ground water

Predictability of Surface Mine Spoil Hydrologic Properties in the Appalachian Plateau

by Jay W. Hawkins[1]

Abstract

Prevention of acid mine drainage at surface coal mines in the Appalachian region relies to an extent on minimizing ground water contact with acid-forming materials, and maximizing ground water contact with alkalinity-yielding materials. Acid-forming materials are often selectively handled to minimize or prevent contact with ground water. Controlling ground water contact with acidic or alkaline materials depends on forecasting the level and range of fluctuation of the postmining water table within the mine backfill. Physical measurements and aquifer testing of more than 120 wells from 18 reclaimed mines in Kentucky, Ohio, Pennsylvania, and West Virginia have led to improved forecasting of the postmining ground water system. Factors that influence the ground water regime include spoil lithology and particle size, age of reclamation, spoil thickness, distance from the final highwall, and pit floor dip angle and direction. Spoil hydraulic conductivity (K) exhibits a 95% confidence interval range of six orders of magnitude about a mean K of 1.7×10^{-5} m/sec. Spoil aquifer saturated thickness is related to the overall thickness of the spoil, the lithology of the spoil, dip of the pit floor, and distance to the highwall. Saturated spoil thickness has a 95% confidence interval of 2.2 to 3.6 m about the mean of 2.9 m. The predicted saturated zone averages 19% of the total spoil thickness.

Introduction

An essential element in the prevention and abatement of acid mine drainage (AMD) from surface coal mines is forecasting characteristics of the postmining ground water system. Ground water is important because it dissolves the metal-sulfate salts formed from pyrite oxidation, and is a chemical component in the formation of AMD through hydrolysis. Ground water also releases alkalinity through dissolution of alkaline strata, primarily calcium carbonate-rich rocks.

AMD prevention and mitigation techniques in the Appalachian Plateau frequently require that the acid-forming materials (AFMs) and alkaline materials be selectively placed in the backfill to keep them separated and in contact with ground water, respectively. For selective placement (special handling) to be effective, the water table location and ground water flow characteristics through the spoil aquifer should be predicted. The influence of seasonal fluctuations in ground water levels is equally important.

AFMs are segregated during mining and placed in isolated pods or layers in the mine backfill, which are projected to be above the level of the postmining water table, and capped by a low-permeability material. Conversely, alkaline materials are positioned to maximize ground water contact. The problem with materials special handling is an inability to reasonably predict the characteristics of the postmining ground water system. Premining water levels are no longer valid, because the premining aquifers above the coal have been destroyed and the backfill represents a completely new aquifer system with vastly different hydrologic characteristics. If postmining aquifer properties can be estimated prior to reclamation, then hydrologic engineering can be used to control or prevent ground water from contacting AFMs or facilitate ground water contact of alkalinity-producing materials.

During surface mining, strata overlying the coal (overburden) are removed by blasting and excavating. Once the coal is extracted, the fragmented overburden (spoil) is dumped and pushed into the pit during backfilling. Initially,

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material placed on the elevated areas (spoil ridges and piles) tends to be poorly sorted. Larger spoil particles will however roll to the base of the spoil ridges creating well sorted, highly transmissive zones. Extreme heterogeneity is introduced into the backfill material by the broad range of particle sizes and differences in particle sorting (Hawkins 1998).

Heterogeneties introduced during mining and reclamation cause spoil to exhibit a dual-flow ground water system. Mine backfill contains a substantial percentage, by volume, of large (macro) voids. The void volume may equal the spoil swell (a volume increase from mining), which may be as high as 20% to 25%. Porosity values of 16% and 23% have been recorded by field measurements in mine spoil in the western and eastern coalfields, respectively (Rahn 1976; Hawkins 1998). The macro voids are within a matrix of unconsolidated material composed of clay-sized (< 2 microns) to very large boulder-sized (> 2 m) particles. The macro voids behave similar to a karst aquifer, capable of storing and transporting large quantities of water and may exhibit multiple water tables within the same unit (Caruccio et al. 1984), whereas spoil material itself behaves as a highly transmissive unconsolidated porous medium. Mine spoil exhibits an average hydraulic conductivity two orders of magnitude greater (geometric mean) than adjacent unmined strata (Hawkins 1998).

The ability to predict, with reasonable accuracy, where the ground water table in spoil aquifers will reestablish and the range of fluctuation are elemental for successful mine drainage prediction and pollution prevention. Additionally, more accurate K estimates will allow these sites to be numerically modeled to predict the location and anticipated fluctuation of the postmining ground water table.

Purpose

Environmental failures at reclaimed surface coal mines (e.g., creation of acidic, metal-rich discharges) where special handling of acid-forming and/or alkalinity-yielding materials were performed illustrate the need for a better understanding of the postmining ground water regime. This study was initiated to better define some poorly quantified aspects of surface mine spoil ground water hydrology. The purpose of this paper is to assess the possibility of forecasting water levels and K values of reclaimed surface mine spoil prior to mining. If a reliable forecasting methodology can be developed, special handling plans for preventing AMD for surface coal mines can be improved. The water level and K forecasting performed herein are based on the factors of mine backfill age, spoil lithology, spoil thickness, dip of the pit floor, and distance to the closest unmined strata (highwall). Spoil age was selected as parameter, because spoil properties evolve with time. Lithology impacts the initial size of the spoil particles and ultimate particle size with weathering. Spoil thickness relates to the degree of compaction of the material nearest to the pit floor. Pit floor dip influences the direction of ground water movement and velocity. Adjacent highwalls tend to impound ground water, or impede its movement into the spoil. These factors were also selected because they are available from premining permitting information, which allows a wider use of any methodology developed. Several other possible controlling factors were originally considered such as blasting, infiltration estimates, ground slope, etc. These other factors were rejected from lack of data, or extreme difficulty in collection accurate site-specific data.

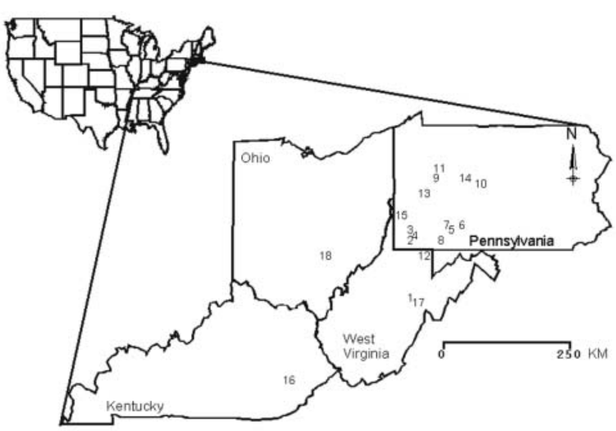

Figure 1. Location map of the test sites.

Table 1
Distribution of Test Sites

Site Number	Number of Wells	State
1	16	WV
2	7	PA
3	13	PA
4	2	PA
5	1	PA
6	5	PA
7	2	PA
8	2	PA
9	12	PA
10	7	PA
11	13	PA
12	4	WV
13	13	PA
14	3	PA
15	4	PA
16	5	KY
17	6	WV
18	9	OH

Methods

Aquifer testing and physical measurements were performed on 124 wells installed in the backfills of 18 reclaimed surface mines in the bituminous coalfields of Kentucky, Ohio, Pennsylvania, and West Virginia. Table 1 shows the number of wells for each of the mines shown in Figure 1.

Aquifer tests included slug injection (falling head) or slug withdrawal tests. A solid cylinder or a measured volume of water was used to raise the water level in the monitoring wells during the slug injection tests. A bailer or a solid cylinder was used to lower the water level during the slug withdrawal tests. Projected water level displacement ranged from slightly < 1 to > 10 m. Actual displacements were usually much lower. The high porosity and presence of large voids in spoil at times require large slug volumes to obtain a reasonable water level displacement. Recoveries to static water levels were measured using pressure transducers. Data loggers, in the log mode, initially recorded water levels at 0.2 second intervals to the nearest 5 mm. The time interval between measurements increased with each log cycle, with a maximum interval of one minute. The slug tests analyses were performed using methods developed by Bouwer and Rice (1976) and Bouwer (1989), which were designed for unconfined conditions. Mine spoil behaves as an unconfined aquifer under most circumstances (Hawkins 1998).

Data including overburden thickness, lithology, extent of mining, strike and dip of the pit floor, and age of reclamation were obtained primarily from the state surface mine permit files. Rock type percentages (e.g., shale and sandstone) were determined volumetrically from drill hole logs and planimetered areas. Spoil thickness was based on drill logs of the monitoring wells and supplemented with direct field measurements. Pit floor dip was calculated using three or more premining drill holes. The location and distance to a highwall or a lowwall was measured from existing mine reclamation maps or directly in the field. Spoil aquifer saturated thickness at each well was determined by field measurements taken prior to the aquifer testing.

Data Analyses Results

Data sets were analyzed using a variety of summary and nonparametric statistical methods to determine the predictability of postmining water table levels and K values in reclaimed mines. All data were analyzed with the same testing methods. The more salient and usable results are presented in this paper. The complete raw data set is not included here, but will be provided upon request.

Summary Statistics

A summary of the aquifer testing results illustrates a wide range of K values in the data set (Table 2). K ranges over seven orders of magnitude from 4.0×10^{-9} to 7.0×10^{-2} m/sec. Data analysis indicates a nonnormal (positively skewed) distribution, so the median and geometric mean were used to represent the central tendency of the raw data. Both values were 1.7×10^{-5} m/sec. The 25th and 75th percentiles show that 50% of the data fall between 1.7×10^{-6} and 1.7×10^{-4} m/sec. The distribution of K data becomes normal when transformed (log base 10), yielding a mean of 1.7×10^{-5} m/sec, which equals the median.

Within single mines with five or more monitoring wells, K varied between one to greater than five orders of magnitude, which is similar to the four order of magnitude range (10^{-7} to 2×10^{-3} m/sec) recorded by Maher and Donovan (1997) for a mine in central West Virginia. Median K values for the mines with five or more wells ranged from 2.6×10^{-7} to 1.1×10^{-3} m/sec.

Saturated thickness of reclaimed spoil measured at the 124 wells ranged from 0.2 to 11.0 m, with a median of 2.9 m and a geometric mean of 2.5 m (Table 2). Because the raw data were shown to be slightly nonnormally distributed, the data set was transformed yielding a 95% confidence interval for the mean (2.9 m) of 2.2 to 3.6 m.

Spoil thickness exhibited a range of 3.8 to 32.0 m. These data were normally distributed and yielded a mean of 15.2 m with a 95% confidence interval of 0.8 to 29.6 m (Table 2).

The age of the reclaimed sites ranged from 10 to 360 months (Table 2). The data were normally distributed with a mean of 133.1 months and a 95% confidence interval about the mean of 117.3 to 149.0 months.

Percent sandstone of the spoil data set (Table 2) had a mean of 57%. The large standard deviation yields a predicted 95% confidence interval that is beyond the constraints of percentage. However, the 25th and 75th percentiles were 38.4%

Table 2
Summary Data

Maximum	K in m/sec	Saturated Thickness in Meters	Spoil Thickness in Meters	Age of Spoil in Months	Sandstone %	Shale %	Strata Dip in Degrees	Distance to Highwall in Meters
Mean	1.93×10^{-3}	3.3	15.2	133.1	57.1	42.9	1.1	193.5
Median	1.72×10^{-5}	2.9	13.8	144.0	55.6	44.4	1.0	42.1
Geometric Mean	1.70×10^{-5}	2.5	13.4	103.1	65.8	34.2	1.0	59.2
Standard Deviation	8.84×10^{-3}	2.2	7.2	89.1	25.9	25.9	1.6	320.7
Minimum	4.45×10^{-9}	0.2	3.8	10.0	0	10.0	0.2	1.5
Maximum	7.58×10^{-2}	11.0	32.0	360.0	90.0	100.0	7.1	1524.0*
Range	7.58×10^{-2}	10.8	28.2	350.0	90.0	90.0	6.9	1522.5
Lower Quartile	1.69×10^{-6}	1.4	9.6	68.0	38.4	13.9	0.6	20.6
Upper Quartile	1.69×10^{-4}	4.5	20.5	156.0	86.1	61.6	1.9	170.1

*This value is for sites with a post-mining highwall. Several mines had no remaining highwall.

and 86.1%, respectively. The percent shale did not require analysis because it would exhibit a mirror image of the sandstone, since overburden strata were identified to be either sandstone or shale. To simplify the lithologies to one parameter, a ratio of sandstone to shale is employed throughout most of the remainder of the analyses.

The dip of the pit floor measured at the 18 sites ranged from 0.2° to 7.1° with a median of 1.0° (Table 2). Because the raw data were shown to be nonnormally distributed, the data set was transformed. The 25th and 75th percentiles were 0.6° and 1.9°, respectively.

The measured distance of the wells to the highwall ranged from 1.5 m to there being no remaining highwall. The median distance was 42 m for the sites that had remaining highwalls (Table 2). The distance of the wells to the highwall were determined to be nonnormally distributed, so these data were transformed. The mean value was 59.2 m with a 95% confidence interval of 40.2 to 87.1 m.

Bivariate and Multivariate Analyses

Initial data analyses indicate that K or aquifer saturated thickness could not be predicted by a relatively simple model. Forecasting methodologies had to include several variables that impact K and saturated thickness. Most attempts at simple and multiple regression were less than successful, yielding $r^2 < 20\%$. However, several analyses did yield reasonable predictive regression models. Some general predictive methodologies have also been found using other analytical procedures. To permit the use of regression analyses, the data were transformed to approximate a normal distribution when needed.

For reclaimed mines < 60 months old, reasonable multiple regression results ($r^2 = 76.3\%$, significant at the 95% confidence level) were observed for saturated thickness of spoil (independent variable) against the sandstone/shale ratio of the spoil, age of the spoil, total spoil thickness, and the distance to the highwall (dependent variables) (Equation 1). The r^2 for mines ≥ 60 months old ($r^2 = 41.2\%$, significant at the 95% confidence level) was lower than for younger reclaimed mines (Equation 2).

$$S_{st} = -1.085 - 0.394R_{ssh} - 0.000795D_h + 0.159T_s + 0.082M \qquad (1)$$

where M > 60 months

$$S_{st} = 0.170 + 0.0841R_{ssh} + 0.00951M + 0.184T_s - 0.000794D_h \qquad (2)$$

where M < 60 months
and where
S_{st} = spoil saturated thickness
R_{ssh} = sandstone to shale ratio
D_h = distance to the highwall
T_s = spoil thickness
M = age of spoil in months

Significant differences (95% confidence level) were observed between median K values based on pit floor dip. Median K of sites with a dip < 2° was significantly greater (2.7×10^{-5} m/sec) than those sites with a dip ≥ 2° (2.1×10^{-6} m/sec) based on Kruskal-Wallis and Kolmogorov-Smirnov tests. Similar results, i.e., significantly different medians, were achieved using exploratory data analysis, which is graphically illustrated by notched box and whisker plot (Figure 2). Lack of overlap of the notches about the median indicates the medians come from two different populations significant at a 95% confidence level (McGill et al. 1978). The 2° pit floor dip angle threshold was established primarily through an iterative analysis process.

Increasing saturated thickness is related to increasing spoil thickness (Table 3). When the spoil thickness is > 15 m, the saturated thickness median of 4.1 m is significantly greater than the saturated thickness median of 2.1 m when the spoil is < 15 m thick at a 95% confidence level. The differences of median saturated thickness continue with greater spoil thicknesses of above and below 20 and 25 m, which were significant at a 95% confidence level. These assessments were determined using the Kruskal-Wallis and Kolmogorov-Smirnov tests.

No significant relationships were found between spoil thickness and K ($r^2 < 1.0\%$). Multiple regression analyses to predict K were unsuccessful, regardless of the data transformations and variable combinations used. It was anticipated, a priori, that there may be a relationship between K and spoil thickness, lithologic content, saturated thickness, and age of the backfill. Previous work on these data showed there are significant differences between median K values of sites of differing ages. Sites < 31 or > 100 months old exhibited a significantly lower median K compared to sites 31 to 100 months or more old. The smaller K values associated with mines < 31 months old are attributed to the poor interconnection of voids and pore spaces of the relatively freshly reclaimed spoil in which the water table may take up to 24 months to rebound (Hawkins 1998). On the other hand, small K values at mines > 100 months old appear to be caused by spoil compaction, rock weathering, piping, and settlement that decrease the void and pore spaces as these sites age. While these relationships are still valid, no reasonable correlation for K could be approximated using regression analysis for age or any of the other factors.

Saturated thickness was shown to have a relationship to spoil lithology. The median saturated thickness for spoil with sandstone content ≥ 35% (3.1 m) is significantly greater than the median for sites with < 35% sandstone content (1.8 m); however, no reasonable regression correlation

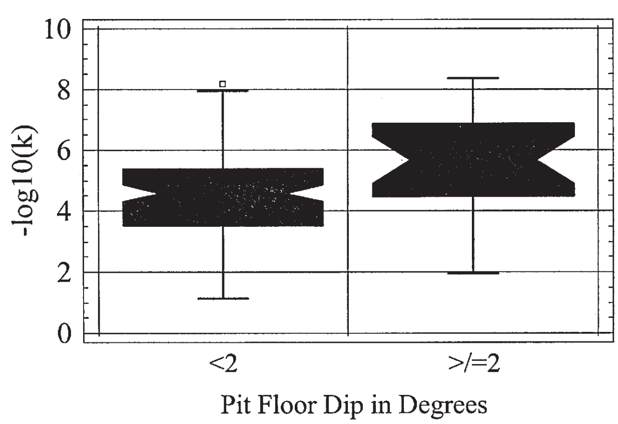

Figure 2. Comparison of spoil K values by pit floor dip.

Table 3 Relationship of Spoil Thickness and Saturated Thickness	
Total Spoil Thickness	**Median Saturated Thickness**
< 15 m	2.1 m
>15 m	4.1 m
< 20 m	2.5 m
> 20 m	4.1 m
< 25 m	2.9 m
> 25 m	5.2 m

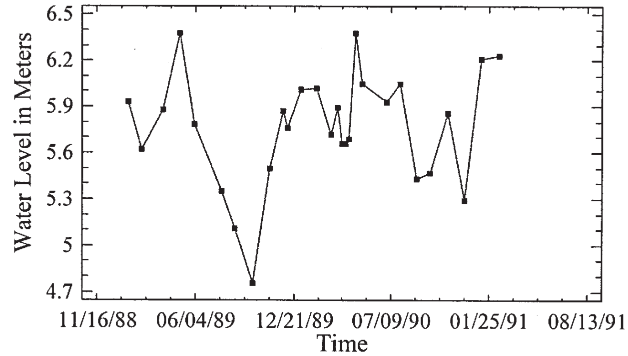

Figure 4. Water level fluctuation in well 1 of site 1.

between saturated spoil thickness and lithology could be obtained.

More than two years of water level monitoring from 13 wells located within site 1 (Figure 1) were analyzed to estimate the range of water table fluctuations in a mine spoil aquifer. Of specific interest were the fluctuations above the average levels recorded. The mean maximum rise above the average static water level for the wells was determined to be 36.5% with a standard deviation of 6% (the data were log transformed). Therefore, 97.5% of wells in that spoil aquifer should rise no more than 48.5% above their respective means. It is interesting to note that the greater the average saturated thickness, the lower the maximum rise in percentage was observed (Figure 3). Large water table fluctuations are related to the elevated K values common to the spoil and to rapid high-volume of recharge from precipitation events observed in mine spoil (Hawkins and Aljoe 1990). Figure 4, well 1 from site 1 during a 26-month period, is a typical example of the range of water level fluctuations in mine spoil. While water table fluctuations from this mine may not represent all surface coal mines in the Appalachian coalfields, these data yield a starting point from which special handling plans can be formulated. Future collection of additional data from other mines should help refine these values.

Summary and Discussion

Data analysis illustrates that spoil tends to be extremely heterogeneous, and the K value obtained at a well probably represents a small portion of the spoil immediately surrounding that well. There is a broad distribution

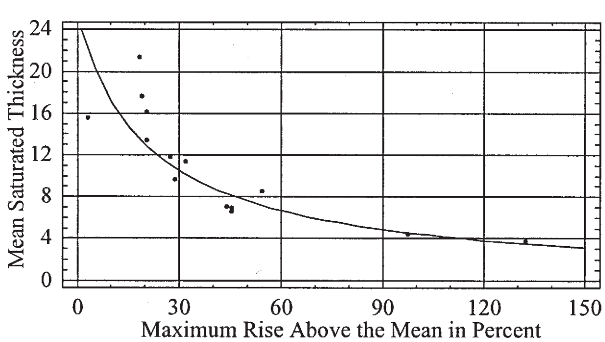

Figure 3. Analysis of the mean static water level vs. the highest recorded maximum above the mean in percentage for mine site 1.

of K values; 95% of the values occur over a range of six orders of magnitude (1.2×10^{-8} to 2.2×10^{-2} m/sec) about the mean (1.69×10^{-5} m/sec) for all of the sites. The range is similar, although shifted to larger values overall, compared to glacial sediments, which may range from 10^{-12} to 10^{-5} m/sec (Freeze and Cherry 1979). The high heterogeneity of mine spoil aquifers is created mainly from reclamation practices, and is facilitated by changes in overburden lithology; however, some useful predictive relationships have been developed.

A narrow range of saturated spoil thickness was predicted, i.e., 95% between 2.2 to 3.6 m. This range is useful to improve placement of alkaline-yielding or AFMs below or above the saturated zone, respectively. Thicker saturated zones are directly related to the thickness of the spoil. For spoil thicknesses above and below 15, 20, and 25 m, median water table levels are significantly higher and lower, respectively. Placement of acidic material in areas with thicker spoil should be adjusted upward accordingly.

The saturated thickness and spoil thickness data indicate that, on average, ~19% of the spoil is saturated. The rest of the spoil is unsaturated most of the time. Some portions, however, may receive periodic flushing from water level increases caused by recharge events. This ~1:5 ratio is valuable for the placement of AFMs, which should be above the postmining water table. It is equally important in the placement of the alkaline materials, which should be located well within the saturated zone to maximize the release of alkalinity.

Greater saturated thicknesses were associated with higher sandstone content (> 35%). This relationship is likely related to the higher rates of recharge associated with blocky sandstones. Avery (1997), using spring flow time series, estimated recharge rates at 55% of precipitation on a sandstone-rich reclaimed mine site in central West Virginia. Ketchum et al. (2000) estimated similar recharge rates for incident precipitation (46% and 64%), but calculated greater recharge for shorter subannual intervals (79% to 83%) for the same mine.

Blocky sandstone-rich mine spoil tends to create discrete surface openings or exposed voids, which permit rapid high-volume recharge to the backfill (Hawkins and Aljoe 1991; Wunsch et al. 1992). Surface water runoff tends to enter the exposed openings and rapidly recharge the backfill. Conversely, shale-rich spoils (> 65%) tend to break into smaller fragments initially and weather more readily. These spoils do not have large exposed voids and therefore frequently have lower recharge rates compared to sandstone-rich spoils. These differences suggest that recharge rate may have a greater impact on the ultimate thickness of the saturated zone and water table fluctuations in mine spoil than the intrinsic transmissive properties.

Analyses indicate that prediction of saturated thickness is directly dependent on the sandstone/shale ratio, age of the spoil, total spoil thickness, and the distance to the highwall. This relationship is strongest for sites < 60 months old, but is still somewhat viable for sites > 60 months in age. The decreased predictability at the older sites appears to result from differing degrees of spoil compaction, piping, settling, and rock weathering commonly observed between mine sites.

Larger median K values were recorded when pit floors dip < 2° (2.7×10^{-5} m/sec) compared to sites where pit floors dip ≥ 2° (2.1×10^{-6} m/sec). This may be an indirect result of the thicker saturated spoils establishing a better developed aquifer on sites with the less steeply dipping pit floor. If the dip is relatively steep, infiltrating ground water will migrate to the pit floor, and tend to flow under a steeper gradient toward the toe-of-the-spoil through discrete pathways. Ground water velocities ranging from 1 to > 370 m per day have been recorded in mine spoil of the Appalachian Plateau (Hawkins 1998).

Conclusions

Mine spoil aquifers are highly heterogeneous, but some trends and associations have been observed for reclaimed surface mines in the Appalachian Plateau region. These include the following items.

- Spoil aquifer saturated thickness is generally between 2.2 and 3.6 m with a 95% confidence; however, a maximum of 11.0 m has been recorded.
- Thicker spoils tend to have significantly thicker saturated zones.
- The saturated zone averages nearly 1 m for every 5 m of spoil thickness.
- Spoil with > 35% sandstone will exhibit higher median saturated thicknesses (3.1 m) than sites with < 35% sandstone (1.8 m). The difference likely is due to higher recharge rates associated with sandstone-rich spoils.
- The predictability of the saturated thickness depends on many variables including sandstone/shale ratio, age of the spoil, total spoil thickness, and the distance to the highwall.

Perhaps the most useful forecasting tool derived through these analyses is the rule-of-thumb of 1 m of saturated thickness for every 5 m of spoil thickness. Using this formula, the anticipated saturated zone for spoil 30 m thick is about 6 m. It must be remembered, however, that this is the mean value and the water table will fluctuate about this mean. A preliminary safety factor was calculated from more than two years of water level monitoring from 13 wells on site 1. Based on these data, 97.5% of the wells did not rise more than 48.5% above the mean water level; therefore, a safety factor of 50% is put forth. With the addition of a safety factor, AFMs should be placed at least 9 m above the pit floor, where the spoil is 30 m thick.

A second consideration is that spoil comprised of ≥ 35% sandstone will commonly have a greater saturated thickness (median of 3.1 m) than spoil with < 35% sandstone (median of 1.8 m). The higher permeability of sandstone-rich spoil that permits greater recharge also allows a greater amount of oxygen diffusion into the subsurface (Guo and Cravotta 1996), which may permit continued pyrite oxidation and acidic drainage production. AFMs should therefore not be placed at a depth so shallow as to permit appreciable amounts of continuing pyrite oxidation.

The postreclamation saturated thickness can also be forecasted using multiple regression, which includes sandstone and shale content, distance to the final highwall, spoil thickness, and age of reclamation. The saturated spoil thickness can be reasonably forecasted ($r^2 = 76.3\%$) for any time period up to 60 months after reclamation. The predictability decreases somewhat, however, for mines reclaimed longer than 60 months ($r^2 = 41.2\%$).

The information presented herein is intended to provide some basic tools to predict postmining spoil aquifer properties. With these tools, planning and implementation of special handling and hydrologic engineering for surface coal mines should improve. This, in turn, should improve the efficacy of AMD prevention.

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