PREDICTING POST-MINING WATER QUALITY OF SURFACE MINES BY ACID-BASE ACCOUNTING

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Abstract

Acid-Base Accounting (ABA) is an analytical procedure that provides values to help assess the acid- or alkaline-producing potential of overburden rocks prior to coal mining. This procedure was developed at West Virginia University in the late 1960s. After the passage of laws requiring an assessment of surface mining on water quality, ABA became the preferred method to predict post-mining water quality, and permitting decisions for surface mines are based on the values determined by ABA. In order to predict the post-mining water quality, the amount of acid-producing rock is compared to the amount of alkaline-producing 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/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 to actual overburden mass. A poor relationship existed between MPA and post-mining water quality, NP was intermediate, and NNP and the NP/MPA ratio showed the best prediction accuracy. In this study, NNP and the NP/MPA ratio gave identical water quality prediction results. So using NP/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 sites, NP/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 inaccurate ABA data, received water from an adjacent underground mine, or included some mining practice that degraded the water. In general, an NP/MPA ratio of <1 produced mostly acid drainage sites, between 1-2 produced mostly alkaline drainage sites, while NP/MPA ratios of >2 produced alkaline drainage with a few exceptions. Using the NP/MPA ratio, ABA is a good tool to assess overburden quality before mining and to predict post-mining drainage quality after mining, and was correct in 50 out of 56 cases (89%).

Introduction

Most coal mining state regulatory agencies began requiring the prediction of acid- and alkaline-producing 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 Surface Mining and Reclamation Law, 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). ABA was originally designed to distinguish layers in the overburden that could be used as topsoil substitutes or as hard durable rock for valley fills. But since the method identified acid- and alkaline-producing materials in the overburden, this method was the first technology available to predict the quantity of acid-producing materials prior to mining (Skousen et al., 1990). 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).

ABA, 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 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 and is expressed in metric tons/1000 metric tons (mt/1000 mt, or parts/1000 parts) of overburden (Kania, 1998). Refinements have been made recently on the NP method to discount artifacts from slower-reacting, non-alkaline-producing 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 rock 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 test results in a percent of sulfur present in the rock and is then multiplied by a constant to determine the MPA in mt/1000 mt. For the complete oxidation of pyrite and neutralization of all generated acidity,

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

1 mol of FeS_2 (64 g of sulfur) is neutralized by 2 mols of $CaCO_3$ (200 g of $CaCO_3$). Therefore, the constant is 31.25 and it takes 31.25 mt of $CaCO_3$ to neutralize 1000 mt 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:

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

In this reaction, 1 mol of FeS_2 is neutralized by 4 mols of $CaCO_3$. So using this equation, 1000 mt of rock containing 1% pyritic sulfur requires 62.5 mt 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 using the above methods, total NNP is determined for each stratigraphic layer by subtracting the MPA from the NP. Conceptually, a positive number indicates more potentially alkaline-producing strata in the overburden and a negative number indicates more potentially acid-producing strata in the overburden. The NP/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 toxic materials in the 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:

1) all sulfur in a sample will react to form acid,
2) all material in the sample which consumes acid in the laboratory will generate alkalinity in the field,
3) pyrite oxidation rate is less than or equal to the rate of neutralization,
4) NP and %S below certain thresholds do not influence water quality.

Because of these assumptions, many researchers have questioned the ability of ABA to accurately predict post-mining drainage quality (diPretoro and Rauch, 1988; Erickson and Hedin, 1988).

In the initial usage of ABA as a predictor of post-mining water quality, overburden calculations were made only according to layer thickness (thickness-weighted), giving equal weight to layers at the top and bottom of the column. However, most surface mines of Appalachia have hilly to mountainous topography with horizontal strata. So, a 2-meter-thick rock stratum high in the overburden contains much less volume of material than a 2-meter-thick rock stratum low in the overburden. Therefore, this method of interpretation overestimated the amount of alkaline material high in the overburden column, and created a situation where insufficient alkaline material was 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.

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, neutral, or alkaline 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 two 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 using actual 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 using the surface area and the measured thickness (Smith and Brady, 1990). No volume estimation technique has ever been compared to actual amounts of overburden moved on a surface mine.

Even though mass-weighting using 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/MPA ratio) best predicted post-mining water quality. In studies by diPretoro and Rauch (1988), Erickson 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 mt/1000 mt and NNP >30 mt/1000 mt produced net alkalinity in post-mining drainage. Erickson and Hedin (1988) found that an NNP >80 produced alkalinity and an NNP <20 typically produced acidity, but this study had no sites with NNPs between 20 and 80 mt/1000 mt. 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 mt/1000 mt and NNP >12 mt/1000 mt 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/MPA ratios 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/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 are also questions as to the most reliable and accurate method of volume adjustment to obtain mass of acid and alkaline 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/MPA ratio values, and then compared these values with post-mining water quality.

Methods

Site Selection and Data

Study sites were chosen to represent surface mining operations throughout the state of West Virginia (Figure 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 added, 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 WV Department of Environmental Protection. In order 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 overburden cores drilled above or near the highest point of mining (ABA data must include depth, thickness, rock type, %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 method modified from diPretoro and Rauch (1988) by Paul Ziemkiewicz. The cross-sectional area perpendicular to the highwall was calculated from depth and pit width, assuming the area was a right triangle. The cross-sectional area of each layer was calculated by interpolation using 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 measured slopes of unique shapes were measured, then the volumes for all the unique shapes were summed together to obtain total overburden amounts for the site. 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-most and lower-most 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 %S into metric tons of MPA and metric tons of NP. Spreadsheets for each overburden volume/mass calculation method are available from the authors.

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

Results and Discussion

Thirteen of the 56 sites were found in southern West Virginia (Figure 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 reason for the majority of sites to be found in northern counties is because of the general geology of West Virginia and its impact 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 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 (Figure 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 material or limestone in the strata, while the western part may have limestone or other alkaline-producing rocks associated with coal seams. Smith et al. (1976) separated these unique geologic settings into "surface mining provinces" (SMP on Figure 1 and Table 3). SMP 1 occurs in southern WV and is comprised of low sulfur and low carbonate rocks. SMP 2 occurs in the eastern part of the northern coalfield and contains coal beds and rocks with high sulfur and low carbonate content. SMP 3 is found in the western part of the northern coalfield with rocks 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. SMP 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).

Overburden Volume and Mass

Overburden volume estimates from three methods were converted to mass and compared to actual truck weights on five differently sized and shaped sites. The PADEP method was consistently closer to the actual overburden mass than the other two methods, giving an average % error of only –4% (Table 5). The Ziem method generally overestimated overburden mass. The average % 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 –3%, 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 over estimation 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 actual area over a 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/MPA 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 eleven sites that gave net acid water, eight were from Upper Freeport surface mines in Preston County (SMP 2), 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 Kittanning coal mine in Clay County (SMP 1), and a Pittsburgh coal mine in Upshur County (SMP 3). So 73% of the acid sites were from SMP 2, 18% were from SMP 3, and 9% were from SMP 1.

Not all SMP 2 surface mines produced acid drainage. Four operations in Preston County (SMP 2) mined the Bakerstown coal, which all produced very alkaline post-mining water quality, and the other three sites in Preston County were alkaline-producing Kittanning and Pittsburgh coal surface mines.

In comparing NNP with NP/MPA ratio for each site, there was no difference in the interpretation on its acid- or alkaline-producing status. For example, all negative NNP values showed <1 NP/MPA ratio, and a range of 0.4 to 17.4 mt/1000 mt NNP occurs in the 1 to 2 NP/MPA ratio. Therefore, for convenience, the rest of the ABA site categories will use the NP/MPA ratio

The prevailing thought is that sites with overburden NP/MPA ratios of <1 should produce acid mine drainage, while ratios of >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/MPA ratio with lines separating NP/MPA ratio categories of <1, 1-2, and >2.

In our study, eight sites had NP/MPA ratios of <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 WV) gave post-mining water qualities of –15 to 228 mg/L $CaCO_3$, but most were in the range of 5 to 60 mg/L $CaCO_3$.

Of the eight sites that gave NP/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). The other six sites with NP/MPA ratios between 1 and 2 were in northern and southern WV counties and included all SMPs.

Forty of the 56 sites had NP/MPA ratios >2. Of these sites, four produced net acid water. The Cr, SH, D2, and HP sites had NP/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), while the other was a Redstone/Pittsburgh coal mine from Upshur County (HP, and borders 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 excessive 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 thereby 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 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 alkaline-producing potential of the backfill material.

The 7-ha HP site is only slightly acidic 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 an otherwise alkaline-producing site to generate acid mine drainage. It is possible that non-alkaline-producing carbonates were counted as alkaline-producing carbonates in this overburden, which gave erroneously high NP numbers.

Figures 2 through 6 graphically show some of the ABA overburden parameters versus net alkalinity of post-mining water quality. Figure 2 showed no relationship ($R^2 = .02$) between MPA in mt/1000 mt and net alkalinity of post-mining water. Acid mine drainage occurred on sites with very low MPA (2.7 mt/1000 mt) to high MPA (20.1 mt/1000 mt). And alkaline drainage occurred on sites with 20 to 45 mt/1000 mt MPA. So the critical parameter for post-mining water quality prediction was not total sulfur or potential acidity calculated from total sulfur measurements. Brady et al. (1994) similarly found no relationship between MPA and post-mining water quality.

diPretoro and Rauch (1988) suggested that sites with NP <20 would produce acid drainage, while Brady et al. (1994) indicated this value was <10. Total NP correlated with net alkalinity in post-mining water on our 56 sites (Figure 3, $R^2 = .12$). Nineteen sites had total NP <20 mt/1000 mt with only six having acid water (32%). Twelve sites had NP values <10 mt/1000 mt and only four (33%) produced acid drainage (Table 7). Five sites out of 37 with NP >21 mt/1000 mt (14%) gave acid drainage, and two of these acid sites had total NP >40 mt/1000 mt. Therefore, 86% of sites with NP >21 mt/1000 mt gave alkaline drainage. From our data, NP was not a clear indicator for acid post-mining water quality.

Total NNP combines MPA and NP into one variable, which was plotted against net alkalinity (R^2 = .15, Figure 4). 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 mt/1000 mt gave acid drainage, two sites with NNPs of –1.9 and –0.9 gave neutral drainage, and three sites with NNPs between 0.4 and 1.6 gave a mixture of drainage. 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 mt/1000 mt. Therefore, six of eight sites (75%) with <0 NNP produced acid drainage, while 32 of 36 sites (89%) with >12 NNP produced alkaline drainage (Table 7). Twelve sites between 0 and 12 NNP all produced alkaline drainage except one.

The NP/MPA ratio is also used to predict acid drainage. Figure 5, plotting NP/MPA ratio against net alkalinity, shows the same trend as NNP versus net alkalinity (R^2 = .12). The same four sites with acid water and high NP/MPA ratios (2.2 to 8.9) are apparent on this graph. Six acid drainage sites fit the general prediction pattern of NP/MPA ratios of <1 producing acid drainage, and one site with a 1.2 NP/MPA ratio also produced slightly acid drainage. So, in general, an NP/MPA ratio of <1 will produce mostly acid drainage sites, between 1-2 will produce mostly alkaline drainage sites, while NP/MPA ratios of >2 will produce alkaline drainage with a few exceptions.

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 (Figure 6). All 19 sites >15 ha gave alkaline water, while eleven 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 calcareous strata.

In comparing our data to that of Brady et al. (1994), we found very 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/MPA ratios.

Summary and 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/MPA ratios were determined for 56 surface coal mining sites and compared to post-mining water quality. The MPA showed a poor relationship, NP was intermediate, while NNP and NP/MPA ratio were equally good in predicting water quality from overburden. Eight of 56 sites had NP/MPA ratios of <1, and six of these eight sites (75%) produced acid drainage. The two remaining sites with NP/MPA ratios <1 were from southern WV and produced only slightly alkaline drainage. Eight sites had NP/MPA ratios of 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/MPA ratios >2 produced acid drainage (90%), but all four had very high ratios and would not have been expected to produce acid drainage.

From these data, all six sites in northern West Virginia (SMP 2 and 3) with NP/MPA ratios <1 produced acid drainage. For all sites with an NP/MPA ratio >1, 43 out of 48 (90%) produced alkaline drainage, but only two of the five acid sites with an NP/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/MPA ratios >1 produced only slightly acid water (-15 to -17 mg/L $CaCO_3$ acidity). In general, an NP/MPA ratio of <1 will produce mostly acid drainage sites, between 1-2 will produce mostly alkaline drainage sites, while NP/MPA ratios of >2 will produce alkaline drainage with a few exceptions.

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

ABA Parameter	Calculated Value	Predicted Water Quality	Source
NP	<20	net acid	
(mt/1000 mt)	>40	net alkaline	diPretoro and Rauch, 1988
	<10	net acid	
	>21	net alkaline	Brady et al., 1994
NNP	<10	net acid	
(mt/1000 mt)	>30	net alkaline	diPretoro and Rauch, 1988
	<20	net acid	
	>80	net alkaline	Erickson and Hedin, 1988
	<0	net acid	
	>12	net alkaline	Brady et al., 1994
	<0	net acid	
	>15	net alkaline	Skousen et al., 1987
NP/MPA	<1	net acid	
	>2	net alkaline	Perry, 1998

Table 2. Unit weight (mt/ha-m[1]) of rocks used in this study to calculate volumes and mass of overburden materials (Caterpillar, 1991).

Rock Type	Unit Weight (mt/ha-m)[1]
Soil	18,174
Sandstone	28,122
Shale	32,324
SS/SH	30,228
Mudstone	32,627
Limestone	31,664
Coal	16,461

[1]mt/Ha-m is a conversion from tons/Ac-ft (x 8.922)

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

County	Number of Sites	SMP	Northern or Southern WV
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

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

Group	Coal Seam	Number of 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 & 6 Block)	5
Kanawha	Alma-Eagle	2
	Gilbert-Eagle	1
	Peerless	2
	Glenalum Tunnel	1

Table 5. Comparison of overburden amounts (total metric tons of overburden, NP, MPA, and NP/MPA ratio) calculated by three different methods (Ziem, S&S, and PADEP) and the actual overburden amounts determined from haulage trucks.

Site	Method	Total Overburden	% Error	NP	MPA	NP/MPA
		(mt)		(mt/1000 mt)		
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
	Actual	**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
	Actual	**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
	Actual	**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
	Actual	**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
	Actual	**97,672,582**				
	Average % Error					
	Ziem		118			
	S&S		- 23			
	PADEP		- 4			

Table 6. Summary of Acid-Base Accounting sites with size, location, overburden amounts, NP/MPA ratios and accompanying post-mining water quality. Sites are sorted by NP/MPA ratio.

Site Ref	Ha	County	Coal Seam	Overburden	Total MPA		Total NP		Total NNP		NP/MPA	Net Alkalinity
				(mt)	(mt)	(t/1000 t)	(mt)	(t/1000 t)	(mt)	(t/1000 t)		mg CaCO3/L
4H	6	Preston	UF	337588	2221	6.6	-752	-2.2	-2973	-8.8	0.1	**-15**
Bf	7	Preston	UF	934128	14882	15.9	3000	3.2	-11882	-12.7	0.2	**-277**
CF	4	Monongalia	Waynesburg	1038498	9665	9.3	4273	4.1	-5392	-5.2	0.4	**-70**
ED	15	Preston	UF	20355	40998	20.1	20949	10.3	-20049	-9.8	0.5	**-432**
PM	7	Fayette	Glenalum Tunnel	1065799	2498	2.3	1550	1.5	-948	-0.9	0.6	12
MP	9	Preston	UF	3381693	150361	44.5	107596	31.8	-42765	-12.6	0.7	**-20**
IL	4	Preston	UF	652264	5171	7.9	3666	5.6	-1505	-2.3	0.7	**-35**
PR	3	Clay	UK	505750	4683	9.3	3720	7.4	-964	-1.9	0.8	5
GF	3	Preston	UF	327022	2915	8.9	3176	9.7	261	0.8	1.1	78
Al	11	Clay	MK	1958976	5227	2.7	6101	3.1	875	0.4	1.2	**-15**
MC	29	Nicholas	Gilbert, Eagle	5468383	19477	3.6	28436	5.2	8960	1.6	1.5	35
WS	17	Grant	Elklick	1545580	23277	6.9	34464	10.2	11187	3.3	1.5	55
CH2	58	Monongalia	Waynesburg	13854644	313265	22.6	486060	35.1	172795	12.5	1.6	151
ST2	6	Grant	Elklick	388118	5142	13.2	8417	21.7	3276	8.4	1.6	20
Id	2	Preston	Bakerstown	222380	6206	27.9	10065	45.3	3858	17.4	1.6	117
SH1	6	Preston	LF	706917	5183	7.3	10409	14.7	5226	7.4	2.0	120
Cr	1	Preston	UF	130380	2367	18.2	5287	40.6	2920	22.4	2.2	**-59**
SC	6	Preston	Pitt	1265219	12441	9.8	29186	23.1	16745	13.2	2.3	121
KE	62	Monongalia	Waynesburg	19520492	454663	23.3	1171080	60.0	716417	36.7	2.6	86
F2	39	Kanawha	5B & 6B, UK	38302154	205345	5.4	536360	14.0	331015	8.6	2.6	43
PT	13	Taylor	Pitt	1882875	21871	11.6	60977	32.4	39106	20.8	2.8	50
ST1	23	Grant	Harlem	989438	13199	13.3	36650	37.0	23451	23.7	2.8	35
CT2	20	Barbour	Red/Pitt	3496292	80383	23.0	230110	65.8	149726	42.8	2.9	15
SH	2	Preston	UF	453277	3878	8.6	12223	27.0	8345	18.4	3.1	**-40**
HG	83	Webster	UF, M/U K	72731064	297532	4.1	943949	13.0	646417	8.9	3.2	95
LR	12	Tucker	Harlem	2537008	14657	5.8	48491	19.1	33834	13.3	3.3	8
CH1	13	Monongalia	Waynesburg	4738442	61185	12.9	205853	43.4	144668	30.5	3.4	136
D2	6	Preston	UF	2748993	26318	9.6	94939	34.5	68622	25.0	3.6	**-16**

FM	47	Preston	LF, UK	17594460	162661	9.2	634981	36.1	472320	26.8	3.9	23
GY	1	Harrison	Red/Pitt	82539	1503	18.2	5970	72.3	4466	54.1	4.0	155
OS	15	Monongalia	Waynesburg	6302681	88079	14.0	359870	57.1	271791	43.1	4.1	136
B9	2	Braxton	LK	562023	1330	2.4	5597	10.0	4267	7.6	4.2	124
BG	56	Webster	Peerless	14265548	77564	5.4	333650	23.4	256086	17.9	4.3	15
DV	3	Monongalia	Waynesburg	705602	8608	12.2	37218	52.8	28611	40.6	4.3	35
B1	4	Nicholas	UF	818249	1743	2.1	8515	10.4	6772	8.3	4.9	38
CV	28	Barbour	Bakerstown	3256168	26896	8.3	142318	43.7	115422	35.5	5.3	80
NA	9	Mineral	Bakerstown	3180669	24547	7.7	139353	43.8	114806	36.1	5.7	2
BK	11	Taylor	Pitt	2187471	19098	8.7	111656	51.0	92376	42.2	5.9	52
ME	24	Monongalia	Sewickley/Red	14046738	194594	13.9	1244119	88.6	1049525	74.7	6.4	40
L2	32	Fayette	Alma-Eagle	28720220	43374	1.5	281035	9.8	237661	8.3	6.5	60
DC	37	Grant	UF	17629079	68662	3.9	450492	25.6	381831	21.7	6.6	115
FT	15	Monongalia	Red/Pitt	2842694	109896	38.7	741010	260.7	631114	222.0	6.7	40
TM	34	Nicholas	U/M K, 5B	14070755	13496	1.0	93787	6.7	80292	5.7	7.0	21
BN	7	Monongalia	Waynesburg	2482974	24799	10.0	196801	79.3	172001	69.3	7.9	331
SH2	4	Monongalia	Waynesburg	1113515	10576	9.5	88637	79.8	78061	70.1	8.4	18
JR	9	Preston	Bakerstown	997810	7358	7.4	65758	65.9	58400	58.5	8.9	200
HP	7	Lewis/Upshur	Red/Pitt	1387021	7206	5.2	64270	46.3	57064	41.1	8.9	**-17**
LC	28	Harrison	Red/Pitt	12325583	183503	14.9	1646794	133.6	1463291	118.7	9.0	164
MR	4	Randolph	Peerless	715516	2149	3.0	19452	27.2	17304	24.2	9.1	12
WY	18	Grant	UF	5139305	29337	5.7	274223	53.4	244887	47.6	9.4	25
TR	39	Upshur	Red/Pitt	13133228	196988	15.0	1898430	144.5	1701442	129.5	9.6	160
AR	35	Webster	UF, M/U K	32218656	94264	2.9	931925	28.9	837662	26.0	9.9	228
BR	14	Monongalia	Sewickley/Red	2909166	33061	11.3	368999	126.8	335938	115.5	11.2	156
St	9	Preston	Bakerstown	2587492	13749	5.3	287981	111.3	274232	106.0	21.0	140
WF	12	Preston	Bakerstown	1282311	3761	2.9	85179	66.4	81418	63.5	22.9	78
SM	2	Preston	UF	98975	366	3.7	11342	114.6	10977	110.9	31.0	110

Table 7. Comparison of acid-base accounting 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	% of Sites Accurately Predicted This Study	% of Sites Accurately Predicted Brady et al.
NP	<10	net acid	33	73
	>21	net alkaline	86	100
NNP	<0	net acid	75	78
	>12	net alkaline	89	100
NP/MPA	<1	net acid	75	NA
	>2	net alkaline	89	NA

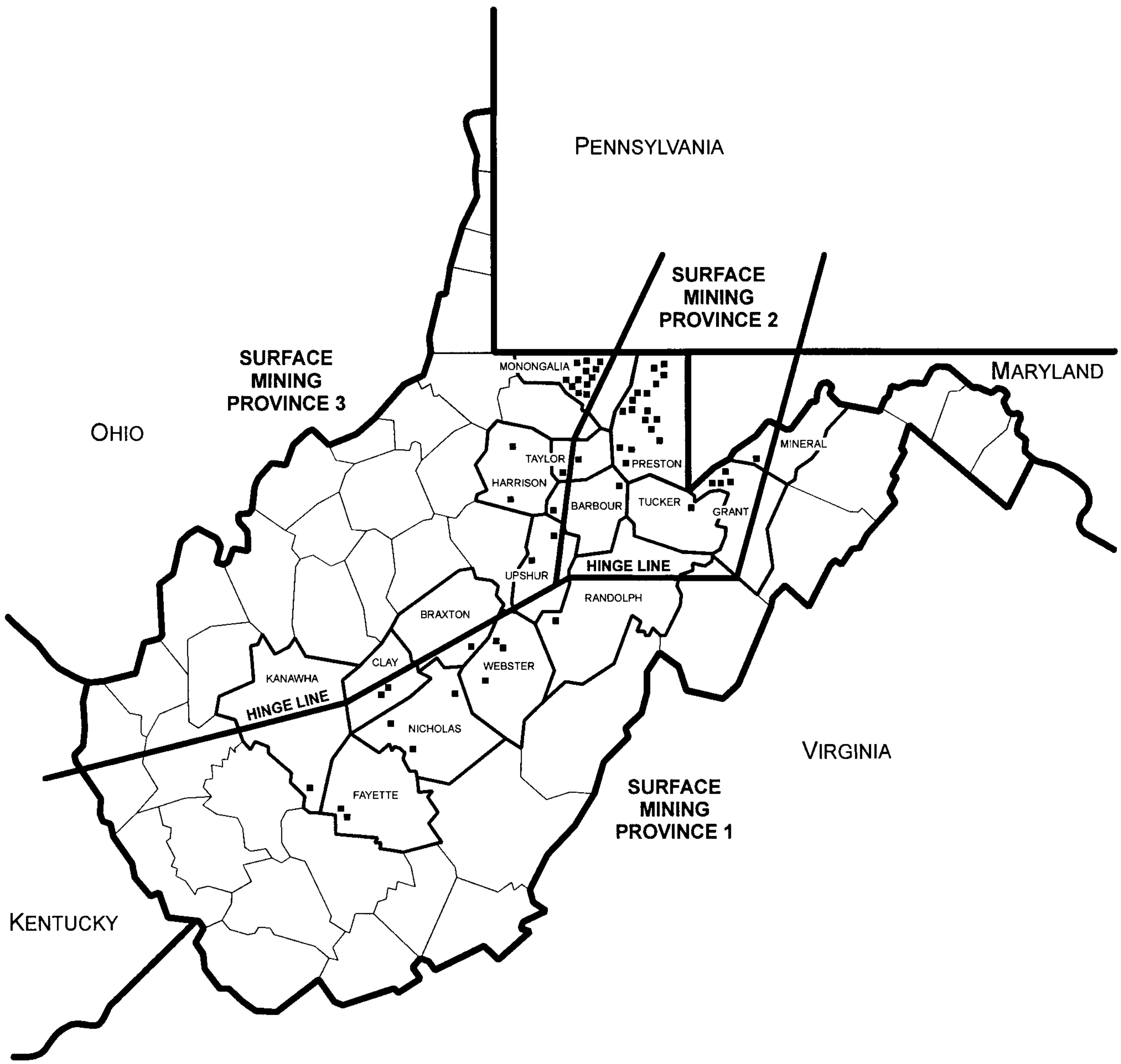

Figure 1. Location of 56 study sites in West Virginia and boundaries of the Surface Mining Provinces (SMP).

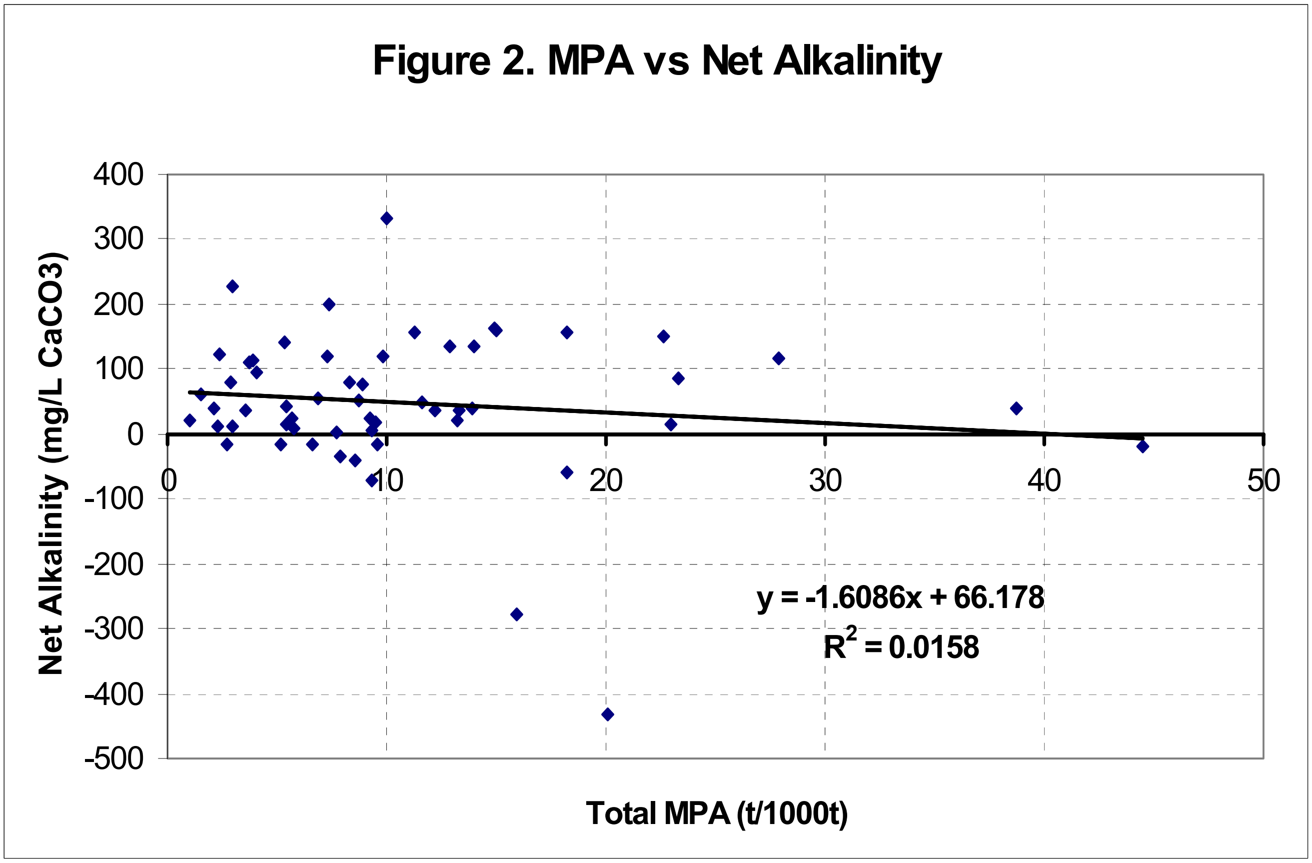

Figure 2. Maximum potential acidity (MPA) and net alkalinity of drainage water for each of 56 sites in West Virginia.

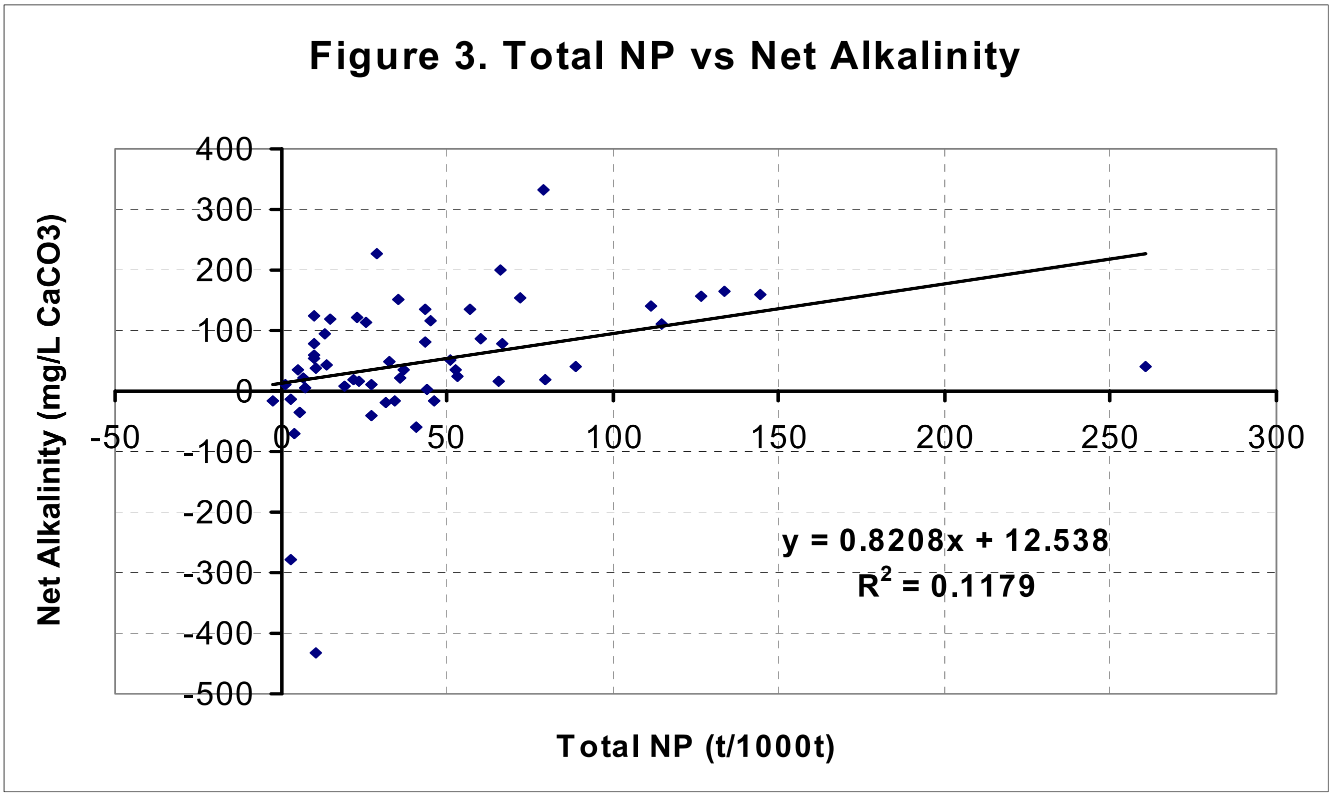

Figure 3. Total neutralization potential (NP) and net alkalinity of drainage water for each of 56 sites in West Virginia.

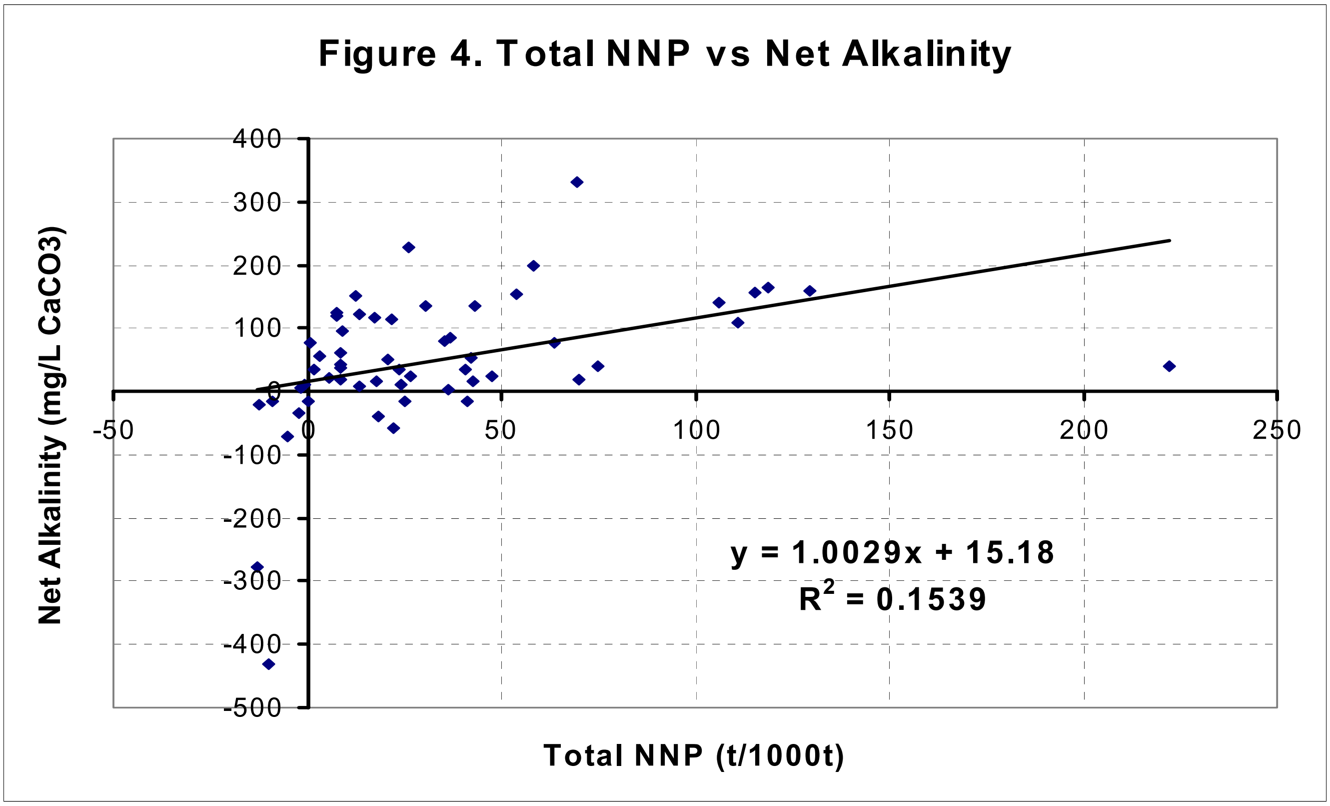

Figure 4. Total net neutralization potential (NNP) and net alkalinity of drainage water for each of 56 sites in West Virginia.

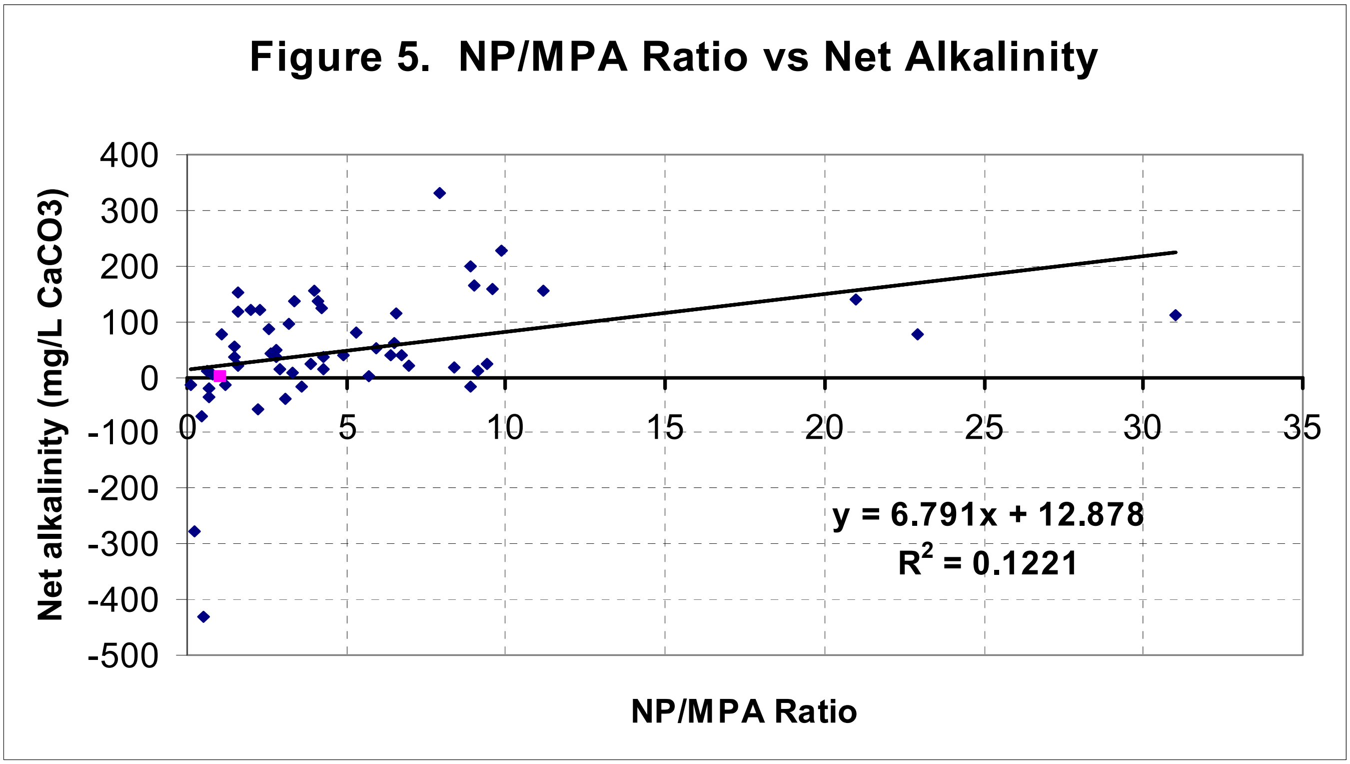

Figure 5. The ratio of neutralization potential and maximum potential acidity (NP/MPA) and net alkalinity of drainage water for 56 sites in West Virginia.

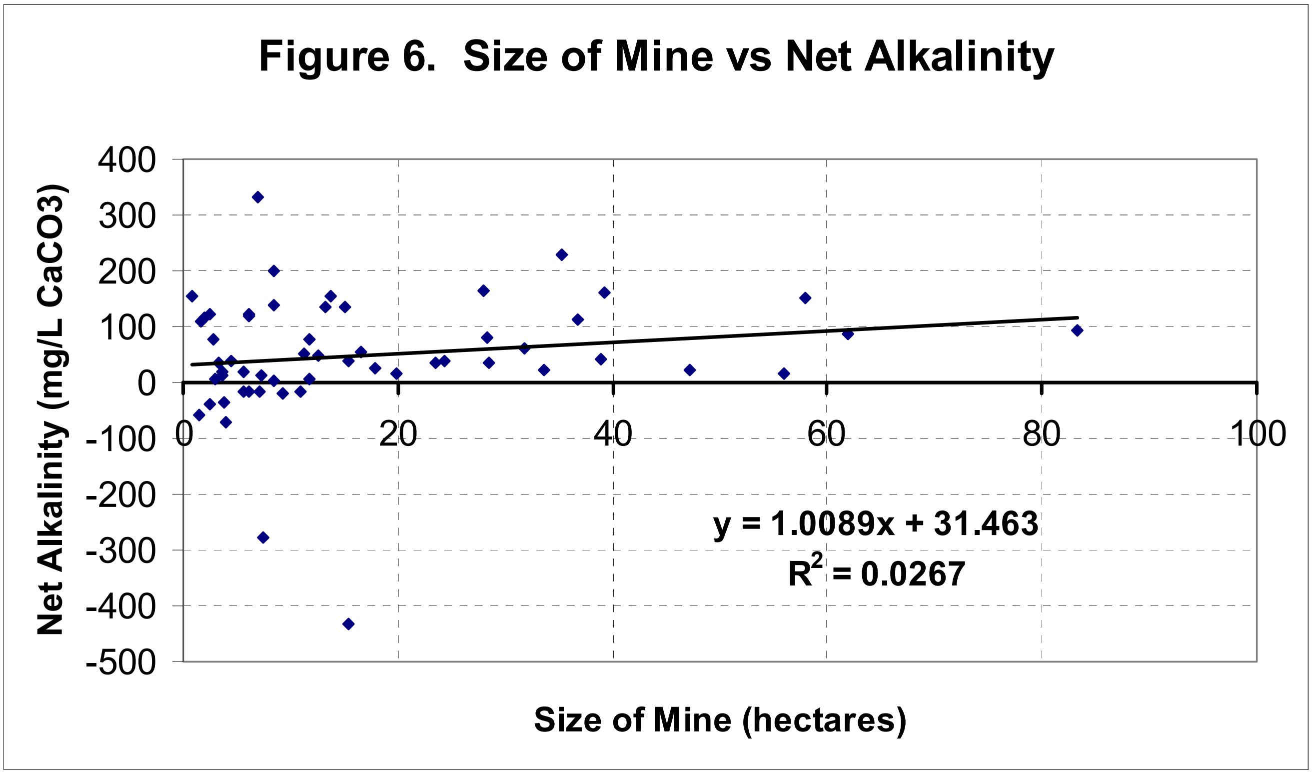

Figure 6. The size of the surface mine and net alkalinity of drainage water for each of 56 sites in West Virginia.