each site (Smith and Brady, 1990).

In 1988 studies by diPretoro and Rauch (1988) and Erickson and Hedin (1988) compared mass-weighted ABA data with post-mining water quality. In both studies, mass-weighted values were calculated from volumes, assuming a right triangle–shaped area to be mined. Although this method can only be considered an approximate technique for volume adjustment, it yielded more realistic volumes than the simple thickness-weighted approach of the past.

Researchers at the Pennsylvania Department of Environmental Protection (PADEP) developed a method of volume adjustment with measurements of the areas to be mined (Brady et al., 1994). Due to the difficulty of measuring the surface area of each individual stratum, only the surface area of the upper and lower strata was measured. A computer spreadsheet then interpolated the area of each layer between the two, assuming a constant slope. Volumes were calculated for each interval with the surface area and the measured thickness (Smith and Brady, 1990). No volume estimation technique has ever been compared with amounts of overburden moved on a surface mine.

Even though mass-weighting with volume adjustments gave more realistic ABA information, the question remained as to which of the ABA parameters (MPA or NP) or a combination of parameters (NNP or NP to MPA ratio) best predicted post-mining water quality. In studies by diPretoro and Rauch (1988), Erick-

Table 1. Summary of water quality prediction from studies in West Virginia and Pennsylvania (Perry, 1998).

ABA parameter†	Calculated value	Predicted water quality	Source
	Mg/1000 Mg		
NP	<20	net acid	diPretoro and Rauch, 1988
	>40	net alkaline	
	<10	net acid	Brady et al., 1994
	>21	net alkaline	
NNP	<10	net acid	diPretoro and Rauch, 1988
	>30	net alkaline	
	<20	net acid	Erickson and Hedin, 1988
	>80	net alkaline	
	<0	net acid	Brady et al., 1994
	>12	net alkaline	
	<0	net acid	Skousen et al., 1987
	>15	net alkaline	
NP to MPA ratio (unitless)	<1	net acid	Perry, 1998
	>2	net alkaline	

† ABA, acid–base accounting; NP, neutralization potential; NNP, net neutralization potential; MPA, maximum potential acidity.

son and Hedin (1988), and Brady et al. (1994), NP and NNP were found to be the best indicators of post-mining drainage quality (Table 1). diPretoro and Rauch (1988) showed that sites with NP > 40 Mg/1000 Mg and NNP > 30 Mg/1000 Mg produced net alkalinity in post-mining drainage. Erickson and Hedin (1988) found that an NNP > 80 produced alkaline water and an NNP < 20 typically produced acidic water, but this study had no sites with NNPs between 20 and 80 Mg/1000 Mg. A mass-weighted study by Brady et al. (1994) resulted in NP and NNP values much lower than these earlier studies. They showed that sites with NP > 21 Mg/1000 Mg and NNP > 12 Mg/1000 Mg produced alkaline drainage. In addition to NP and NNP, the ratio of NP to MPA has also been used as an indicator of post-mining water quality (Perry, 1998). diPretoro and Rauch (1988) found that sites with a NP to MPA ratio of <2.4 generally resulted in acid mine drainage and sites with >2.4 usually produced alkaline drainage.

Although all three studies identified the importance of NP, NNP, and NP to MPA ratio in predicting post-mining water quality, all three gave different values of NP and NNP as thresholds. Also, these values only represented trends in the relationship of NP and NNP to water quality prediction, and all sites did not fit the predictions. There is also uncertainty in the most reliable and accurate method of volume adjustment to obtain mass of acid-producing and acid-neutralizing overburden materials for use in prediction. Therefore, we collected data for 56 sites, used three methods of volume adjustment to compute overburden mass for determining MPA, NP, NNP, and NP to MPA ratio values, and then compared these values with post-mining water quality.

MATERIALS AND METHODS

Site Selection and Data

Study sites were chosen to represent surface mining operations throughout the state of West Virginia (Fig. 1). No special consideration was given to the surface mining area, coal seam, mining method, special handling plans, or post-mining water quality. For all sites, special handling plans were not considered and estimates were based on overburden properties from drill cores only and ABA calculations. If alkaline amendments were made, the amount of material was added to the overall NP of the site.

Data for each site were obtained from mine operator files or from surface mine permits on file with the West Virginia Division of Environmental Protection. To be included in the data set, each site had to meet the following four criteria. First, a detailed topographic map was necessary to show the boundaries of mining, location of core holes, coal outcrops, depth of overburden, and post-mining water sampling points. Second, a complete ABA data set was required from one overburden core drilled above or near the highest point of mining (ABA data must include depth, thickness, rock type, percent S, and NP for all layers down to and including the coal pavement). Third, amounts of alkaline material imported to the site were needed, if practiced. Fourth, post-mining drainage data were necessary including flow, pH, alkalinity, and acidity from seeps or springs discharging from the site. The first three criteria were relatively easy to meet, but the post-mining water quality data were harder to obtain, and many additional sites were eliminated from the data set due to insufficient water data. Fifty-three of the 56 sites had water data for at least five separate sampling times and values were averaged to determine the post-mining discharge quality for each site. The other three sites had water samples taken in the fall of 2000 only, but other records and regulatory personnel were contacted to assure that these samples represented the historical water quality on these sites.

Overburden Volume and Mass Calculations

Volumes of each layer in the overburden were determined in three ways. The first way (Ziem) was a right-triangle method modified from diPretoro and Rauch (1988). The cross-sectional area perpendicular to the highwall was calculated from depth and pit width. The cross-sectional area of each layer was calculated by interpolation with layer depths and the average slope. Layer volumes were calculated by multiplying layer cross-sectional area by total pit length.

A second method, Simmons and Skousen (S&S), is a modification of the Ziem method in that it separated each mining site into unique topographic shapes (concave vs. convex slopes, narrow vs. bowl-shaped valleys, steep vs. gentle slopes, etc.). Widths, lengths, depths, and slopes of unique shapes were measured, then the volumes for all the unique shapes on the site were summed together to obtain total overburden amounts. This method incorporated varying slopes and land surfaces into the volume calculation.

The third method, the PADEP method, used a planimeter to determine the surface area of the upper- and lower-most

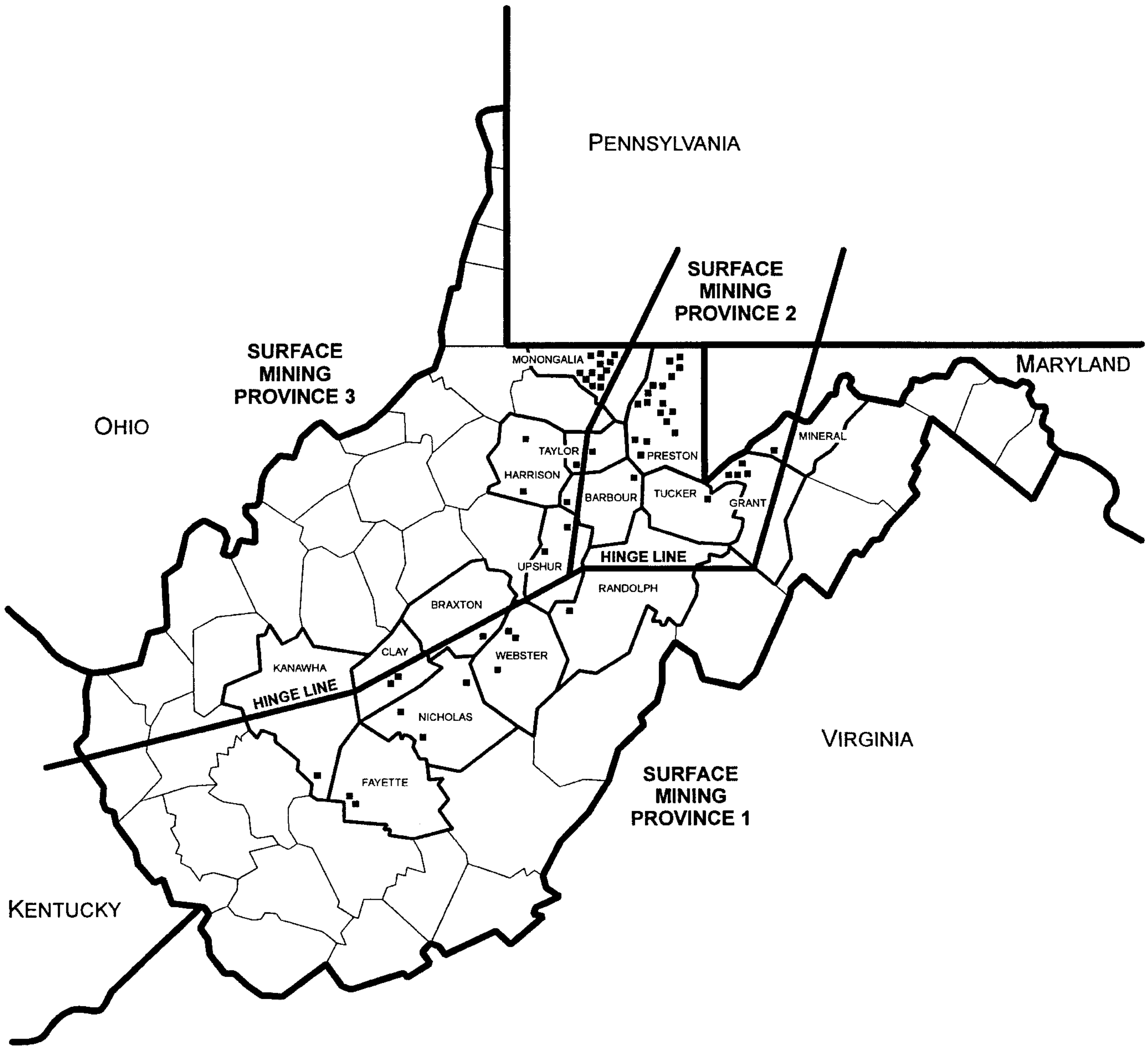

Fig. 1. Location of 56 study sites in West Virginia and boundaries of the surface mining provinces (SMP).

strata within the mined area boundary. A spreadsheet then interpolated the upper and lower area of each layer, assuming a constant slope, and then multiplied the average layer area by its thickness to obtain volume (Smith and Brady, 1990). The Ziem and PADEP methods were far less time consuming in estimating volumes than the S&S method.

Volumes for each method were then converted to mass by multiplying the volume of each stratigraphic unit by the unit weight of the rock type present (Table 2). The metric tons of overburden present in each layer were used to convert percent S into metric tons of MPA and metric tons of NP. Spreadsheets for each overburden volume and mass calculation method are available from the authors.

On five different-sized coal mine operations used in this study, we were able to determine mass of overburden materials hauled during the operation by collecting data from computers mounted on overburden haulage trucks. These masses were compared with calculated masses from overburden volume estimates by the three methods.

RESULTS AND DISCUSSION

Thirteen of the 56 sites were found in southern West Virginia (Fig. 1). The remaining 43 northern West Virginia sites included 17 sites in Preston, 12 sites in Monongalia, and a few sites in each of nine other counties (Table 3). The majority of sites were found in northern counties because of the general geology of West Virginia and its influence on water quality. The coal geology of West Virginia is divided into the northern and southern coalfields, both of which were formed during the Pennsylvanian Period (Barlow, 1974). The southern coalfield contains coal seams found in the Pottsville Group (Pocahontas, New River, and Kanawha Formations), which generally have higher overall rank and heating value, and lower sulfur and ash contents than northern coals. The northern coalfield contains coal seams in the Allegheny, Conemaugh, and Monongahela Groups, which

Table 2. Unit weight of rocks used in this study to calculate volumes and mass of overburden materials (Caterpillar, 1991).

Rock type	Unit weight
	Mg/ha-m†
Soil	18 174
Sandstone	28 122
Shale	32 324
Sandstone-shale	30 228
Mudstone	32 627
Limestone	31 664
Coal	16 461

† A conversion from U.S. tons/acre-ft (×8.922).

are generally high in sulfur and ash content. The high sulfur content of the coal and associated rocks in the northern coalfield makes these coals prone to acid mine drainage generation during mining. The dividing line between coalfields is the "hinge line" (Fig. 1).

The high-sulfur geology in the northern coalfield is also separated by the amount of carbonate or calcareous material in the rocks. The eastern part of the northern coalfield is characterized by low amounts of calcareous or acid-neutralizing (limestone) material in the strata, while the western part may have limestone or other acid-neutralizing rocks associated with coal seams. Smith et al. (1976) separated these unique geologic settings into "surface mining provinces" (SMP on Fig. 1 and Table 3). Surface Mining Province 1 occurs in southern West Virginia and is comprised of rocks in the Pottsville Group having low sulfur and low carbonate content. Therefore, the majority of the coals and associated rocks in SMP 1 do not have much acid-producing or acid-neutralizing potential. Surface Mining Province 2 occurs in the eastern part of the northern coalfield and contains coal beds and rocks from the Allegheny and Conemaugh Groups with high sulfur and low carbonate content. Surface Mining Province 3 is found in the western part of the northern coalfield with rocks from the Monongahela Group containing high sulfur and high carbonate content. So the SMP concept provides a general prediction of the acid mine drainage potential of rocks disturbed in each of the provinces with unique geologic settings (see also Brady et al., 1998). Surface Mining Province 2 is of special interest because it has the highest potential for acid mine drainage, but it is also the most geologically variable. Hence, 13 sites were in SMP 1, 25 in SMP 2, and 18 were in SMP 3. Coal seams extended from the Glenalum Tunnel coal seam found in the Pottsville Group (Kanawha Formation) upward to the Waynesburg coal seam at the top of the Monongahela Group (Table 4).

Table 3. Locations of our 56 study sites including the county, the surface mining province (SMP), and position in West Virginia.

County	Sites	SMP	Northern or southern West Virginia
Barbour	2	2, 3	N
Braxton	1	1	S
Clay	2	1	S
Fayette	2	1	S
Grant	4	2	N
Harrison	2	3	N
Kanawha	1	1	S
Mineral	1	2	N
Monongalia	12	3	N
Nicholas	3	1	S
Preston	17	2	N
Randolph	1	1	S
Taylor	2	2, 3	N
Tucker	1	2	N
Upshur	2	3	N
Webster	3	1	S

Overburden Volume and Mass

Overburden volume estimates from three methods were converted to mass and compared with truck weights on five differently sized and shaped sites. The PADEP method was consistently closer to the overburden mass than the other two methods, giving an average percentage error of only −4% (Table 5). The Ziem method generally overestimated overburden mass. The average percent error for the Ziem method was 118%, with a maximum of 320%. The S&S was better than the Ziem method, with an average error of −23%, but consistently underestimated overburden masses and required considerably more time and effort than did the other two methods.

The differences among the three methods were due, in part, to fundamental differences in how volumes were calculated. In the Ziem method, a single, average cross-sectional area perpendicular to the highwall was calculated from measurements and had to represent all topographic changes across the entire pit length. So changes in pit width, slopes, and highwall curvature all contributed error to the estimate. The BN (7-ha contour mine), DC (37-ha area mine), and HG (83-ha long-contour mine) sites had large overestimation errors with the Ziem method.

The S&S method was an improvement in that some, but not all of this variability was accounted for by dividing the site into relatively homogenous, similarly shaped sections. The sheer magnitude of measurements and the time-consuming nature of this method made this a cumbersome technique, even though it was thought that this method would provide a more accurate method for estimating volume.

The PADEP method was superior because a single-measured or interpolated area parallel to the earth's surface was multiplied by depth. Because the depth of any layer is significantly less than the total pit length, the average area only has to represent the area over a

Table 4. Coal seams represented in the acid–base accounting study.

Geology group	Coal seam	Sites
Monongahela	Waynesburg	8
	Sewickley–Redstone	2
	Redstone–Pittsburgh	6
	Pittsburgh	3
Conemaugh	Elklick	2
	Harlem	2
	Bakerstown	6
Allegheny	Upper Freeport	13
	Lower Freeport	1
	Freeports + Kittannings	3
	Kittannings (5 and 6 Block)	5
Pottsville	Alma–Eagle	1
	Gilbert–Eagle	1
	Peerless	2
	Glenalum Tunnel	1

Table 5. Comparison of overburden amounts (total Mg of overburden, neutralization potential [NP], maximum potential acidity [MPA], and NP to MPA ratio) calculated by three different methods (Ziem, Simmons and Skousen [S&S], and Pennsylvania Department of Environmental Protection [PADEP]) and the overburden amounts determined from haulage trucks.

Site	Method	Total overburden	Error	NP	MPA	NP to MPA ratio
		Mg	%	Mg/1000 Mg		
CH1	Ziem	3 852 869	−27	43.4	54.1	0.80
	S&S	4 738 441	−11	43.4	12.9	3.36
	PADEP	4 708 563	−12	41.9	13.6	3.08
	Measured	5 325 274				
BN	Ziem	8 480 647	164	70.1	11.9	5.89
	S&S	2 482 974	−22	79.3	10.0	7.93
	PADEP	3 453 915	8	70.8	12.0	5.92
	Measured	3 205 621				
KE	Ziem	37 873 619	22	58.9	19.9	2.96
	S&S	19 520 492	−37	60.0	23.3	2.58
	PADEP	30 190 263	−3	62.8	19.8	3.16
	Measured	31 014 560				
DC	Ziem	71 098 594	320	21.8	3.9	5.51
	S&S	13 629 079	−20	25.6	3.9	6.56
	PADEP	14 989 431	−12	27.6	4.1	6.79
	Measured	16 938 880				
HG	Ziem	206 547 356	111	12.6	5.6	2.25
	S&S	72 731 064	−26	13.0	4.1	3.17
	PADEP	95 154 555	−2	12.0	4.0	3.03
	Measured	97 672 582				
			Average error			
	Ziem		118			
	S&S		−23			
	PADEP		−4			

relatively short distance. The use of digital topographic maps and Geographic Information System–based programming has the potential to refine the interpolated measurements and thus improve volume estimates.

In spite of large differences in overburden mass estimates, this had a surprisingly small effect on NP and MPA estimates among the methods. By using the NP, MPA, and NP to MPA ratio values of PADEP as a reference, only 6 of 30 estimates by the Ziem and S&S methods were off by more than 10%, but two were very far off (Table 5).

Water Quality Prediction

Eleven of the 56 sites gave net acid water (Table 6). Of the 11 sites that gave net acid water, eight were from Upper Freeport surface mines in Preston County (SMP 2 and Allegheny Group), and these Upper Freeport sites gave the highest acid concentrations in water at our sites (Table 6). The other three acid sites were a Waynesburg coal mine in Monongalia County (SMP 3), a Pittsburgh coal mine in Upshur County (SMP 3), and a Kittanning coal mine in Clay County (SMP 1). So, 73% of the acid sites were from SMP 2, 18% were from SMP 3, and 9% were from SMP 1.

Four operations in Preston County mined the Bakerstown coal (SMP 2 and Conemaugh Group), which all produced very alkaline post-mining water quality. Three other sites in Preston County (Kittanning and Pittsburgh coal surface mines) also produced alkaline water.

In comparing NNP with NP to MPA ratio for each site, there was no difference in the prediction of producing acid or alkaline post-mining water. For example, all sites with a negative NNP value were found to have a <1 NP to MPA ratio, and sites with a range of 0.4 to 17.4 Mg/1000 Mg NNP were found to occur in the 1 to 2 NP to MPA ratio. Therefore, for convenience, the rest of the ABA site categories will use the NP to MPA ratio.

The prevailing thought is that sites with overburden NP to MPA ratios < 1 should produce acid mine drainage, while ratios > 2 should produce net alkaline drainage. Those between 1 and 2 could generate either acid, alkaline, or neutral drainage (Perry, 1998). Table 6 lists the sites according to NP to MPA ratio.

In our study, eight sites had NP to MPA ratios < 1, and six of these sites produced net acid water (Table 6). The two sites that were not acid producers were from Fayette and Clay Counties (SMP 1) and both had very low total MPA and total NP, and had only slightly negative NNP. All ABA values for these two sites suggest that the overburden would not affect water quality significantly, and indeed the water quality is only slightly alkaline. In fact, the thirteen sites in SMP 1 (southern West Virginia and Pottsville Group geology) gave post-mining water qualities of −15 to 228 mg/L alkalinity as $CaCO_3$, but most were in the range of 5 to 60 mg/L alkalinity as $CaCO_3$.

Of the eight sites that gave NP to MPA ratios between 1 and 2, only one produced net acid water, and only slightly so. This Al site was a Middle Kittanning mine in Clay County (SMP 1 and Allegheny Group geology). The other six sites with NP to MPA ratios between 1 and 2 were in northern and southern West Virginia counties and included all SMPs.

Forty of the 56 sites had NP to MPA ratios > 2. Of these sites, four produced net acid water. The Cr, SH, D2, and HP sites had NP to MPA ratios of 2.2, 3.1, 3.6, and 8.9, respectively. It is hard to conceive that ratios of 3.1 and 3.6, and especially 8.9 could produce acid drainage. Three of the sites were from Upper Freeport Preston County mines (Cr, SH, and D2, and all in SMP 2 with Allegheny Group geology), while the other was a

Table 6. Summary of acid–base accounting sites with size, location, overburden amounts, neutralization potential (NP) to maximum potential acidity (MPA) ratios, and accompanying post-mining water quality. Sites are sorted by NP to MPA ratio.

Site	Size	County	Coal seam	Overburden	Total MPA		Total NP		Total net NP		NP to MPA ratio	Net alkalinity
	ha			Mg	Mg	Mg/1000 Mg	Mg	Mg/1000 Mg	Mg	Mg/1000 Mg		mg $CaCO_3$/L
4H	6	Preston	UF	337 588	2 221	6.6	−752	−2.2	−2 973	−8.8	0.1	−15
Bf	7	Preston	UF	934 128	14 882	15.9	3 000	3.2	−11 882	−12.7	0.2	−277
CF	4	Monongalia	Waynesburg	1 038 498	9 665	9.3	4 273	4.1	−5 392	−5.2	0.4	−70
ED	15	Preston	UF	20 355	40 998	20.1	20 949	10.3	−20 049	−9.8	0.5	−432
PM	7	Fayette	Glenalum Tunnel	1 065 799	2 498	2.3	1550	1.5	−948	−0.9	0.6	12
MP	9	Preston	UF	3 381 693	150 361	44.5	107 596	31.8	−42 765	−12.6	0.7	−20
IL	4	Preston	UF	652 264	5 171	7.9	3 666	5.6	−1 505	−2.3	0.7	−35
PR	3	Clay	UK	505 750	4 683	9.3	3 720	7.4	−964	−1.9	0.8	5
GF	3	Preston	UF	327 022	2 915	8.9	3 176	9.7	261	0.8	1.1	78
Al	11	Clay	MK	1 958 976	5 227	2.7	6 101	3.1	875	0.4	1.2	−15
MC	29	Nicholas	Gilbert, Eagle	5 468 383	19 477	3.6	28 436	5.2	8 960	1.6	1.5	35
WS	17	Grant	Elklick	1 545 580	23 277	6.9	34 464	10.2	11 187	3.3	1.5	55
CH2	58	Monongalia	Waynesburg	13 854 644	313 265	22.6	486 060	35.1	172 795	12.5	1.6	151
ST2	6	Grant	Elklick	388 118	5 142	13.2	8 417	21.7	3 276	8.4	1.6	20
Id	2	Preston	Bakerstown	222 380	6 206	27.9	10 065	45.3	3 858	17.4	1.6	117
SH1	6	Preston	LF	706 917	5 183	7.3	10 409	14.7	5 226	7.4	2.0	120
Cr	1	Preston	UF	130 380	2 367	18.2	5 287	40.6	2 920	22.4	2.2	−59
SC	6	Preston	Pitt	1 265 219	12 441	9.8	29 186	23.1	16 745	13.2	2.3	121
KE	62	Monongalia	Waynesburg	19 520 492	454 663	23.3	1 171 080	60.0	716 417	36.7	2.6	86
F2	39	Kanawha	5B & 6B, UK	38 302 154	205 345	5.4	536 360	14.0	331 015	8.6	2.6	43
PT	13	Taylor	Pitt	1 882 875	21 871	11.6	60 977	32.4	39 106	20.8	2.8	50
ST1	23	Grant	Harlem	989 438	13 199	13.3	36 650	37.0	23 451	23.7	2.8	35
CT2	20	Barbour	Red-Pitt	3 496 292	80 383	23.0	230 110	65.8	149 726	42.8	2.9	15
SH	2	Preston	UF	453 277	3 878	8.6	12 223	27.0	8 345	18.4	3.1	−40
HG	83	Webster	UF, M-U K	72 731 064	297 532	4.1	943 949	13.0	646 417	8.9	3.2	95
LR	12	Tucker	Harlem	2 537 008	14 657	5.8	48 491	19.1	33 834	13.3	3.3	8
CH1	13	Monongalia	Waynesburg	4 738 442	61 185	12.9	205 853	43.4	144 668	30.5	3.4	136
D2	6	Preston	UF	2 748 993	26 318	9.6	94 939	34.5	68 622	25.0	3.6	−16
FM	47	Preston	LF, UK	17 594 460	162 661	9.2	634 981	36.1	472 320	26.8	3.9	23
GY	1	Harrison	Red-Pitt	82 539	1 503	18.2	5 970	72.3	4 466	54.1	4.0	155
OS	15	Monongalia	Waynesburg	630 2681	88 079	14.0	359 870	57.1	271 791	43.1	4.1	136
B9	2	Braxton	LK	562 023	1 330	2.4	5 597	10.0	4 267	7.6	4.2	124
BG	56	Webster	Peerless	14 265 548	77 564	5.4	333 650	23.4	256 086	17.9	4.3	15
DV	3	Monongalia	Waynesburg	705 602	8 608	12.2	37 218	52.8	28 611	40.6	4.3	35
B1	4	Nicholas	UF	818 249	1 743	2.1	8 515	10.4	6 772	8.3	4.9	38
CV	28	Barbour	Bakerstown	3 256 168	26 896	8.3	142 318	43.7	115 422	35.5	5.3	80
NA	9	Mineral	Bakerstown	3 180 669	24 547	7.7	139 353	43.8	114 806	36.1	5.7	2
BK	11	Taylor	Pitt	2 187 471	19 098	8.7	111 656	51.0	92 376	42.2	5.9	52
ME	24	Monongalia	Sewickley-Red	14 046 738	194 594	13.9	1 244 119	88.6	1 049 525	74.7	6.4	40
L2	32	Fayette	Alma-Eagle	28 720 220	43 374	1.5	281 035	9.8	237 661	8.3	6.5	60
DC	37	Grant	UF	17 629 079	68 662	3.9	450 492	25.6	381 831	21.7	6.6	115

Continued on next page.

Table 6. Continued.

Site	Size	County	Coal seam	Overburden	Total MPA		Total NP		Total net NP		NP to MPA ratio	Net alkalinity
FT	15	Monongalia	Red-Pitt	2 842 694	109 896	38.7	741 010	260.7	631 114	222.0	6.7	40
TM	34	Nicholas	U-M K, 5B	14 070 755	13 496	1.0	93 787	6.7	80 292	5.7	7.0	21
BN	7	Monongalia	Waynesburg	2 482 974	24 799	10.0	196 801	79.3	172 001	69.3	7.9	331
SH2	4	Monongalia	Waynesburg	1 113 515	10 576	9.5	88 637	79.8	78 061	70.1	8.4	18
JR	9	Preston	Bakerstown	997 810	7 358	7.4	65 758	65.9	58 400	58.5	8.9	200
HP	7	Lewis-Upshur	Red-Pitt	1 387 021	7 206	5.2	64 270	46.3	57 064	41.1	8.9	−17
LC	28	Harrison	Red-Pitt	12 325 583	183 503	14.9	1 646 794	133.6	1 463 291	118.7	9.0	164
MR	4	Randolph	Peerless	715 516	2 149	3.0	19 452	27.2	17 304	24.2	9.1	12
WY	18	Grant	UF	5 139 305	29 337	5.7	274 223	53.4	244 887	47.6	9.4	25
TR	39	Upshur	Red-Pitt	13 133 228	196 988	15.0	1 898 430	144.5	1 701 442	129.5	9.6	160
AR	35	Webster	UF, M-U K	32 218 656	94 264	2.9	931 925	28.9	837 662	26.0	9.9	228
BR	14	Monongalia	Sewickley-Red	2 909 166	33 061	11.3	368 999	126.8	335 938	115.5	11.2	156
St	9	Preston	Bakerstown	2 587 492	13 749	5.3	287 981	111.3	274 232	106.0	21.0	140
WF	12	Preston	Bakerstown	1 282 311	3 761	2.9	85 179	66.4	81 418	63.5	22.9	78
SM	2	Preston	UF	98 975	366	3.7	11 342	114.6	10 977	110.9	31.0	110

Redstone–Pittsburgh coal mine from Upshur County (HP, bordering SMP 2 and 3).

The 1-ha Cr site was mined relatively slowly with the surface mine pits remaining open for long periods (personal communication from past inspectors and operators). Perry et al. (1997) noted that acid mine drainage was enhanced on potentially acid-producing sites when mining and reclamation was done slowly. Quickly reclaiming disturbed areas prone to acid mine drainage decreases the amount of time pyritic material is exposed to oxidation and weathering. The slow mining of the Cr site may have allowed prolonged oxidation of pyritic materials, thereby creating a larger problem with acid drainage than if the site had been mined more quickly.

The 2-ha SH surface mine removed the down dip coal outcrop of a 15-ha Upper Freeport underground mine. Therefore, the acid water draining the underground mine passes through the reclaimed backfill of the SH surface mine generating acid seeps in the slopes at SH. Without this underground mine water influence, based on inspector opinions, this site would not be producing acid mine drainage.

The 6-ha D2 site produced net acid drainage for the first seven years after mining and reclamation, but has been producing alkaline drainage for the past two years. It is evident that acid salts in the overburden were released quickly and leached as water moved through the backfill. Over time, as the salts were leached and no more acid was generated, the acid drainage has been gradually overcome by the acid-neutralizing materials in the backfill.

The 7-ha HP site has only slightly acidic water with primarily manganese in the water. It is not adjacent to an underground mine, nor does it appear that coal refuse was placed on the site, nor was there any other unusual reclamation practice that may have caused a very high NP to MPA ratio site to generate acid mine drainage. It is possible that nonacid-neutralizing carbonates (siderite) were counted as acid-neutralizing carbonates in this overburden, which gave misleadingly high NP numbers (Skousen et al., 1997).

The ABA overburden parameters were plotted versus net alkalinity of post-mining water quality. No relationship existed ($R^2 = 0.02$) between MPA in Mg/1000 Mg and net alkalinity of post-mining water (figure not shown). Acid mine drainage occurred on sites with very low MPA (2.7 Mg/1000 Mg) to high MPA (20.1 Mg/1000 Mg), while alkaline drainage occurred on sites with 20 to 45 Mg/1000 Mg MPA. As indicated by others (Brady et al., 1994), MPA by itself is not the critical parameter for predicting post-mining water quality, nor is it expected to be a reliable predictor. On the other hand, an NP of <20 was suggested by diPretoro and Rauch (1988) to produce acid drainage, while Brady et al. (1994) indicated this value to be <10. Total NP in our study correlated with net alkalinity in post-mining water on our 56 sites ($R^2 = 0.12$, figure not shown), but the NP values used by these two former studies did not fit our data. In our study, 19 sites had total NP < 20 Mg/1000 Mg, with only six having acid water (32%). Twelve sites had NP values < 10 Mg/1000 Mg and only four (33%) produced acid drainage (Table 7). Five sites

Table 7. Comparison of acid–base accounting (ABA) values between the data of this study and that of Brady et al. (1994) to post-mining water.

ABA parameter	Calculated value	Predicted water quality	Percentage of sites accurately predicted	
			This study	Brady et al.
			%	
NP†	<10	net acid	33	73
	>21	net alkaline	86	100
Net NP	<0	net acid	75	78
	>12	net alkaline	89	100
NP to MPA‡ ratio	<1	net acid	75	NA
	>2	net alkaline	89	NA

† Neutralization potential.
‡ Maximum potential acidity.

out of 37 with NP > 21 Mg/1000 Mg (14%) gave acid drainage, and two of these acid sites had total NP > 40 Mg/1000 Mg. Therefore, 86% of sites with NP > 21 Mg/1000 Mg gave alkaline drainage. From our data, NP was not a clear indicator for acid post-mining water quality, as others have suggested (Perry and Brady, 1995).

Total NNP combines NP and MPA into one value for each site, which was plotted against net alkalinity (R^2 = 0.15, figure not shown). Past predictions have used >12 NNP (Brady et al., 1994; Perry and Brady, 1995), >15 NNP (Skousen et al., 1987), and >30 NNP (diPretoro and Rauch, 1988) as values that should produce net alkaline water. Values of <0 NNP (Brady et al., 1994; Perry and Brady, 1995; Skousen et al., 1987) and <10 NNP (diPretoro and Rauch, 1988; Erickson and Hedin, 1988) have been used as predictors of acid drainage. In our data, six sites with NNP values of −12.7 to −2.3 Mg/1000 Mg gave acid drainage, two sites with NNPs of −1.9 and −0.9 gave neutral drainage (should be acid), and three sites with NNPs between 0.4 and 1.6 gave a mixture of drainage (should be alkaline). Four sites (the same problem sites as noted above), all with >18 NNP, produced slightly acid drainage (59 to 16 mg/L net acidity). Again, if these four sites are excluded, all of the acid mine drainage sites had NNP < 0.4 Mg/1000 Mg. Therefore, six of eight sites (75%) with <0 NNP produced acid drainage, while 32 of 32 sites (100%, excluding the four anomalous sites) with >12 NNP produced alkaline drainage (Table 7). Twelve sites between 0 and 12 NNP all produced alkaline drainage, except one.

The NP to MPA ratio is also used to predict acid drainage. Figure 2, plotting NP to MPA ratio against net alkalinity (R^2 = 0.12), shows the same trend as NNP versus net alkalinity. The four sites with acid water and high NP to MPA ratios (2.2 to 8.9) are apparent on this graph. Six acid drainage sites fit the general prediction pattern of NP to MPA ratios < 1 producing acid drainage, and one site with a 1.2 NP to MPA ratio also produced slightly acid drainage. So, in general, an NP to MPA ratio of <1 will produce mostly acid drainage sites, between 1 and 2 will produce mostly alkaline drainage sites, while NP to MPA ratios > 2 will produce alkaline drainage sites with a few exceptions. The NP to MPA ratio is better because NNP (the difference between NP and MPA) is confounded by scale (the size of the mine and the amount of overburden).

We wondered if any relationship existed between the size of the mine (equating to total amounts of overburden moved) and net alkalinity of post-mining water (Fig. 3). All 19 sites > 15 ha gave alkaline water, while 11 of the 37 sites 15 ha or less in size (30%) gave acid water. Small mines move less overburden and therefore have less chance of intercepting acid-neutralizing strata.

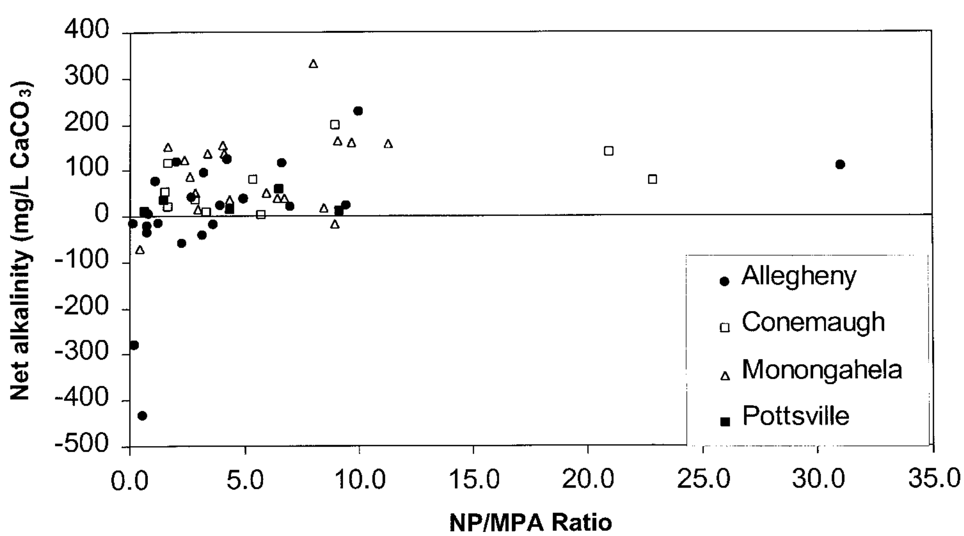

Fig. 2. The ratio of neutralization potential (NP) to maximum potential acidity (MPA) and net alkalinity of drainage water for 56 sites in West Virginia.

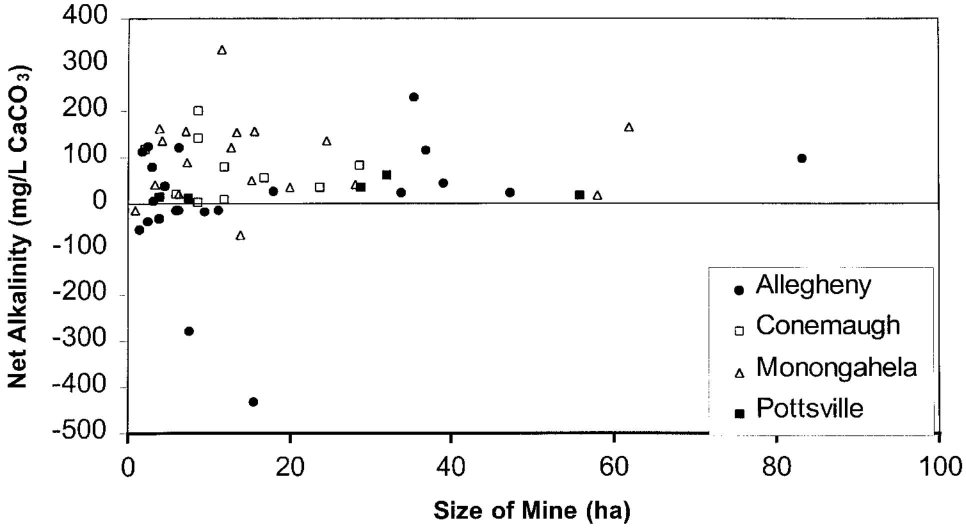

Fig. 3. The size of the surface mine and net alkalinity of drainage water for each of 56 sites in West Virginia.

In comparing our data with that of Brady et al. (1994), we found similar results (Table 7). We did not find a good relationship with our post-mining water quality data on acid sites and NP, but better relationships existed between NNP and NP to MPA ratios.

CONCLUSIONS

Acid–base accounting values have been adopted to help in the prediction of post-mining water quality on surface mines. Calculation of ABA parameters are based on volume adjustments for overburden, and three methods were tested to determine which one should be used. The volume adjustment method developed by the PADEP was found to be the most accurate and reliable method to calculate overburden mass.

Total MPA, NP, NNP, and NP to MPA ratios were determined for 56 surface coal mining sites and compared with post-mining water quality. The MPA showed a poor relationship, NP was intermediate, while NNP and NP to MPA ratio were equally good in predicting water quality from overburden. Eight of 56 sites had NP to MPA ratios < 1, and six of these eight sites (75%) produced acid drainage. The two remaining sites with <1 NP to MPA ratios were from southern West Virginia (SMP 1 and Pottsville Group geology) and produced only slightly alkaline drainage. Eight sites had NP to MPA ratios between 1 and 2, and only one of these eight sites (13%) produced acid drainage, and only slightly so. Thirty-six of 40 sites with NP to MPA ratios > 2 produced alkaline drainage (90%), but the four that produced acid drainage had very high ratios and would not have been expected to produce acid drainage. These four sites had acid water for reasons other than overburden quality.

From these data, all six sites in northern West Virginia (SMP 2 and 3) with NP to MPA ratios < 1 produced acid drainage. For all sites with an NP to MPA ratio $>$ 1, 43 out of 48 (90%) produced alkaline drainage, but only two of the five acid sites with an NP to MPA ratio of >1 (Upper Freeport Preston County surface mines in SMP 2) gave post-mining acid water above 40 mg/L $CaCO_3$. The other three acid drainage sites with NP to MPA ratios > 1 produced only slightly acid water (-15 to -17 mg/L $CaCO_3$ acidity). In general, an NP to MPA ratio of <1 will produce mostly acid drainage sites, between 1 and 2 will produce mostly alkaline drainage sites, while NP to MPA ratios > 2 will produce alkaline drainage with a few exceptions (generally because of other factors not accounted for in ABA).

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