Hydrogeologic Characterization of Local Scale Hydraulic Properties In A Weathered Acidic Minespoil[1]

Thomas P. Maher, Jr. and Joseph J. Donovan[2]

Abstract. Measurements of hydraulic conductivity were performed in a central West Virginia shallow minespoil aquifer, within the Northern Appalachian coal fields. The aquifer studied occurs within spoil that has produced acid mine drainage for 12 to 18 years. Thirty five wells, ranging in depth from 12-23 meters, were tested by slug test and pump test methods. Hydraulic conductivity estimates based on slug tests range over 4 orders of magnitude, but two modes are present in the data over narrower (2 order) ranges. The high-conductivity mode ($K=10^{-3.9}$ to $10^{-2.7}$ m/s) is interpreted as high-void ratio spoil, possibly basal rubble, and the low-conductivity zone ($K=10^{-6.3}$ to $10^{-4.2}$ m/s) as a matrix-porosity spoil aquitard, through which the more permeable zone is recharged. Storativity estimates from slug tests indicate confined conditions within the high-conductivity zone; pump-test storativities suggest vertical leakage from the aquitard associated with this zone. Results may be interpreted to indicate the aquifer is stratified into two layers: an upper matrix-porosity zone with gravity yield characteristics and a lower semi-confined zone in extremely permeable but heterogeneous mine floor materials. The confined high-K zone may control horizontal flow within much of the spoil as well as the discharge rate to springs.

Additional Key Words: hydrogeology, groundwater, hydraulic conductivity, acid mine drainage

Introduction

Mine spoil is the waste product of surface coal mining, used to backfill excavated mine workings. Particle size in spoil commonly ranges from clay to large boulders. In high-sulfur coal fields of the Appalachian and other regions, spoil piles tend to produce acid mine drainage (AMD) due to pyrite oxidation, threatening water quality of nearby streams and groundwater. The acid-leaching process involves (a) fluid transport of infiltrating oxygenated recharge into acid-producing pyritic zones and (b) fluid transport away from these zones, carrying weathering products (mainly metals and hydrogen-ion acidity) from oxidation and hydrolysis reactions. Therefore, the flow and transport characteristics of groundwater in this complex porous medium are of considerable interest in understanding and controlling off-site discharge of metals and acidity.

Prior research into the hydrogeology of reclaimed spoils has focused on transient resaturation behavior following mining (Van Voast and Reiten, 1988) and potentiometric patterns describing groundwater flow directions (Hawkins and Aljoe, 1990). While the spoil medium is widely described as spatially variable in its flow and storage properties, vertical and lateral patterns of this heterogeneity are not well understood. Hydraulic testing to collect information from wells regarding flow characteristics has been performed by various techniques, including low-discharge pumping and "slug" tests (Van Voast and others, 1977; Houghton and others, 1984; Hawkins and Aljoe, 1991; Hawkins and Aljoe, 1990; Aljoe, 1994; Hawkins, 1994; Gabr and others, 1994; Wunsch and Dinger, 1994). The results of Van Voast and Reiten (1988) suggest a range of vertically-averaged hydraulic conductivity over about 3 orders of magnitude, from 10^{-7} to $3x10^{-5}$ m/sec, with low storage characteristics, in the range of 10^{-5} (i.e., an artesian storativity derived primarily from porous-medium elasticity and fluid compressibility). The univariate hydraulic conductivity

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[1]Paper presented at the 1995 National Meeting of the American Society for Surface Mining and Reclamation, Gillette, Wyoming, June 5-8, 1995.

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Proceedings America Society of Mining and Reclamation, 1995 pp 741-756
DOI: 10.21000/JASMR95010741
https://doi.org/10.21000/JASMR95010741

frequency distribution has been described as log normal and skewed in the high conductivity direction (Van Voast and others, 1977), similar to that of some natural aquifers.

Despite knowledge gained from such testing, results of numerical modeling based on large-scale flux measurements indicate poor correlation between small-scale test results and large-scale flows. Several investigations have encountered difficulty in applying results of local well tests to parameterize groundwater flow models calibrated using observed hydraulic heads. Aljoe (1994) dismissed the applicability of local-well test data, indicating they underestimated measured flows by as much as 80% when used to parameterize an analytic-element flow model. Hawkins (1994) had to increase field-test values of hydraulic conductivity as much as 200 times to derive an acceptable model fit to match heads and spring flows.

Several reasons may exist for the discrepancy between well-test values and reality. The first is violation of assumptions involved in test interpretation. Estimation of hydraulic parameters from radial-flow tests is based on analytical solutions to the radial-flow equation that assume idealized infinite and uniform aquifer conditions. These conditions are rarely met even approximately in heterogeneous deposits such as spoil, and test results may diverge widely from type-response curves. This is even more true for pump-test techniques, which exert a wider area of test influence in the aquifer and encounter a more extensive suite of heterogeneities than do local scale methods such as slug tests. Testing of heterogeneous deposits employing different analytical methods, therefore, might be expected to infrequently agree, and interpretation of such data may be subjective and subject to non-systematic errors. An additional problem is related to the spatial structure of heterogeneities, e.g. the continuous nature of local-scale heterogeneities. For example, interpretation of well tests often requires assumption of vertical homogeneity within the test interval, leading to the expectation that an "average" hydraulic value might control large-scale flow through the spoil. Finally, there is the problem of ambiguity in interpreting test response, when non-ideal response is observed. Such response may be difficult to recognize unless very high-resolution response measurements are made. Given these difficulties, the question arises: are local-scale aquifer tests interpolating "mean" hydraulic parameters meaningful and appropriate, or should realistic efforts to quantitatively describe flow through spoil be supported by data from other sources?

In this paper, we examine local-scale response to radial-flow testing in a 15-year old minespoil backfill. The purpose is to infer flow mechanisms which control hydraulic response at different scales of hydraulic testing. To accomplish this, we will 1) observe and interpret patterns of response to slug tests, 2) compare transmissivity and mean hydraulic conductivity estimates for the slug test sample to larger-scale estimates from pump tests, and 3) examine the statistical distribution of results. Results are intended to shed light on questions concerning 1) effective test procedures and analytical techniques to estimate hydraulic properties, 2) the nature of flow heterogeneities within spoil; and 3) the distribution of K values which control large-scale flow characteristics and effluent rates of AMD from springs.

Description of mine-spoil aquifers

Mine spoil aquifers of the type described in this investigation contain a fluctuating phreatic surface (water table) recharged by infiltration of precipitation and, in some cases, lateral inflow of natural groundwater flow from the highwall (Figure 1). That a continuous aquifer exists at such sites has been confirmed by observation of rapid well water-level response to vertical infiltration (Frysinger, in preparation). Man-made structures at the spoils surface (diversion ditches, lagoons, etc.) may also induce locally intense recharge (Gabr and others, 1994). Groundwater generally flows down gradient along the slope of the underlying pit floor, which is much less permeable than the spoil, e.g. an aquitard or aquiclude. Discharge generally occurs via a series of isolated springs along the down-dip dump face. The irregular distribution and variable quantity of flow from springs suggests that a heterogeneous flow regime influences the specific path and velocity of groundwater flow through the mine spoil.

Heterogeneity in mine spoil may be caused by several factors, including variations in overburden lithology, materials handling and segregation, and backfilling method. Backfilling using lifts likely induces vertical heterogeneity, associated both with the number/height of lifts employed and with mechanical segregation of large granular materials; such large-caliber material is prone to roll down the dump face, concentrating coarser cobbles and boulders at the base of lifts. Such basal rubble zones have been described as more transmissive than overlying spoil (Van Voast and Reiten, 1988) and may explain the observation of low storativity in these zones observed by previous investigators. Another observation has been inversion of lithology and solid-phase geochemistry in spoil from that originally present in overburden stratigraphy (Cravotta and others, 1994).

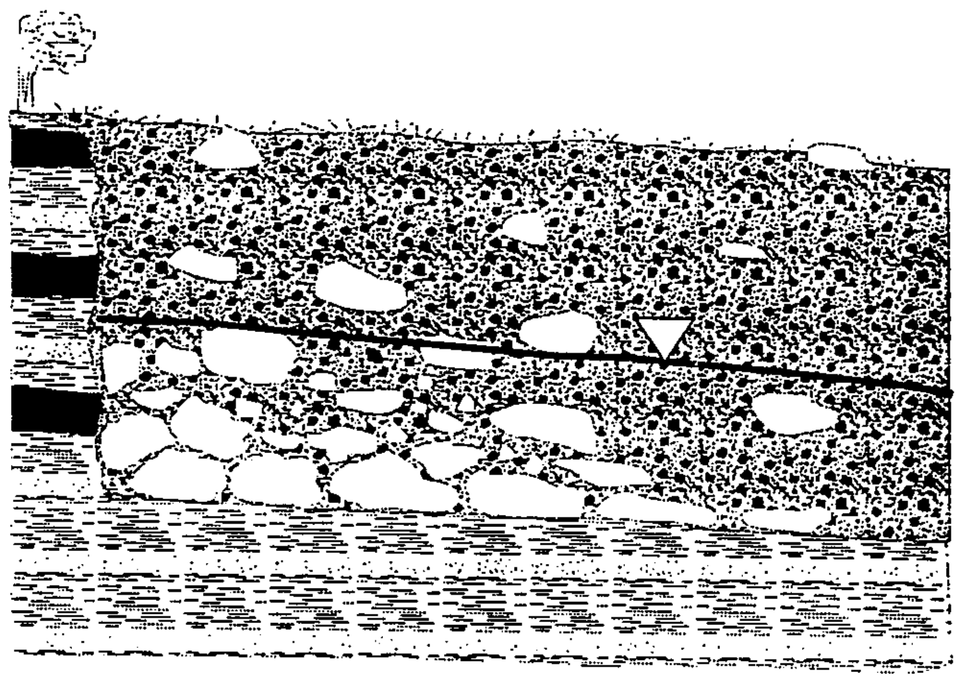


Figure 1. Schematic model of a mine-spoil aquifer

Hydraulic properties also likely change during reclamation, due to both leaching of pyrite and silicate minerals and to precipitation of reaction products. Alkaline amendments may further reduce hydraulic conductivity or induce vertical heterogeneity by causing metal oxide precipitation. Compaction and subsidence also affect hydraulic properties early in reclamation; migration of fines due to fluid flow may cause large voids to fill or collapse (Pionke and Rigowski, 1982).

Study Area

The study area is a reclaimed acidic mine backfill in Upshur County near Alton, West Virginia (Figure 2). The site consists of relatively flat-topped mine-spoil benches flanked by three short first-order tributaries to the Buckhannon River; these tributaries are the receiving streams for AMD discharge. AMD discharges from the site at an approximate rate of 700 cubic meters per day from springs located near the base of the spoil with specific conductivity ranging from 1100 to 2500 microsiemens (mS) and pH from 2.8 to 4.0. The site was mined in stages from 1974-82 and started producing AMD within about 3 years of backfilling; parts of the spoil are nearing the end of their second decade of leaching. The mine was abandoned for long-term reclamation in 1985. Forty 6-inch and two 4-inch diameter PVC casing monitoring wells were installed to or below the pit floor during mining and early reclamation; the spoil is a maximum of approximately 25 m thick. Perforations were placed across the saturated spoil and into underlying bedrock, according to reports from the drilling contractor. Well logs, pit-floor depths, and construction data were not retained. The best estimate of spoil saturated thickness is the depth of water in each well, and this figure is employed in hydraulic conductivity calculations. The actual saturated thickness may be less than this (i.e., because the wells may be overdrilled), causing the vertically-averaged hydraulic conductivity estimates to be biased towards low values. While uncertainty in this saturated thickness exists, it is not considered to be a first-order source of error.

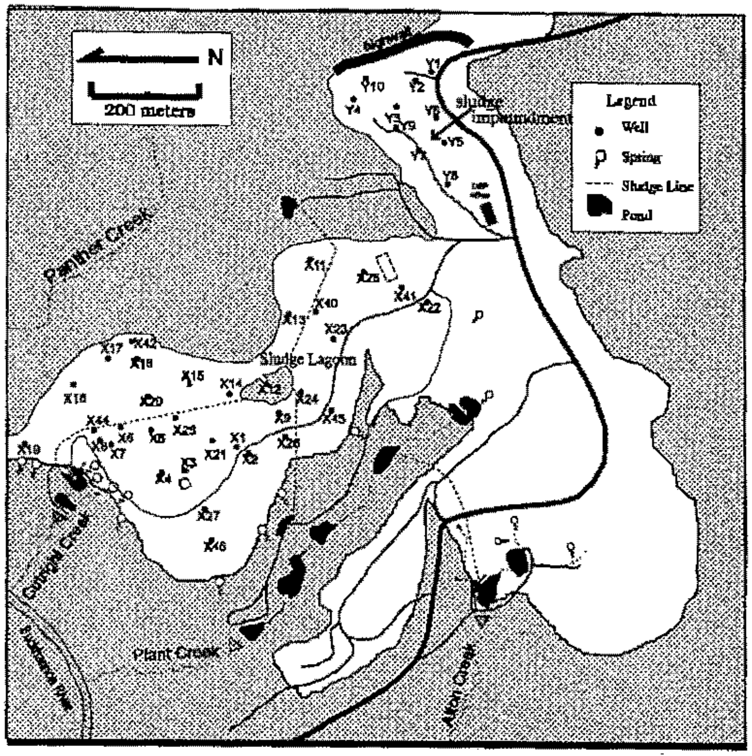


Figure 2. Map of study area, showing location of springs and wells

Methods and Interpretations

Data Collection

Rising head (slug withdrawal, or bailer) tests were conducted during the summer and fall of 1994 in 40 wells located at the Alton site. The large sample was employed to allow statistical evaluation of the distribution of hydraulic characteristics. The initial water level was measured using an electric probe, and subsequent head changes were recorded using a datalogger-coupled 5-psi vented pressure transducer set near the well bottom. Both 0.9- and 1.8-meter long 4.5-inch OD PVC bailers were filled with well water and the well water level was allowed to re-equilibrate; then the slug was removed instantaneously. The transducer was used to monitor water level depth until full recovery using a closely-spaced logarithmic time interval set initially at 0.2 second increments. The small time scale allowed precise measurement of aquifer response to a slug withdrawal. To determine reproducibility, slug tests of equal displacement were repeated in 6 selected wells at increments of several days, with good reproducibility of results (+-10% in all cases). Observed times to full slug recovery ranged between 10 and 50,000 seconds.

In addition to the slug tests, constant-discharge pump tests of 8 hours duration were performed at wells X8, X17, X23, and X27 using a number of nearby wells for water level response observation. Test wells and discharges are shown in Table 1. Pumping rates ranged from 25-110 liters/minute. Wells selected for pumping represent a biased set; only relatively high-yielding pumping wells can be used, causing high estimates of hydraulic characteristics to be represented. However, interpretation of test response was made based on observation wells, not the pumping well, making the results non-specific to the immediate vicinity of the pumping well. Discharge was maintained at +-10% using a paddle-wheel flow meter. Response was measured using continuous-monitoring Stevens drum recorders or with interval-monitoring vented pressure transducers coupled to dataloggers.

Slug Test Data Interpretation

The slug test may be employed to determine local, vertically-averaged hydraulic conductivity (K, dimensions of L/T) immediately surrounding the borehole, under the assumption of vertical homogeneity. Several analytical solutions (Hvorslev, 1951; Bouwer and Rice, 1976; Cooper *et al.*, 1967) allow calculation of either hydraulic conductivity or transmissivity (T, in dimensions of L2/T), which is for uniform confined aquifers the product of K and aquifer thickness. In addition to transmissivity, the Cooper *et al.* analysis allows estimation (often crude) of aquifer storativity (S, dimensionless) as well as comparison of water level response to those of ideal type curves for aquifers of various storage characteristics. All these solutions involve graphical fitting procedures for parameter estimation, and all are based on the same radial flow equation and should yield similar interpretations for the same dataset, assuming the boundary conditions for each is met by test circumstances (Dawson and Istok, 1991). In practice, due to the sensitivity of the various methods to water level recovery at various times, there is some variance between methods, especially in interpretation of non-ideal datasets as are commonly obtained in heterogeneous materials.

Interpretations of hydraulic parameters were completed using the Cooper et al. (1967) method. Log recovery time is plotted versus residual dimensionless slug head (H/H_o). The technique uses type-curve matching method in which one of a family of type curves, described by parameter a, is selected which best matches the field data. An arbitrary match point between data (yielding a value of time) and the type curve (yielding a value of dimensionless time, or Tt/r_c^2, where r_c=inner casing radius) is selected which allows estimation of transmissivity. Using the shape parameter a (=S r_b^2/r_c^2, where r_b=borehole radius), storativity (S) may be estimated. This estimate in general may be quite imprecise, although distinction may generally be drawn between confined and unconfined-type response (Cooper *et al.*, 1967). Other methods, such as that of Bouwer and Rice (1976), provide no indication of storativity.

The possibility of bias exists in combining well data derived from two different bailer lengths. To test this possibility, results were examined at wells where both slug sizes were employed. In addition to determining if merging the two sets of results was possible, it was anticipated that results might suggest the impact of local wellbore storage effects on hydraulic conductivity estimates.

Analysis of both slug and pump tests was performed using AQTESOLV (Geraghty and Miller, 1989), a radial flow solver package. The 1.8- and 0.9-meter 4.25-inch O.D. bails were calculated to displace 1.03- and 0.52-meters high columns of water (H_o), respectively, within 6-inch ID casing. The initial drawdown after the slug was removed was in most cases less than the calculated full heights, attributed to well-annulus storage and/or early drainage from high-permeability layers or zones within the aquifer near the well bore. Therefore, reduced values of H_o were employed, and determined accurately from the high resolution field data; field data shows a characteristic fluctuation in head values during the slug withdrawal, and H_o is assigned as the first stable head value after the bailer is removed from the well.

Several deviations from ideal response were observed. The Cooper *et al.* slug test plots were broken into three separate categories of response, including:

Type 1: "Conventional" single response
Type 2: "Very rapid" single response
Type 3: Double response (rapid response followed by slow response)

Examples of the three response types are shown in Figure 3. Type 1 is the expected type response for a uniform artesian aquifer according to the analytical model, showing a characteristic sigmoidal curve. Type 2 is similar to the Type 1 response but it recovers extremely rapidly, within 20 seconds, and has an extremely steep slope. Type 3 response is the most non-ideal of the three and contains an early rapid recovery phase (10% of the full recovery time or less) followed by slower recovery similar to Type 1. Hawkins and Aljoe (1990) witnessed similar double-recovery response during testing of a mine spoil aquifer.

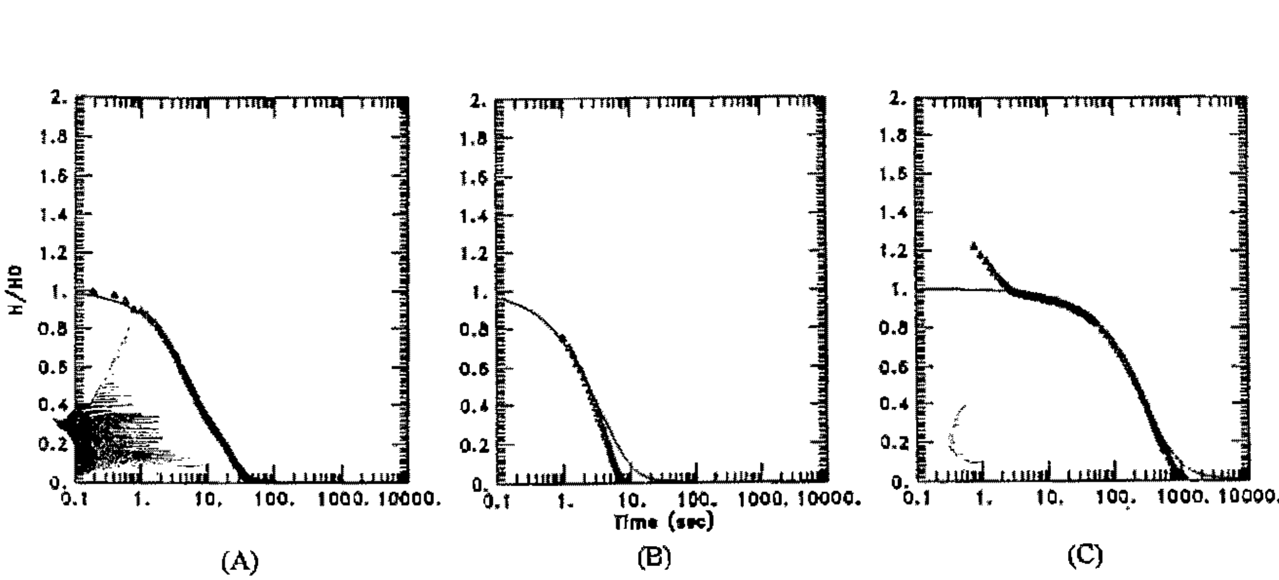


Figure 3. Differing types of water-level recovery observed in response to slug withdrawal: (A) Type 1 (single response); (B) Type 2 (rapid single response); (C) Type 3 (double response)

To estimate values of transmissivity and storativity, the slug test data was interpreted as follows. First, Type 1 tests could be interpreted unambiguously, and the storativity estimates are considered realistic but crude (+/- 1 order of magnitude). Second, Type 2 tests could also be interpreted unambiguously, but the storage estimates are likely of no physical significance and reflect the high transmissivity and/or porosity of these zones. Lastly, Type 3 tests were interpreted to yield a transmissivity/storage estimate for its late response (similar to Type 1) component and the early drainage storage effects were consistently overlooked. The results of the Cooper *et al.* analysis are listed on Table 1.

Slug test response was also analyzed using the Bouwer and Rice analytical model for unconfined aquifers to determine if a reasonable agreement in values exist. Line fitting methodology was followed as described by Bouwer (1989); a straight line fit was achieved using the recovery slope found directly after the early time storage effects. Table 2 shows the results of the comparison between K values derived from the two analytical techniques. Hydraulic conductivity values from response Type 1 and 3 agreed to within 0.20 and 0.24 log units, respectively, suggesting that the analytical models reasonably agree. The largest deviation between K values exist in the Type 2 response; as much as 0.40 log unit difference exists due to the non-ideal nature of the response. For this reason, the Bouwer and Rice K for this response type will be used in place of values from the Cooper et al. analysis. We do not know or believe that this analytical model is better than the Cooper *et al.* model, but the simplicity of the matching technique may reduce some error.

The response characteristics and subsequent T and K values may be interpreted as the following. Type 1 response may indicate a moderately to slightly transmissive test zone, with storativity reasonably estimated from the type curve value. Type 2 response could represent two phenomena: a rapid drainage of holes or voids around the well (not within the aquifer), and/or rapid drainage of very permeable zone(s) within the aquifer. Type 3 response likely represents a combination of high permeability zones (either in the aquifer or well annulus) and lower-permeability aquifer zones. Unfortunately, there is no unambiguous way to distinguish well-storage effects from highly-conductive aquifer response.

Well ID	Saturated Thickness (m)	Cooper et. al. Method <<< 0.9 meter long bail >>> K (m/s)	T (m2/s)	S (unity)	<<< 1.8 meter long bail >>> K (m/s)	T (m2/s)	S (unity)	Test Response Type	pump test T (m2/s)	pump test S (unity)	pump well ID	pump Q L/min
x01	4.47	4.70E-04	2.10E-03	1.03E-05	3.84E-04	1.72E-03	1.08E-05	1				
x02	1.80	**** Plugged ****										
x03	2.83	1.41E-05	4.00E-05	3.60E-04	9.54E-06	2.70E-05	3.10E-04	3	1.60E-03	1.00E-03	x27	45
x04	4.29	9.25E-04	3.97E-03	7.97E-04	8.92E-04	3.82E-03	4.65E-07	1				
x05	1.88	2.00E-07	3.76E-07	2.90E-04				3				
x06	2.07	2.31E-06	4.77E-06	1.00E-05				1				
x07	2.29	1.32E-03	3.02E-03	2.63E-13				2				
x08		**** Not Measured ****										
x09	3.30	4.24E-05	1.40E-04	1.00E-07	4.18E-05	1.38E-04	1.00E-07					
x11	1.66	9.23E-07	1.53E-06	2.50E-04				3				
x12	2.52	3.97E-04	1.00E-03	1.40E-04	3.97E-04	1.00E-03	1.00E-04	1	1.43E-03	9.00E-03	x13	110
x13	6.54	2.15E-03	1.40E-02	4.71E-16	1.90E-03	1.25E-02	5.55E-12	2	3.89E-02	1.00E-03	x23	45
x14	5.19	4.41E-05	2.29E-04	1.00E-05	3.80E-05	1.97E-04	1.00E-07	3				
x15		**** Plugged ****										
x16	2.67	8.14E-04	2.17E-03	2.23E-16	4.19E-04	1.12E-03	4.69E-10	2	2.10E-03	7.00E-03	x17	25
x17	2.33	5.06E-04	1.18E-03	1.08E-07	5.10E-04	1.19E-03	1.09E-07	2				
x18	3.44				6.91E-06	2.38E-05	1.00E-02	1				
x19	1.75	4.29E-04	7.49E-04	1.00E-07				2				
x20	2.13				3.98E-06	8.49E-06	1.00E-05	1				
x21	3.74	1.92E-03	7.20E-03	1.00E-06				2				
x22	2.81	9.04E-04	2.54E-03	1.00E-05	6.11E-04	1.72E-03	1.00E-05	2				
x23	2.46	2.76E-04	6.80E-04	7.80E-02	1.80E-04	4.42E-04	7.30E-02	1	4.60E-04	8.00E-03	x13	110
x24	2.15				3.86E-06	8.30E-06	1.00E-05	3	4.70E-03	2.00E-03	x23	45
x26		**** Not Measured ****										
x27	4.82	3.07E-05	1.48E-04	1.00E-07	5.40E-05	2.60E-04	1.00E-08	3				
x28		**** Dry ****										
x40	1.70	**** Plugged ****										
x41	2.81	2.70E-03	7.60E-03	1.00E-06	1.42E-03	4.00E-03	1.00E-07	2				
x42	2.63	1.89E-05	4.96E-05	5.00E-03				1				
x44	4.16	2.40E-05	1.00E-04	1.23E-04				1	8.90E-04	3.00E-03	x17	25
x45		**** Plugged ****										
x46	5.03	1.62E-06	8.16E-06	3.14E-04	2.03E-06	1.02E-05	1.00E-06	3				
y01	1.55	**** Plugged ****										
y02	2.84	2.36E-04	6.68E-04	1.17E-02				1				
y03	2.87	6.78E-04	1.94E-03	6.88E-04	6.98E-04	2.00E-03	2.83E-08	1				
y04	4.26				3.02E-03	1.29E-02	4.10E-18	2				
y05	3.63				1.49E-04	5.40E-04	1.00E-02	3				
y06	4.19	1.26E-03	5.28E-03	3.87E-05	1.11E-03	4.67E-03	3.43E-06	1				
y07	1.34	**** Plugged ****										
y08		**** Dry ****										
y09	1.30	1.75E-03	2.27E-03	1.00E-04				2				
y10	3.30	2.16E-03	7.13E-03	1.00E-07				2				

Table 1. Results of slug test and pump test interpretations.

Well ID	Test Response Type	Cooper et. al. K (m/s)	Bouwer & Rice K (m/s)	log unit Difference	Well ID	Test Response Type	Cooper et. al. K (m/s)	Bouwer & Rice K (m/s)	log unit Difference
x01	1	3.84E-04	2.24E-04	0.234	x17	2	2.33E-04	1.36E-04	0.234
x03	3	9.54E-06	6.50E-06	0.167	x18	1	6.91E-06	4.46E-06	0.190
x04	1	8.92E-04	5.59E-04	0.203	x19	2	4.29E-04	1.16E-04	**0.568**
x05	3	2.00E-07	1.52E-07	0.118	x21	2	1.92E-03	1.40E-03	0.138
x06	1	2.31E-06	1.53E-06	0.179	x22	2	6.11E-04	3.40E-04	0.255
x07	2	1.32E-03	3.20E-04	**0.615**	x23	1	1.80E-04	2.21E-04	-0.090
x09	3	4.18E-05	1.71E-05	0.388	x24	1	3.86E-06	1.51E-06	0.407
x11	3	9.23E-07	7.72E-07	0.078	x27	3	3.07E-05	1.39E-05	0.344
x12	1	3.97E-04	3.96E-04	0.001	x46	3	1.62E-06	1.25E-06	0.113
x13	2	1.90E-03	5.45E-04	**0.542**	y02	1	2.36E-04	1.76E-04	0.127
x14	3	3.80E-05	1.25E-05	**0.483**	y03	1	6.78E-04	2.63E-04	0.411
x16	2	4.19E-04	9.90E-05	**0.627**	y04	2	3.02E-03	6.15E-04	**0.691**

Table 2. Comparison of K values derived from the two analytical techniques.

Comparison of Short and Long Slugs

Results of 14 tests using both 1.8-meter and 0.9-meter bailer lengths are compared in Figure 4. A fairly strong regression fit exists (arithmetic R^2=0.84), but there is a slight bias. The shorter slug overestimates transmissivity values; the slope of the regression line is 0.72. This may reflect differences in permeability and porosity of the aquifer directly outside the well due to the effects of drilling and well development. A larger bailer volume will create a greater radius of influence, and include aquifer properties from greater distances that influence test response. The difference is not negligible, but is small relative to the overall range of transmissivity observed. Therefore, data from the short- and long-bails were considered amenable to combination for statistical analysis

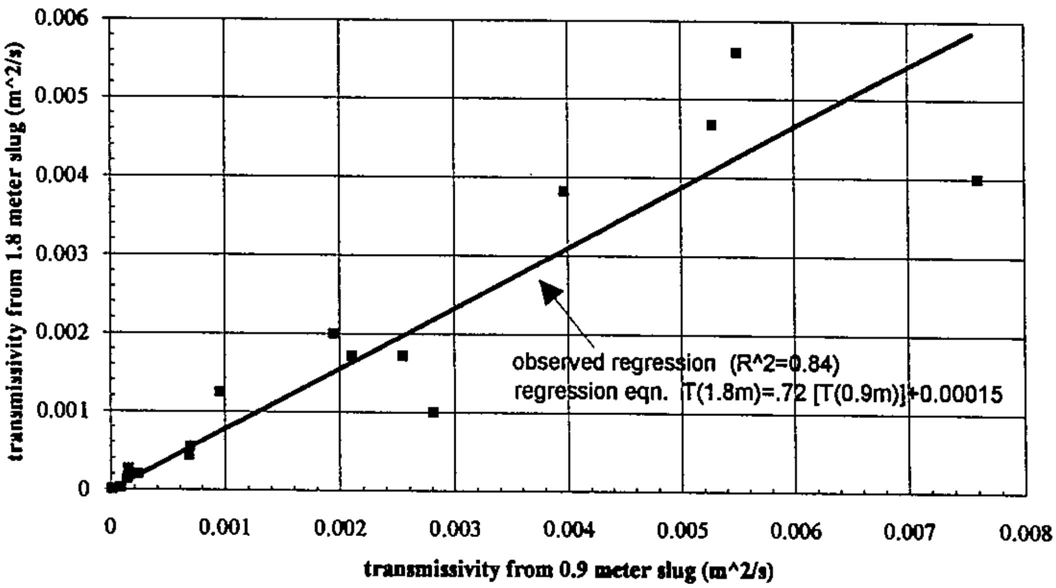


Figure 4. Comparison of slug-test hydraulic conductivities for 1.8-meter and 0.9-meter slug lengths.

Pump Test Interpretation

Analysis of results was performed using conventional Theis curve-fitting for infinite artesian aquifers (Dawson and Istok, 1991). The drawdown curves at observation wells were interpreted to indicate aquifer transmissivity and storativity over the first 10-200 minutes of the test, ignoring increased rate of drawdown observed late in the test resulting from boundary effects. Pumping-well drawdown was measured with a datalogger but was not considered usable for test interpretation due to well losses.

Results

Hydraulic Conductivity Distribution

A wide range of flow conductance values were observed. Figure 5 shows the frequency distribution of transmissivity (T) and Figure 6 the frequency distribution for average hydraulic conductivity (K) values, calculated by dividing the T values by the well saturated thickness. The sample set was calculated using the 1.8-meter slug data for wells at which this test was performed, and the 0.9-m slug data otherwise.

Evident in both sets of data, but most strikingly for the K data, are two distinct modes of the sample distribution. First, the approximate transmissivity limits of the high-conductivity mode range from $10^{-4.2}$ to

$10^{-2.4}$ m²/s (K=$10^{-3.9}$ to $10^{-2.7}$ m/s); the log-normal mean is $10^{-2.9}$ m²/s and $10^{-3.3}$ m/s. The upper range of the high-hydraulic conductivity mode (1 to 3×10^{-3} m/s) is extremely permeable for a granular medium. Second, the limits of the low-conductivity mode range from $10^{-6.6}$ to $10^{-4.2}$ m²/s (K=$10^{-6.3}$ to $10^{-4.5}$ m/s); the log-normal means of this mode equals $10^{-5.1}$ m²/s and $10^{-5.3}$ respectively. The low-conductivity mode is less well represented than the high mode, due in part to the existence of numerous Type 1 and Type 2 wells.

Storativity Distribution

Figures 7 and 8 show the frequency distribution of the storativity and specific-storativity (storativity divided by the well saturated thickness) values determined from the Cooper et al slug test analysis. Two modes are present in the data. A high mode, from $10^{-2.4}$ to $10^{-1.6}$ ($10^{-2.8}$ to $10^{-1.6}$ m^{-1}) with a log-normal mean of 10^{-2} ($10^{-2.35}$ m^{-1}), suggests the presence of unconfined/semi-confined aquifer conditions; note that the specific-storativities are unrealistically high, suggesting that these numbers represent "leaky" response. On the other hand, the low mode, from 10^{-7} to $10^{-3.2}$ ($10^{-7.8}$ to $10^{-3.9}$ m^{-1}) with a log-normal mean of $10^{-4.7}$ ($10^{-5.2}$ m^{-1}), suggests that semi-confined/confined conditions also exist within the spoil aquifer. Storage values from Type 2 tests were omitted due to the non-ideal nature of this response and to error in estimating storativity.

Pump Test Results

In comparison to the slug test results, transmissivities interpreted from pump test response at observation wells bracket a relatively narrow range, from $10^{-3.3}$ to $10^{-1.4}$ m²/s (Table 1). Hydraulic conductivity values vary over a similarly narrow range, from $10^{-3.7}$ to $10^{-2.6}$ m/s. The narrowness in range is in part ascribed to test-type bias, since high yielding pumping wells necessary for the test generally exist in transmissive portions of the aquifer. Nevertheless, the range of pump-test results corresponds well with the median ranges of the high modes of both transmissivity and hydraulic conductivity in the slug test sample. The low-conductivity mode is not represented in these pump-test results.

Some agreement exists between hydraulic values determined from slug and pump tests at the same well locations. Pump test results correspond with values determined from Type 1 slug tests; wells x12, x23, and x44 show that transmissivity values agree within 0.5 log units. Also, storage values also crudely agree; pump test storativity (log-normal mean of $10^{-3.5}$) fall between the two S modes determined from slug testing.

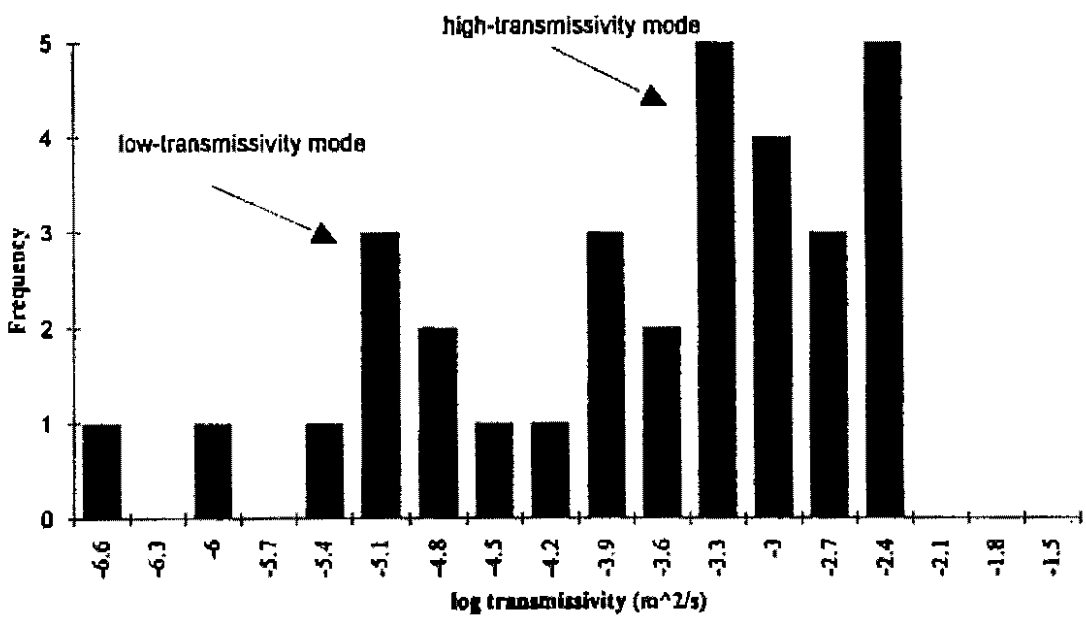


Figure 5. Frequency distribution of transmissivity estimates based on slug tests.

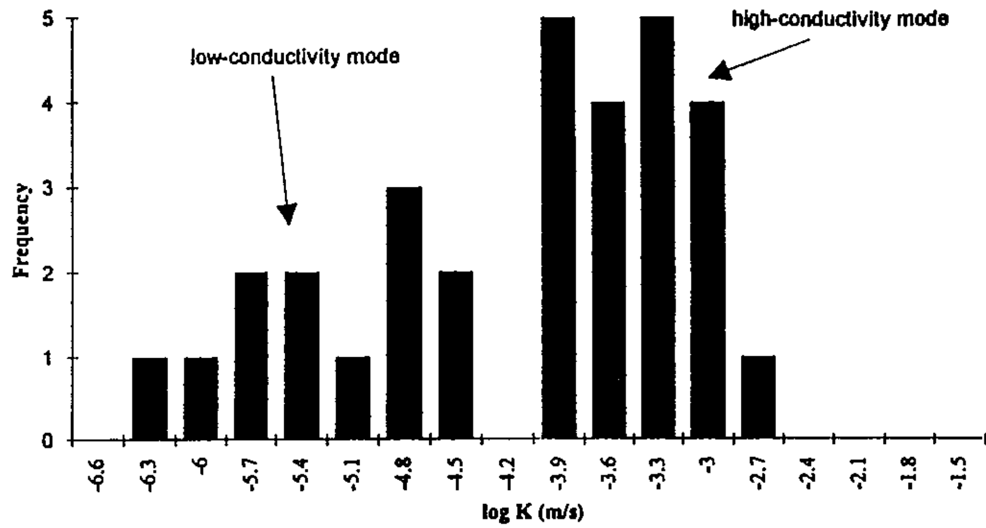
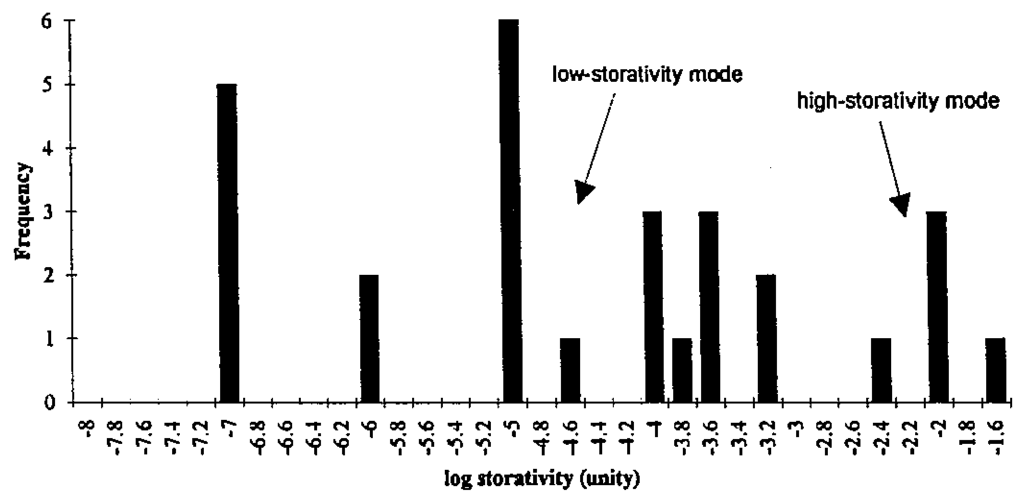
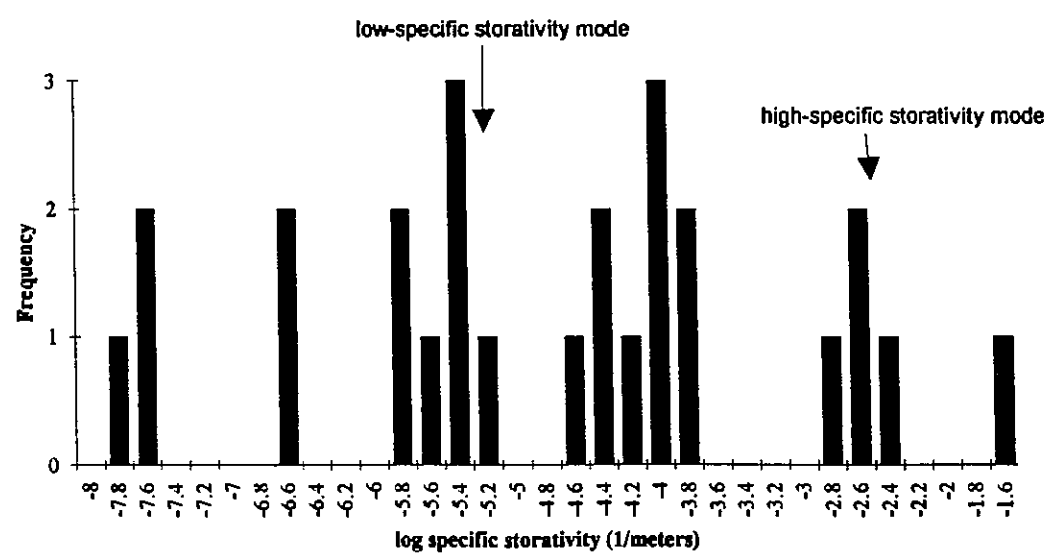


Figure 6. Frequency distribution of vertically-averaged hydraulic conductivity estimates based on slug tests.





Figures 7 and 8. Frequency distribution of storativity and specific storativity estimates based on slug tests.

Discussion

Four key observations arise from these results:

1. Slug tests show three types of aquifer response (Type 1, 42%, Type 2, 35%, and Type 3, 23% of the wells showing aquifer response) which yield a mean log-normal S of $10^{-4.4}$ and a mean log- normal K of $10^{-4.1}$ m/s.

2. The statistical distribution of K and T values from slug tests shows two modes: a very clear high-conductivity mode, and a less well-represented low conductivity mode. Both modes, especially the high-K one, appear approximately log-normal in distribution.

3. The statistical distribution of S and specific-storativity also is bi-modal, with a well-represented low-storativity mode and a distinct high-storativity mode. These values suggest the presence of confined, semi-confined, and unconfined aquifer conditions throughout the mine spoil aquifer.

4. The pump test results show a narrow variance in K values, but within the middle of the high-K mode from the slug test sample. Storativities confirm observation from slug tests suggesting semi-confined conditions.

Some caution is required in interpreting the significance of these results. First, the extent to which wellbore effects have tended to control or cause the Type 2 response is not known. However, it is observed that high-K values interpreted from pump test results correspond well with Type 1 and Type 2 response observed in slug tests. Since the pump-test values were interpreted based on portions of the test that involved over an hour of pumping stress, the results are clearly not related to well-storage effects.

Additional caution is warranted in the assumptions involved in the slug test interpretation. The Cooper *et al.* model assumes artesian response, i.e. only horizontal flow dominates flow of water to the well and that the influence of vertical or unconfined flow is negligible. This assumption is likely unreasonable for the Type 2 and Type 3 wells tested in this study; vertical drainage of groundwater may be a key element of the response characteristics. Therefore, the interpretative model is a simplification of the actual physics of radial flow.

We believe there is clear evidence of a double mode in hydraulic conductivity distribution (and likely in specific-storativity as well) displayed in these data. This distribution is suggested in lateral distribution of conductivity values (inferred from the frequency distributions for the slug-test sample) and in vertical heterogeneity (inferred from measured storativities). The high-conductivity mode may, in some cases, be ascribed to the commonly-cited high-void zone, speculated by numerous others to strongly influence flow, as described in the introduction. This high-K zone is indicated by our results to have a quite broad spatial distribution, as indicated by the high percentage of Type 1 and Type 2 tests and by the significant lateral extent of pumping cones of depression observed during the pump tests. It is likely that, due to its high transmissivity and broad continuity, this component of the spoil will be an important control on large-scale groundwater flow. Because of its continuity, it is not likely that this zone represents discrete vertical fractures or local voids; it may infact be a laterally-continuous feature, similar to a stratigraphic layer. A rubble zone as described by earlier authors (Van Voast and Reiten, 1988) would fit this description; however, the aquifer has not been visually examined.

The double (Type 3) response observed in slug tests is somewhat anomalous. If the Type 3 response in fact represents "dual-storage" behavior as postulated, then the two zones would necessarily be at different hydraulic potentials at the onset of the test, forming a head gradient that would be from low- to the low-conductivity zone is an aquitard under phreatic conditions that slowly drains to the more permeable zone, or (2) that there is an aquitard zone separating the high-conductivity zone from an overlying water-table aquifer. In either case, a leaky-aquifer model is indicated, with the confined high-permeability zones slowly collecting drainage from overlying low-permeability zones. This interpretation is consistent with site observations of a continuous water table and with the semi-confined values of storativity indicated for the pump test response (10^{-3} to $10^{-2.2}$).

The high-conductivity mode of the distribution is distinct from the low-conductivity mode by about 1-3 orders of magnitude. This large difference may help explain the discrepancy between test results and model requirements observed by Hawkins (1994) and Aljoe (1994). The Type 1 and 2 response characteristics would not be observed in slug tests unless bails are removed abruptly and the response in the first 20 seconds of the test is measured accurately. Therefore, it would be relatively easy to overlook the true response, or to dismiss it as well-storage effects. The pump test results are more credible and not subject to such uncertainties; however, pump tests are not amenable to random sampling of well hydraulic characteristics, because not all wells are amenable to pumping.

Conclusions

1. A bi-modal lognormal distribution for hydraulic conductivity and transmissivity in a saturated minespoil aquifer is inferred from a sample of 31 wells using slug test techniques. The modal hydraulic conductivity of the high mode, interpreted as high-void ratio spoil, is $10^{-3.3}$ m/s. The modal hydraulic conductivity of the lower mode, interpreted as matrix-porosity spoil, is about $10^{-5.2}$ m/s. The range of the high-K mode is relatively narrow, over about an order of magnitude.

2. Both pump test results and the univariate parameter distributions suggest large-scale lateral continuity of the high-K component of the aquifer.

3. The relationship between the high-K zone and the low-K zone may be interpreted as an aquifer-aquitard pair, with the aquifer zone occurring at lower hydraulic head and draining the aquitard and overlying water table.

Acknowledgments

This work was undertaken as part of a team project studying hydrogeological aspects of AMD-producing spoils, supported by the National Mine Lands Reclamation Center. In-kind assistance and close collaboration in the research was provided by the West Virginia Division of Environmental Protection; special thanks are due to Michael Reese, manager of Alton Project, and his staff. Kevin Frysinger, Richard Todd, and Steve Klug assisted with the fieldwork.

References

Aljoe, W.W., 1994. Application of an analytical ground water flow model to a pseudokarst setting in a surface coal mine spoil. in U.S. Bureau of Mines Special Publication SP-06D-94, v. 4: p. 190-199.
https://doi.org/10.21000/JASMR94040190

Bouwer, H., and Rice, R.C., 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partly penetrating wells. Water Resources Research, v. 12: p. 423-428.
http://dx.doi.org/10.1029/WR012i003p00423

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

Cooper, H.H., Bredehoeft, J.D., and Papadopulos, I.S., 1967. Response of a finite-diameter well to an instantaneous charge of water. Water Resources Research, v. 3: p. 263-269.
http://dx.doi.org/10.1029/WR003i001p00263

Cravotta, C.A., Brady, K.B., Gustafson-Minnich, L.C., and DiMatteo, M.R., 1994. Geochemical and geohydrological characteristics of bedrock and spoil from two methods of mining a a reclaimed surface coal mine, Clarion County, PA, USA. U.S. Bureau of Mines

Dawson, K.J., and Istok, J.D., 1991. Aquifer testing: design and analysis of pumping and slug tests. Lewis Publishers, Chelsea, Michigan: 344 pp.

Domenico, P.A., and Schwartz, F.W., 1990. Physical and Chemical Hydrogeology. John Wiley & Sons, New York, NY. p. 65.

Gabr, M.A., Bowders, J.A., and Runner, M.S., 1994. Assessment of acid mine drainage remediation schemes on ground water flow regimes at a reclaimed mine site. U.S. Bureau of Mines Special Publication SP 06B-94, v. 2: p. 168-177.

Geraghty and Miller, 1989. AQTESOLV version 1.10: an aquifer test solver. Geraghty and Miller Modeling Group, Reston, Virginia: 156 pp.

Hawkins, J.W., 1994. Modeling of a reclaimed surface coal mine spoil aquifer using MODFLOW. U.S. Bureau of Mines Special Publication SP 06B-94, v. 2: p. 265-274.

https://doi.org/10.21000/JASMR94020265

Hawkins, J.W., and Aljoe, W.W., 1990. Hydrologic characterization and modeling of a heterogeneous acid-producing surface coal mine spoil, Upshur County, West Virginia. in Proceedings, 1990 National Symposium on Mining, Knoxville: p. 43-52.

Hawkins, J.W., and Aljoe, W.W., 1991. Hydrologic characteristics of a surface mine spoil aquifer. in Proceedings 2nd International Conference on the Abatement of Acidic Drainage, Montreal P.Q.: p. 47-58.

Houghton, R.L., Thorstensen, .C.., Fisher, D.W., and Groenewold, G.H., 1984. Hydrogeochemistry of the upper part of the Fort Union Group in the Gascoyne lignite strip-mining area, North Dakota. U.S. Geological Survey Open-File Report 84-131: 184 pp.

Hvorslev, M.J., 1951. Time lag and soil permeability in groundwater observations. U.S. Army Corps of Engineers, Waterways Experiment Station Bulletin 36: 50 pp.

Maher, T. , in preparation, 1995. Analysis of hydrogeologic properties of a weathered acidic minespoil aquifer using radial-well tests. Unpublished Master's thesis, Department of Geology and Geography, West Virginia University.

Pionke, H.B., and Rogowski, A.S., 1982. Placement of acid spoil materials. Reclamation and Revegetation Research, v. 1: p. 3-11.

Van Voast, W.A., Hedges, R.B., and McDermott, J.J., 1977. Hydrologic conditions and projections related to mining near Colstrip, southeastern Montana. Montana Bureau of Mines and Geology Bulletin 102: 43 pp.

Van Voast, W.A., and Reiten, J.C., 1988. Hydrogeologic responses: twenty years of surface coal mining in southeastern Montana. Montana Bureau of Mines and Geology Memoir 62: 39 pp.

Wunsch, D.R., and Dinger, J.S., 1994. The hydrogeology amd Hydrogeochemistry of the Star Fire site, eastern Kentucky. U.S. Bureau of Mines Special Publication SP 06B-94, v. 2: p. 188-197.

https://doi.org/10.21000/JASMR94020188