Proceedings America Society of Mining and Reclamation, 2004

SOME HYDROLOGIC PROPERTIES OF SURFACE MINE SPOIL IN THE APPALACHIAN PLATEAU[1]

Jay W. Hawkins[2]

Abstract: Prevention of acid mine drainage (AMD) at surface coal mines in the Appalachian region relies greatly on minimizing ground-water contact with acid-forming materials and maximizing ground-water contact with alkalinity-yielding materials. Acid-forming materials (AFMs) are often selectively handled to minimize or prevent contact with ground water. Controlling ground-water contact with acidic- or alkaline materials depends on accurate forecasting of the level and range of fluctuation of the post-mining water table and preferred ground water flow paths within the backfill. Physical measurements and aquifer testing of more than 120 wells from 18 reclaimed mines in Kentucky, Ohio, Pennsylvania and West Virginia have improved forecasting of the post-mining ground-water flow system. Flow regime influencing factors include spoil lithology and particle size, age of reclamation, spoil thickness, distance to the final highwall, and pit floor dip angle and direction. Hydraulic conductivity (K) exhibits a broad range of 7 orders of magnitude about a mean K of 1.69×10^{-5} meters/second. Spoil aquifer saturated thickness is related to the thickness of the spoil, spoil lithology, dip of the pit floor and distance to the highwall. Saturated spoil thickness has a 99% confidence interval of 1.86 to 3.97 meters (m) about a mean of 2.91 m. Spoil saturated zone averages 20% of the total thickness.

Additional Key Words: acid mine drainage, hydraulic conductivity, saturated thickness, ground water, water table, selective materials handling.

---

[1] Paper was presented at the 2004 National Meeting of the American Society of Mining and Reclamation and The 25th West Virginia Surface Mine Drainage Task Force, April 18-24, 2004. Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

[2] Jay W. Hawkins, Hydrologist, Office of Surface Mining Reclamation and Enforcement, Appalachian Regional Coordinating Center, Pittsburgh PA 15220.
Proceedings America Society of Mining and Reclamation, 2004 pp 860-878
DOI: 10.21000/JASMR04010860

https://doi.org/10.21000/JASMR04010860

Background

Rocks of the Appalachian Plateau coalfields are comprised mostly of interbedded sandstones, shales, siltstones, claystones, and coal. Freshwater and marine limestones are also present in some parts of the coalfields. Minable coal seams generally range in thickness from 1 to 2 meters. The rocks tend to be flat lying to slightly dipping (<5E).

The rocks tend to be well cemented; hence the primary porosity and permeability are generally low. Ground water in this region is mainly stored in and flows through secondary porosity and permeability created by fractures and bedding-plane separations in the strata. The fractures are primarily formed from stress-relief forces and generally to a lesser extent by tectonic activity (Wyrick and Borchers, 1981). The stress relief fractures tend to be limited to within 60 meters of the surface (Borchers and Wyrick, 1981). Fracture frequency and aperture size decrease with depth (Thomas and Minns, 1993; Hawkins et al., 1996). The low-dipping layered stratigraphy tends to promote a series of perched aquifers supported by underlying confining units (e.g., shales or claystones).

Once the coal is removed during surface mining, the broken up overburden (spoil) is dumped and pushed into the pit during backfilling. During this process, the material placed on the elevated areas (spoil ridges and piles) tends to be poorly sorted. Larger particles will roll to the base of the spoil ridges creating better-sorted highly-transmissive zones. Extreme heterogeneity is introduced into the backfill material by the broad range of particle sizes and particle sorting (Hawkins, 1998).

Sandstone tends to break into larger pieces, whereas the shales tend to break into smaller sized particles. Depending on the cementing minerals, sandstones may weather rapidly to sand-sized particles or remain in large blocks for protracted periods. Shales tend to weather to clays at rates that vary according to chemical composition and degree of induration.

Crucial to the prevention and abatement of acid mine drainage (AMD) from surface coal mines is forecasting characteristics of the post-mining ground-water hydrologic regime. Ground water is important because it is a chemical component in the formation of AMD and integral to the release of alkalinity. Iron disulfides (i.e., pyrite and marcasite); usually no more than a few percent in the coal and overburden, react with oxygen and water to release ferric hydroxide ($Fe(OH)_3$), sulfate (SO_4^{2-}), acidity (H^+), and heat. Ground water also dissolves minerals such as calcium carbonate ($CaCO_3$) in calcareous rocks to yield bicarbonate alkalinity (HCO_3^-) and calcium (Ca^{2+}) (Rose and Cravotta, 1998).

AMD prevention and mitigation in the Appalachian Plateau frequently require that the acid-forming materials (AFMs) and alkaline materials be selectively placed in the backfill. Attempts are made to keep AFMs separated from ground water or ground water in contact with alkaline material. In general, selective handling methods fall into two categories: "dark and deep" and "high and dry." That is, placing AFMs within the saturated or unsaturated zone, respectively. For either technique to be effective, where ground water will be located and how it will flow through the spoil must be known. How seasonal changes in recharge and discharge cause ground-water storage and flow patterns to vary are also important.

There are mining regions outside of the Appalachian Plateau where submergence of the acid-forming materials below the water table to prevent AMD formation is practiced. The metal mining areas of Canada (Dave and Michelutti, 1991) and portions of the U.S. Interior Coal Basin (Robert Evans personal communication, 2001) commonly employ this technique. If the metal sulfides are placed below the water table, contact with atmospheric oxygen is prevented and thus AMD formation is halted (Anonymous, 1965). Even with dissolved oxygen saturation in the ground water near a maximum of 13 mg/L at 5E C (Hem, 1989), AMD production essentially halts (Watzlaf, 1992). On the other hand, the dissolution of alkaline materials requires continued contact with water.

Topography, geology, and hydrology in the eastern coalfields generally preclude submergence of AFMs as an option. Moderate to high topographic relief in this region and high transmissive properties of mine spoil prevent the management of saturated zones thick enough to maintain effective dark and deep conditions. When AFMs are too high in the backfill, they may be within the fluctuating water-table zone; this is the worst possible scenario, because it facilitates alternating periods of oxidation followed by flushing out of the oxidation products. As a consequence, AFMs are segregated during mining and placed in isolated pods or layers in the mine backfill which are projected to be above the post-mining water table apex. Alternately, alkaline materials are placed to maximize ground-water contact. An inherent problem in special handling is the generally poor ability to predict the location and characteristics of the post-mining water table. The antecedent aquifers above the coal have been destroyed and the backfill represents a completely new system of a more unified water-table aquifer with unusual heterogeneous hydrologic characteristics.

Isolated pods of AFMs are often capped with a low-permeability material to prevent vertically-infiltrating ground water from contacting them. Other types of hydrologic engineering techniques used to control or prevent ground water from contacting AFMs or facilitate ground water to contact alkalinity-producing materials, include pit floor and highwall drains, low-permeability caps, seals or grout curtains, and ground water diversion wells. Specific knowledge of spoil hydrologic characteristics should improve the likelihood of these techniques to succeed.

Mine spoil is a highly heterogeneous material that contains a substantial percentage, by volume, of large (macro) voids and exhibits a dual-flow ground-water system (Fig. 1). The void volume may equal the spoil swell (a volume increase from mining) which may be as high as 20 to 25 %. Porosities approaching 16 and 23 % have been recorded by field measurements in 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. An indication of the dramatic changes caused by mining is that the hydraulic conductivity of mine backfill averages (geometric mean) 2 orders of magnitude higher that of adjacent unmined strata (Hawkins, 1995). The macro voids behave similar to karst aquifers, capable of storing and rapidly transporting large quantities of water and may exhibit multiple water tables within the same unit (Caruccio et al., 1984). Whereas, spoil material itself behaves more like a highly-transmissive unconsolidated porous medium (Hawkins, 1998). Because the spoil materials surrounding the macro voids have lower transmissive properties, they control the overall ground water flow system in the backfill under steady-state conditions. However, during

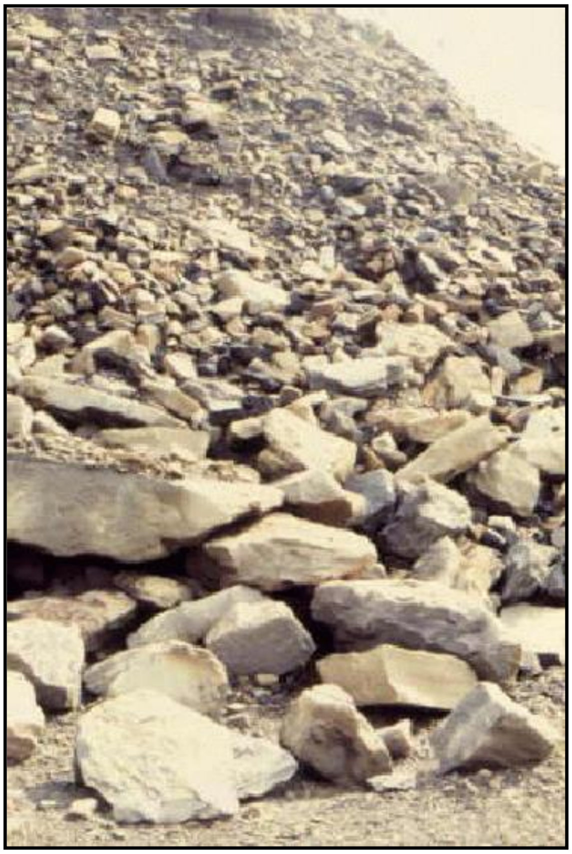

Figure 1. Well-sorted zones forming at the base of spoil ridges with mixed particle sizes on the sides and top.

periods of high recharge or other stresses to the system (e.g., substantial pumping), mine spoil behaves more like a karst system. These stresses can cause spoil to exhibit non-Darcian flow, losing streams that re-emerge a short distance away, and multiple water tables for brief periods during and following the introduced stress (Hawkins and Aljoe, 1990).

Purpose

This study was initiated in an attempt to eliminate many of the unquantified aspects of surface-mine spoil ground-water hydrology and to introduce a degree of predictability. Environmental failures at reclaimed mines (e.g., creation of acidic, metal-rich discharges) where special handling of acid-forming and/or alkalinity-yielding materials was performed, underscore the need for a better understanding of the post-mining ground-water regime.

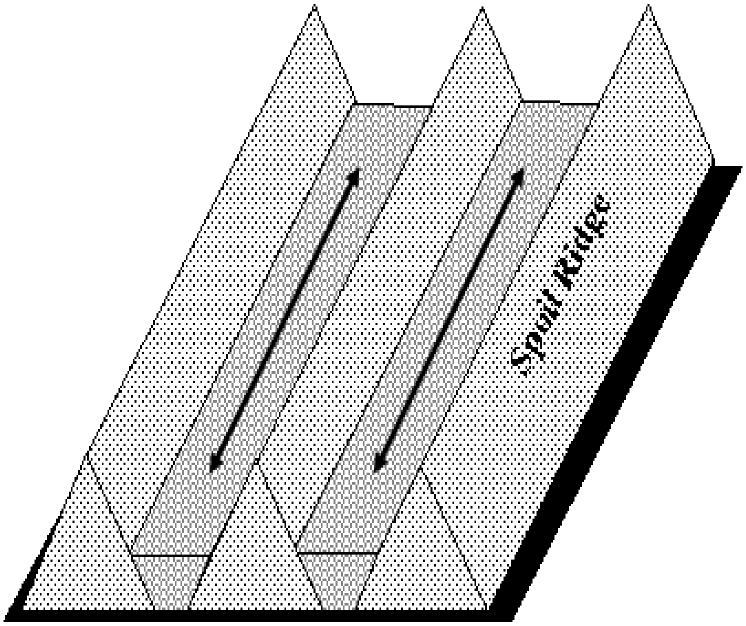

Figure 2. Preferential ground-water flow directions (arrows) in spoil valleys in mine backfill.

The orientation of mining and the configuration of the backfill can dramatically impact the direction of ground-water flow and the location and range of fluctuation of the ground-water table. Highly-permeable zones form in the valleys between spoil ridges and permit substantial ground-water flow parallel to the spoil ridges. Because ground water will follow the path of least resistance, flow perpendicular to the spoil ridges tends to be considerably less than flow parallel to the ridges through the highly transmissive zones formed in the spoil valleys (Fig. 2). Constant-discharge tests at a reclaimed surface mine in central West Virginia, indicated that the hydraulic conductivity (K) differences between buried spoil valleys and ridges can exceed 2 orders of magnitude (Hawkins, 1998). Groenewold and Winczewski (1977) observed that the surface over these highly-transmissive spoil valleys is more susceptible to subsidence from piping of fine-grained spoil materials because of the substantial amount of ground-water movement and available voids.

Numerous geologic and mining-related factors were believed, a priori, to have an influence on the ground water hydrologic regime of mine spoil, including: lithology, thickness of the backfill, age of the reclamation, proximity and location of adjacent unmined strata, and structural dip. Early in this study, other factors, such as types of mining equipment used, mining style, distance to the pre-mining coal outcrop, and blasting details were also examined to determine if they impacted the post-mining hydrology. Later it was determined that these other factors either did not impact the hydrologic regime or these data were unavailable.

Methods

Aquifer testing was conducted on 124 monitoring wells installed in the backfills of 18 reclaimed surface mines in the bituminous coalfields of Pennsylvania, West Virginia, Kentucky, and Ohio (Fig. 3). The aquifer tests were primarily slug injection (falling head) or slug withdrawal tests. The slug tests results were analyzed using a method developed by Bouwer and Rice (1976) and Bouwer (1989).

Site-specific data and information pertaining to mine location, overburden thickness and lithology, extent of mining, strike and dip of the pit floor (stratum underlying the coal) and age of reclamation were obtained primarily from the surface mine permit files. Spoil saturated thickness was determined by field measurements taken prior to the aquifer testing. Percentages of shale and sandstone were determined volumetrically, based on pre-mining drill logs and planimetered areas. Spoil thickness was based on drill logs and direct field measurements. Pit floor dip was calculated from three or more pre-mining drill holes. The location and distance to a highwall or a lowwall was measured from mine reclamation maps.

The data were analyzed using: summary statistics, univariate, bivariate, multivariate, and exploratory data analyses to determine the predictive nature of K values and the post-mining water table levels in spoil.

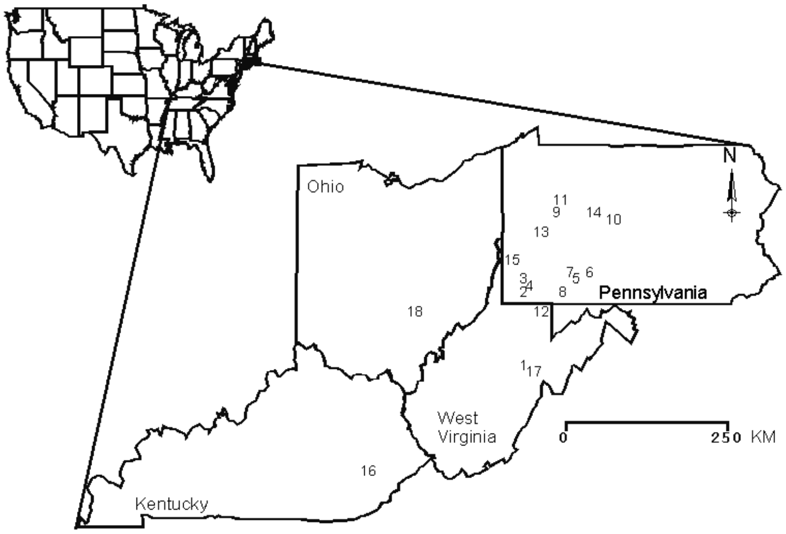

Figure 3. Test mines location map

Data Analyses

Summary Statistics and Distribution Analyses

Aquifer testing results shows a wide range of K values in the data set (Table 1). K ranges over seven orders of magnitude from 4.5 x 10^{-9} to 7.6 x 10^{-2} meters per second (m/s) for the 124 wells. Data analysis indicates a non-normal (positively skewed) distribution, therefore the median and a geometric mean were determined to best represent the central tendency of the raw data. Both values were 1.7 x 10^{-5} m/s. Within mines with 5 or more monitoring wells, K ranged from 1 to greater than 5 orders of magnitude. Median K values for those sites ranged from 2.6 x 10^{-7} to 1.1 x 10^{-3} m/s.

Distribution of the K data for the 124 wells becomes normal when transformed (log base 10). The mean and median of this data set are both 1.69 x 10^{-5} m/s. The 95% confidence interval about the mean is between 1.2 x 10^{-8} and 2.2 x 10^{-2} m/s. This is a fairly broad range, but mine spoil has been shown to range several orders of magnitude within a single mine, not to mention between all the mine sites. On the other hand, undisturbed strata of the Appalachian Plateau commonly exhibit a range of K of just over one order of magnitude (Hawkins, 1995).

The spoil saturated thickness measured at the 124 wells ranged from 0.18 to 11.03 meters (m) with a median of 2.94 m (Table 1). The data set was transformed using a square root function. The 95% confidence interval about the mean (2.91 m) was from 2.21 to 3.61 m. Spoil thickness exhibited a range of 3.8 to 32.0 m.

Table 1: General summary data

	Hydraulic Conductivity (m/s)	Saturated Thickness (Meters)	Spoil Thickness (Meters)	Age of Spoil (Months)	Percent Sandstone	Percent Shale
Average	1.93×10^{-3}	3.26	15.18	133.1	57.13	42.87
Median	1.72×10^{-5}	2.94	13.8	144.0	55.6	44.4
Geometric Mean	1.70×10^{-5}	2.54	13.38	103.1	65.83	34.17
Standard Deviation	8.84×10^{-3}	2.17	7.19	89.05	25.91	25.91
Minimum	4.45×10^{-9}	0.18	3.83	10	0	10
Maximum	7.58×10^{-2}	11.03	32.0	360	90	100
Range	7.58×10^{-2}	10.85	28.17	350	90	90
Lower Quartile	1.69×10^{-6}	1.44	9.565	68	38.4	13.9
Upper Quartile	1.69×10^{-4}	4.52	20.45	156	86.1	61.6

The sandstone content mean is 57%. The large standard deviation yields a predicted 95% confidence interval that is beyond the constraints of percentage. The 25th and 75th percentiles were 38.4% and 86.1%, respectively. The percent shale did not require analysis because it would exhibit a mirror image of the sandstone.

Bivariate and Multivariate Analyses

Data analyses indicate that a relatively simple model to predict the K or the saturated thickness is not an option. There are many variables that influence K and saturated thickness. Most attempts at simple regression and multiple regressions were less than successful. However, a two multiple regressions did yield reasonable predictive models. Some general predictive methodologies have also been found using other statistical procedures.

Reasonable multiple regression results ($r^2 = 76.3\%$, significant at the 95% confidence level) were observed for saturated thickness of spoil (independent variable) compared to the sandstone/shale ratio of the spoil, age of the spoil, total spoil thickness, and the distance to the highwall (dependent variables) for sites < 60 months old (Equation 1). The r^2 for sites ∃ 60 months old ($r^2 = 41.2\%$, significant at the 95% confidence level) was greatly reduced, thus but still somewhat predictable (Equation 2).

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

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

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

Median K of sites with a dip < 2E was significantly higher (2.69×10^{-5} m/s) than those sites with a dip ∃ 2E (2.11×10^{-6} m/s) using the Kruskal-Wallis and Kolmogorov-Smirnov tests. Significantly different medians where also achieved using exploratory data analysis as illustrated by a notched box and whisker plot (see Fig. 4).

Increasing saturated thickness shows a relationship with increasing spoil thickness. When the spoil thickness is 15 m, the saturated thickness median of 4.08 m is significantly higher than the saturated thickness median of 2.08 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, respectively. These assessments were determined using the Kruskal-Wallis and Kolmogorov-Smirnov tests.

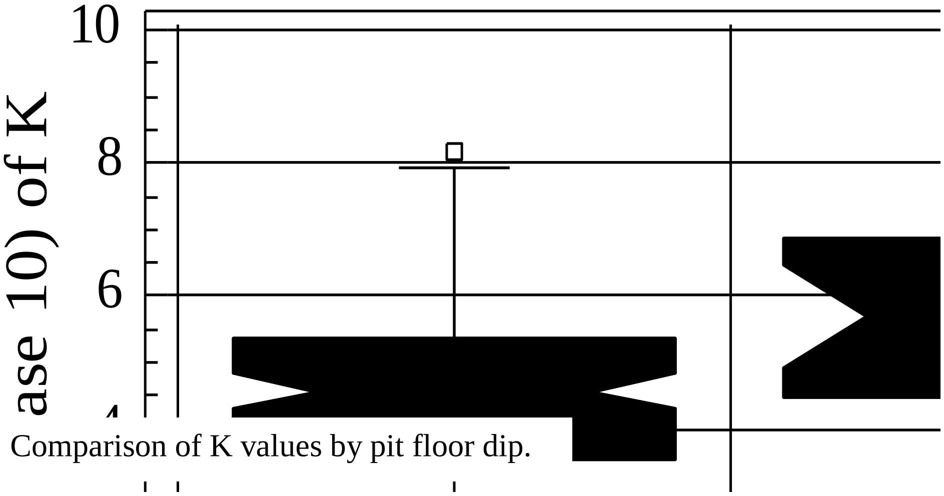

Figure 4. Comparison of K values by pit floor dip.

There is a weak relationship when spoil thickness is plotted against the saturated thickness on a point-by-point basis (See Fig. 5). The relationship becomes much less predictable as the spoil thickness increases (heteroscedastic).

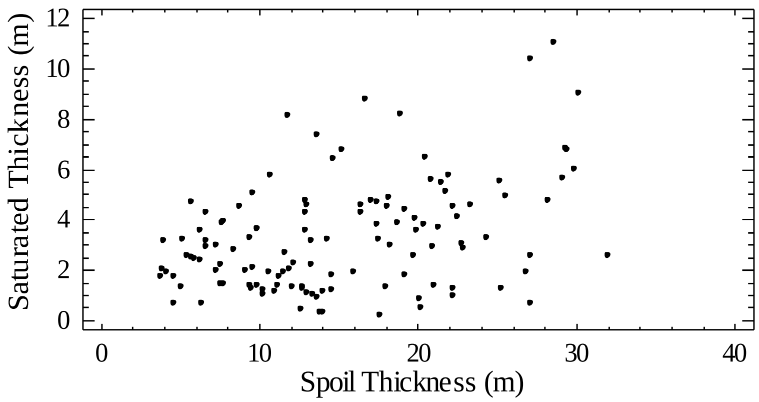

Figure 5.Relationship of total spoil thickness to spoil saturated thickness.

The saturated thickness was related to the lithology of the spoil parent material. The median saturated thickness for spoil with sandstone content ∃35%,(3.11 m) is significantly greater than the median for sites with < 35% sandstone content (1.76 m). No reasonable regression correlation between saturated spoil thickness and lithology was obtained.

Two years of water level monitoring from 13 wells located within Site 1 (Fig. 3) were analyzed to examine water table fluctuations in surface mine spoil. Of specific concern 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%. Therefore, 97.5% of wells in spoil should have a water level rise no more than 48.5% above their respective means. It is interesting to note that the greater the average saturated thickness, the lower maximum rise in percentage was observed (Fig. 6). The broad water table fluctuations are related to the elevated K values common to the spoil and to rapid recharge from precipitation events observed in mine spoil (Hawkins and Aljoe, 1990). Figure 7, well 1 from site 1 over a 26-month period, is an example of the degree of water level fluctuations occurring in mine spoil.

Discussion

Spoil tends to be extremely heterogeneous. This is shown by the broad range of K values, 95% of the K values occur over a range of 7 orders of magnitude, (1.2×10^{-8} to 2.2×10^{-2} m/s) about the mean (1.69×10^{-5} m/s) for all of the sites. The range is similar, although slightly higher overall, to glacial sediments which may range from 10^{-12} to 10^{-5} m/s (Freeze and Cherry, 1979). The range of K observed at mines with 5 or more wells was 2.6×10^{-7} to 1.1×10^{-3} m/s. This broad range indicates that the average or median K for a spoil aquifer cannot be represented by a few wells. Some predictive relationships have been developed from the data.

Fairly narrow ranges of saturated spoil thickness were predicted (i.e., 99% between 1.86 to 3.97 m). This range becomes useful to improve the success rate of special handling of alkaline-yielding or AFMs. However, the high saturated thickness of 11.03 m recorded cannot be discounted for placement of acid-forming materials. Thicker saturated zones are partly related to the thickness of the spoil. Median water table levels are significantly higher and lower, respectively, for spoil thicknesses above and below 15, 20, and 25 meters. Placement of acidic material in areas with thicker spoil should be adjusted upward accordingly.

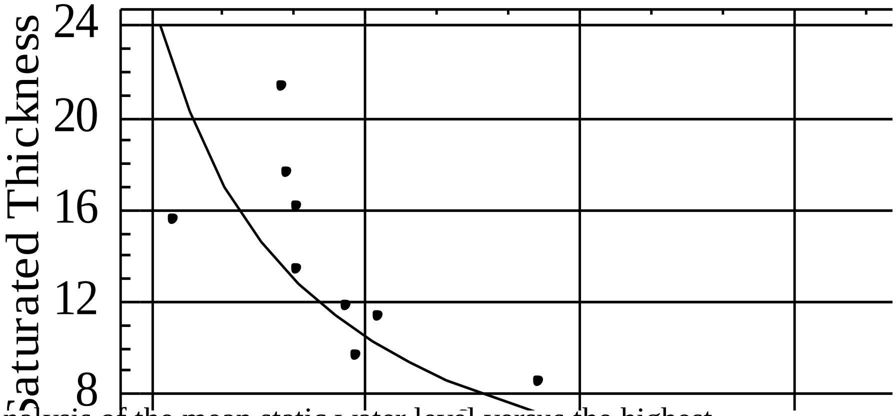

Figure 6. Analysis of the mean static water level versus the highest recorded maximum above the mean in percentage.

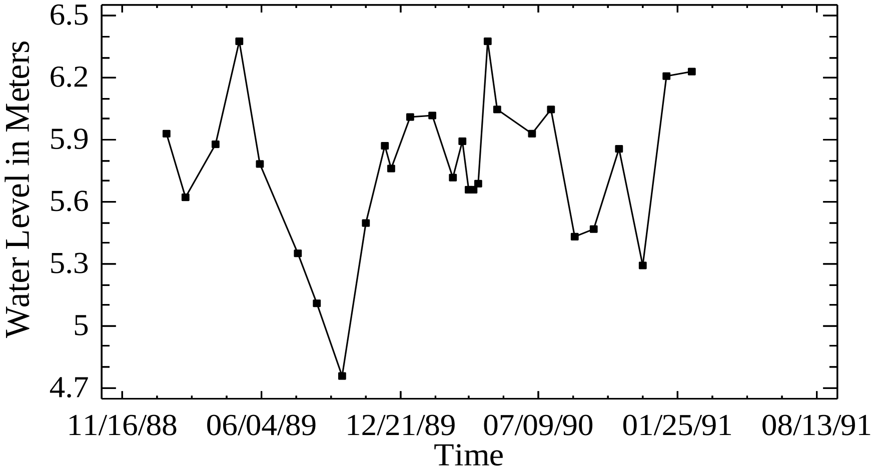

Figure 7. Water level fluctuation in well 1 of site 1.

The saturated thickness and spoil thickness data indicate that on the average about one fifth (19%) of the spoil is saturated. The rest of the spoil is unsaturated much of the time, but may receive periodic flushing from recharge events. This information is important for the placement of both acid-forming and alkaline materials.

The saturated thickness appears to be related to the proximity to the toe of the spoil. In other words, the thinner saturated thickness is associated with the thinner spoil because the thinner spoil is generally close to the original outcrop which is usually a spoil discharge point. The water table will be drawn down in proximity to the discharge point.

Thicker saturated thicknesses were associated with higher sandstone content (> 35%). This relationship is likely related to the higher rates of recharge associated with blocky sandstones. 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). Avery (1997) 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. Surface water runoff enters these exposed voids and rapidly recharges the backfill. Shale-rich spoils (> 65%) do not tend to facilitate the creation of the exposed voids and therefore do not have as high recharge. Therefore, recharge 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.

Multiple regression analyses illustrate that the predictability 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 predictability is greatest for sites < 60 months old, but is still somewhat predictable for sites > 60 months in age. The broader variability on the older sites may be due to the wide range of vegetative cover and differential weathering of the spoil material between sites. Vegetative cover of reclaimed surface mines ranges from very low coverage (e.g., considerable barren areas) to lush growth of grasses and trees. This disparity in vegetative cover can greatly impact recharge amounts. More recently reclaimed sites are under statutory reclamation performance standards, so the growth is somewhat more uniform.

The extent of weathering of the spoil material can vary widely. The breakdown of sandstones or shales is directly dependent on the chemical composition, particle sizes, and cementing minerals. Not all of these rocks weather at the same rates, to the same degree, or yield the same end minerals. Therefore, spoil material that had similar lithologic composition at the time of reclamation, may possess substantially different properties from the effects of > 60 months of physical and chemical weathering. For example, some well indurated sandstones will break into large blocky fragments during mining and remain unchanged for an extended period, while poorly-cemented sandstones can be friable, and will rapidly break down to sand-sized particles and in turn impact the K of the spoil.

Significantly higher K values recorded when pit floors dip < 2E compared to sites where pit floors dip ∃ 2E, may be an indirect result of the thicker saturated spoils located on sites with the less steeply dipping pit floor. Infiltrating ground water in mine spoil tends to migrate downward toward the pit floor and then will flow in a down dip direction along the pit floor. In general, the lower the dip of the pit floor the slower the ground water movement in the down dip direction. Thus, sites with a less steeply dipping pit floor will tend to form thicker saturated zones because the ground water tends to flow at a lower velocity than more steeply dipping sites. The better developed ground-water system and thicker saturated zone facilitates better interconnection of the void spaces created during backfilling and yields greater K values. If the dip is fairly steep (∃ 2E) infiltrating ground water will migrate to the pit floor and flow relatively rapidly down gradient toward the toe-of-the-spoil. Ground-water velocities ranging from 1 to over 370 meters per day have been recorded in mine spoil of the Appalachian Plateau (Hawkins 1998). The rapid movement of the ground water will not create as thick of a saturated zone on steeply-dipping sites and the ground-water aquifer will be less well developed.

Similar results were observed with re-establishment of the water table after reclamation. Reclaimed mines less than 30 months old have significantly lower K values than sites over 30 months old (Fig. 8). This was related to improved interconnection of voids and conduits in the spoil from water table re-establishment (Hawkins, 1998). In the Appalachian Plateau, at least 22 months after reclamation are needed to re-establish the water table to reach equilibrium (Helgeson and Razem, 1980). In some portions of the Plateau water table re-establishment may require 24 to 30 months (Hawkins, 1998).

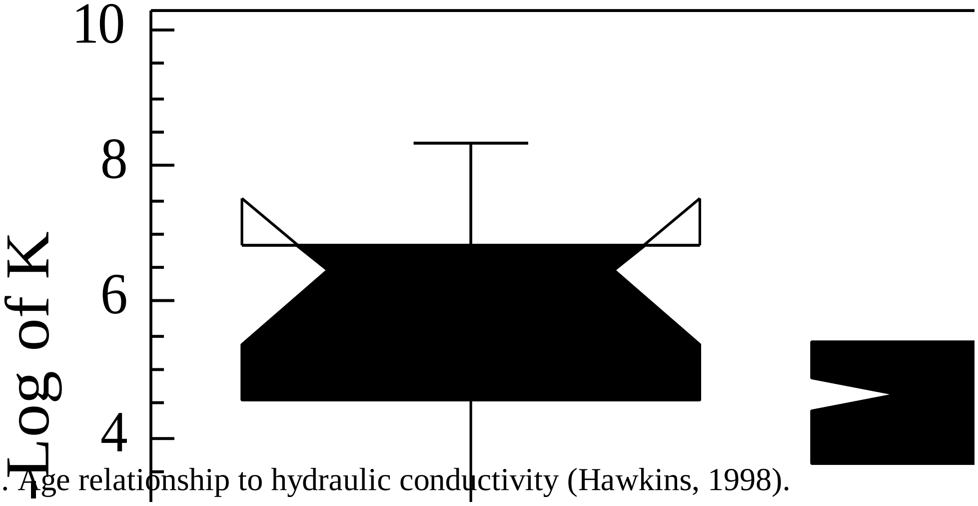

Figure 8. Age relationship to hydraulic conductivity (Hawkins, 1998).

Summary and Conclusions

Although, mine spoil is highly heterogeneous and somewhat unpredictable, some trends and associations have been determined.

- Mine spoil exhibits a very broad range of K values between sites (over 7 orders of magnitude) and within mine sites (nearly 4 orders of magnitude).
- Spoil aquifer saturated thickness is generally between 1.86 and 3.97 m with a 99% confidence.
- Thicker spoils tend to have a significantly thicker saturated zone. The saturated zone averages one meter for each five meters of spoil thickness.
- Spoil with > 35% sandstone will exhibit higher median saturated thicknesses (3.11 m) than sites with < 35% sandstone (1.76 m). The difference is probably due to the high recharge associated with sandstone-rich spoils.
- The predictability of the saturated thickness is dependent on many variables, such as 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 an average one meter of saturated thickness for every five meters of spoil thickness. Using this formula, the anticipated saturated zone for spoil 30 meters thick is 6 meters. However, it must be remembered that this is the mean value and the water table will fluctuate about this mean. A safety factor was calculated from over 2 years of monitoring 13 wells on Site 1 (Fig. 3). Based on these data, 97.5% of the wells did not rise more than 48.5% above the average. Therefore, a safety factor of 50% for the water table location was derived. With the safety factor, AFMs should be placed at least 9 meters above the pit floor, where the spoil is 30 meters thick. Bear in mind that the safety factor was developed from water level monitoring of several wells from one site. It is recommended that in the future additional data be added to refine the anticipated range of water table fluctuation.

A secondary consideration for saturated thickness prediction is that spoil comprised of ∃ 35% sandstone will commonly be greater (median of 3.11 m) than those < 35% sandstone (median of 1.76 m). Special handling of acid-forming materials on these sandstone-rich sites needs to account for this difference. 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. Therefore, the acid-forming materials should not be placed at a depth so shallow as to permit appreciable amounts of pyrite oxidation.

The post-reclamation saturated thickness can also be forecasted using a multiple regression equation. By knowing the sandstone and shale content, the 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 for mines reclaimed longer than 60 months (r^2 = 41.2%).

The analysis of K values and post-mining water table levels has yielded a few predictive rules that can be used when developing and implementing a special handling plan for acid-producing and alkalinity-yielding materials. Numerous factors need to be taken into account during the prediction process. While there will be exceptions to the prediction rules, the information presented here will give individuals a starting point at which to plan special handling and hydrologic engineering. This in turn should improve the efficacy of AMD prevention.

Acknowledgments

I wish to sincerely thank Keith B.C. Brady, Joe Donovan, Robert S. Evans, and Eric F. Perry for their critical review and insightful suggestions to the early versions of this manuscript.

Literature Cited

Anonymous, 1965. Solving the Problem of Acid Mine Drainage, Coal Age, July 1965, pp. 72-77.

Avery, W. H. 1997. Recharge characteristics of an Appalachian mine-spoil aquifer. M.S. thesis, Department of Geology and Geography, West Virginia University, Morgantown.

Borchers, J. W. and G. G. Wyrick, 1981. Application of Stress-Relief Fracturing Concepts for Monitoring the Effects of Surface Mining on Groundwater in Appalachian Plateau Valleys, In the Proceedings of the Symposium on Surface Mining Hydrology, Sedimentology, and Reclamation, University of Kentucky, Lexington, KY, pp. 443-449.

Bouwer, H. 1989, The Bouwer and Rice slug test - an update. Ground Water, vol. 27 no. 3: 304-309. http://dx.doi.org/10.1111/j.1745-6584.1989.tb00453.x.

Bouwer, H. and Rice, R. C. 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely penetrating wells. Water Resour. Res. vol. 12, no. 3: 423-428. http://dx.doi.org/10.1029/WR012i003p00423.

Caruccio, F. T., Geidel, G., and Williams, R. 1984. Induced alkaline recharge zones to mitigate acidic seeps. In Proceedings of the 1984 Symposium of Surface Mining, Hydrology, Sedimentology, and Reclamation, Lexington, KY, 43-47.

Dave, N. K. and Machelutti, R. E. 1991. Field evaluation of wet cover alternatives of high sulphide tailings - final report, In the Proceedings of the Second International Conference on the Abatement of Acidic Drainage, Tome 3, Montreal, Quebec, Canada, 61-81.

Freeze, R. A. and J. A. Cherry, 1979. *Groundwater*, Prentice-Hall, Inc. Englewood Cliffs, New Jersey. 604.

Groenewold, G. H. and L. M. Winczewski. 1977. Probable Causes of Surface Instability in Contoured Strip-Mine Spoils- Western North Dakota. Annual Proceedings of the North Dakota Academy of Science. pp. 160-167.

Guo, W. and C. A. Cravotta, 1996. Oxygen transport and pyrite oxidation in unsaturated coal-

mine spoil. In the proceedings of the 13th Annual Meeting of the American Society of Surface Mining and Reclamation, Knoxville, TN, 3-14.
https://doi.org/10.21000/JASMR96010003

Hawkins, J. W., 1995. Impacts on ground-water hydrology from surface coal mining in northern Appalachia, In the proceedings of Water Resources at Risk, American Institute of Hydrology, Denver CO, IMWA-32-IMWA-43.

Hawkins, J. W., 1998. Hydrologic characteristics of surface-mine spoil, Chapter 3 of *Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania*, K. B. C. Brady, M. W. Smith, and J. Schueck eds. The Pennsylvania Department of Environmental Protection.

Hawkins, J. W. and W. W. Aljoe. 1990. Hydrologic characterization and modeling of a heterogeneous acid-producing surface coal mine spoil, Upshur County, West Virginia, Proceedings of 1990 National Symposium on Mining, Knox https://doi.org/10.21000/JASMR90010043

Hawkins, J. W. and Aljoe, W. W. 1991. Hydrologic characteristics of a surface mine spoil aquifer. In Proceedings of the Second International Conference on the Abatement of Acidic Drainage. Montreal, Quebec, Canada., 47-68.

Hawkins, J. W., K. B. C. Brady, S. Barnes, and A. W. Rose. 1996. Shallow ground water flow in unmined regions of the northern Appalachian Plateau: Part 1. Physical characteristics, Annual Meeting of the American Society for Surface Mining and Reclamation, Knoxville, TN, 42-51.
https://doi.org/10.21000/JASMR96010042

Helgeson, J. O. and A. C. Razem, 1980. Preliminary observation of surface-mine impacts on ground water in two small watersheds in eastern Ohio. In Proceedings of the Symposium of Surface Mining Hydrology, Sedimentology and Reclamation. Lexington, KY. 351-360.

Hem, J. D., 1989. Study and interpretation of the chemical characteristics of natural water, Third Edition, U. S. Geological Survey Water-Supply Paper 2254.

Ketchum, J. N., J. J. Donovan, and W. H. Avery, 2000. Recharge Characteristics of a Phreatic Aquifer as determined by Storage Accumulation, Hydrogeology Journal, Vol 8, 579-593. http://dx.doi.org/10.1007/s100400000088.

Rahn, P.H., 1976. Potential of coal strip-mine spoils as aquifers in the Powder River Basin, Old West Regional Commission, Billings, Montana, Project No. 10470025.

Rose, A. W. and C. A. Cravotta. 1998. Geochemistry of coal mine drainage, Chapter 1 of *Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania*, K.B.C. Brady, M.W. Smith, and J. Schueck eds. The Pennsylvania Department of Environmental Protection.

Thomas, W. A. and Minns, S. A., 1993. Geologic Context of the Distribution of Fractures that Control Ground-Water Flow in the Eastern Kentucky Coal Field, In IMMR Highlights, University of Kentucky, Lexington, KY, 4 p.

Watzlaf, G. R., 1992. Pyrite oxidation in saturated and unsaturated coal waste, In the Proceedings of the 1992 National Meeting of the American Society for Surface Mining and Reclamation, Duluth, MN, 191-205.

Wunsch, D. R., J. S. Dinger, and P.B. Taylor. 1992. Design, construction, and monitoring of the ground-water resources of a large mine-spoil area: Star Fire Tract, eastern Kentucky, Report of Investigations 6 Series XI, Kentucky Geological Survey, Lexington, KY.

Wyrick, G. G. and J. W. Borchers. 1981. Hydrologic effects on stress-relief fracturing in an Appalachian valley, U.S. Geological Survey, Water Supply Paper 2177.

https://doi.org/10.21000/JASMR92010191