MODELING OF A RECLAIMED SURFACE COAL MINE SPOIL AQUIFER USING MODFLOW[1]

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Abstract: Improved prediction of the postmining water levels in mine spoil can be useful in preventing future acid mine drainage production. Using a computer model (MODFLOW), a reclaimed surface mine aquifer under steady-state conditions was simulated. To calibrate the hydrologic model, the hydraulic conductivity of the spoil had to be increased by as much as 200 times above values empirically determined by field tests. These modifications were justified by the presence of large open voids and conduits in the spoil. Simulated recharge to the spoil was primarily from fracture zones in adjacent unmined areas. Recharge from precipitation was established at a low level (10% of the mean precipitation), because of mining-induced changes to the soil structure. The steady-state calibrated model exhibited head levels 8.7% above and a discharge rate that was within 5.7% of measured field conditions. These results indicate that MODFLOW can be successfully used to simulate the ground water table and discharge rates of mine spoil after reclamation. Using the calibrated model, a constant-discharge test was applied to the aquifer. The model did not accurately simulate the results of an aquifer test performed in the field. The heterogeneous nature of the mine spoil is believed to facilitate unquantified anisotropic ground water flow, which was not accounted for in the simulations. However, the steady-state simulation with MODFLOW proved to be useful in modeling spoil under variable site conditions.

Additional Key Words: mine spoil aquifer, ground water modeling

Introduction

The unconsolidated nature of mine spoil has lead many hydrologists to assume that it behaves similarly to a conventional porous medium flow system. Under this assumption, ground water flow is intergranular, laminar, and subject to the limitations of Darcy's law. Caruccio and others (1984) suggested that ground water flows primarily in a pseudokarst manner, through large voids or conduits within the mine spoil. Groenewold and Bailey (1979) described the formation of such voids within mine spoil by piping and differential settling. Void formation is further facilitated by backfilling and other reclamation processes. Large spoil blocks tend to roll to the base of spoil ridges, while smaller particles tend to remain on the ridge top and sides (Rehm et al. 1980). This sorting action creates extreme aquifer heterogeneities in the form of linear high-permeability zones, parallel to spoil ridges, laterally bounded by lower permeability material. The orientation and magnitude of the void areas are dependent on overburden lithology, mining equipment used, surface mining method, direction of mining, and age of reclamation (Hawkins and Aljoe 1991; Aljoe and Hawkins 1992).

Aquifer testing performed by Hawkins and Aljoe (1991) confirmed the existence of large voids in mine spoil. They observed that pseudokarstic characteristics predominate when the aquifer is stressed, during aquifer testing or extreme recharge events. However, aquifer tests (slug, constant-discharge, and tracer tests) indicate that although the voids are common in spoil, ground water flow between voids and flow from the voids to surface discharge points is primarily laminar and diffuse, typical of a porous medium. Under steady-state conditions, the lower permeability of the porous-media material between voids is the primary controller of the volume and velocity of ground water moving through the spoil aquifer. Therefore, under steady-state conditions the aquifer as a whole behaves primarily as a porous medium.

Aquifer testing in mine spoil can be problematic in the sense that most aquifer tests are a hydrologic stress on the spoil aquifer. The methodology and formulae used in the calculation of aquifer parameters

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assume that flow is laminar, which meets the constraints of Darcy's law (Aljoe and Hawkins 1992). However, stresses caused by testing can create rapid, turbulent, nondarcian ground water flow. These possible inconsistencies should be considered when using field-generated aquifer data for modeling ground water flow in mine spoil. The primary goals of this study are to acquaint the ground water modelers with the problems in simulating mine spoil, and to give ground water professionals who work with surface mines an introduction to the problems of modeling surface mine spoil aquifers.

Site Background

The modeled site is a 3.2 ha (8 acre) parcel of a surface coal mine in central West Virginia (fig. 1). The lower and middle Kittanning coals were mined on this site between 1976 and 1977. The site was backfilled to final grade by December 1977. The modeled portion of the site was terrace backfilled with a steep grade existing at the final highwall. The central portion of the site slopes gently westward to the final highwall. A drainage ditch was installed on the site to eliminate surface water impoundment. Spoil was placed downslope below the original coal outcrop, covering unmined areas (outslope area). At the base of the spoil outslope, a "toe-of-spoil" discharge developed, which is the main outflow point for the study area.

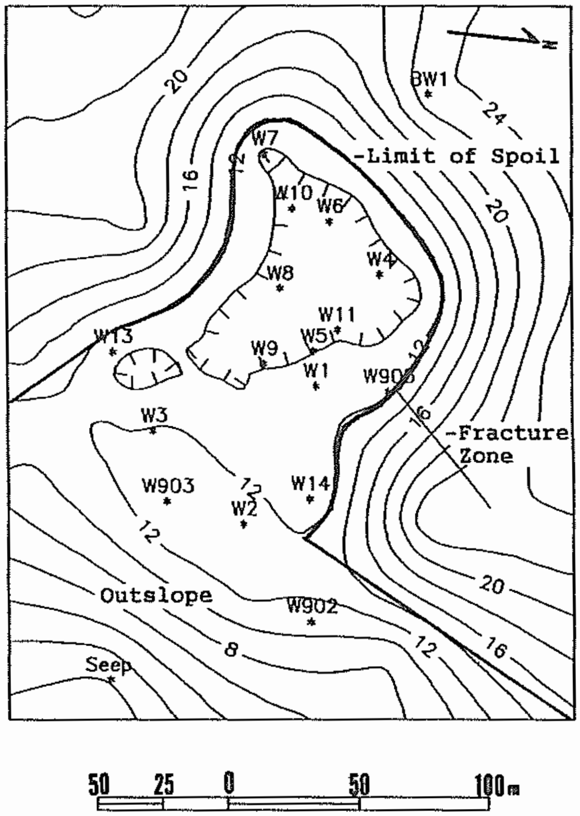

Figure 1. Topographic map of the study site. Contour interval equals 2 m.

Drill hole logs from adjacent unmined areas and existing highwall exposures illustrate that the strata are laterally continuous throughout the study area. The lower Kittanning coal is 1.2 m thick and underlain by a hard-gray claystone. The interburden between the middle and lower Kittanning coals is 4.3 m of a carbonaceous gray shale. The middle Kittanning coal is 1.4 m thick. The strata overlying the middle Kittanning coal are a 0.6 m thick carbonaceous shale and a gray sandstone averaging 11.6 m thick.

The strata at the site dip gently (less than 2%) toward the northwest. Rock exposures around the site illustrate that joint and fracture zones are common in this area. There are two principal orientations of these fractures, between N22E and N45E and between N10W and N38W. The fractures are vertical or nearly vertical and are open up to 3 cm. A prominent fracture zone (1-2 m wide) on the northern edge of the site was identified in the field. This fracture zone was shown to be a major recharge source for the site (Hawkins and Aljoe 1990). In the Appalachian region, ground water flows primarily through fractures in undisturbed strata. The fractures are created from structural stresses and from stress release caused by the removal of the overlying materials by erosion (Wyrick and Borchers 1981). During the computer simulations, other fractured areas in the buried highwall inferred from field data (e.g., water levels and tracer tests) were introduced into the model.

Initially, 15 monitoring wells were installed at the site (fig. 1). One of the wells (BW-1) was drilled through undisturbed strata above the final highwall, and the remaining wells were drilled into the backfill. However, well W12 was too shallow to be of use. In 1990, three additional spoil wells (W902, W903, and W905) were installed. Water levels in the wells were monitored for several years. Hydraulic testing of the spoil (slug injection and/or withdrawal) originally was conducted to characterize geohydrology of the site.

Water level monitoring and aquifer testing were used to set up and calibrate the model. Monitoring of the site indicated that the hydrologic conditions, outflow and head levels, on July 26, 1989, were representative of steady-state conditions. No precipitation had occurred for several weeks prior to this date. Steady-state head levels for the spoil are exhibited by figure 2.

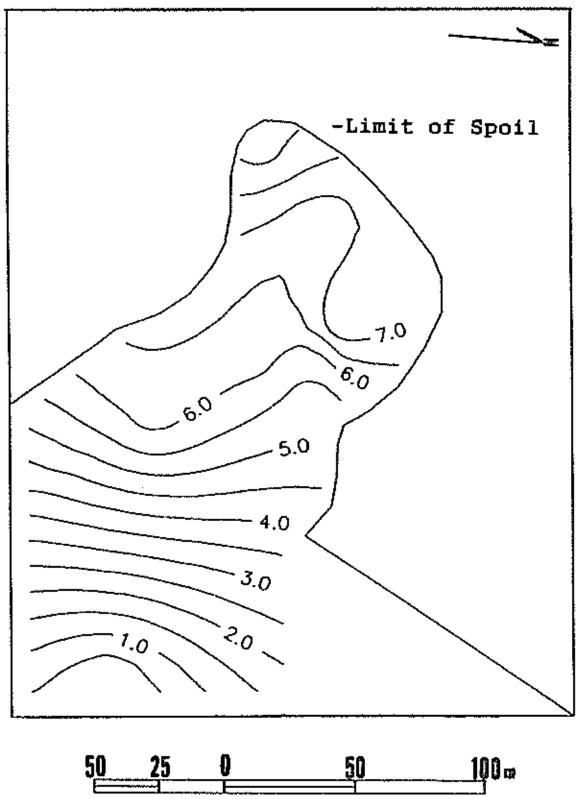

Figure 2. Water table contour map of the spoil for steady-state conditions (July 26, 1989). Contour interval equals 0.5 m.

Model Setup and Calibration

The ground water model selected for this work was MODFLOW, which was developed by the U.S. Geological Survey (McDonald and Harbaugh 1988). MODFLOW is a three-dimensional finite-difference computer model that is composed of a main program and a series of subroutine modules. Modules are created to handle specific tasks of the hydrologic system, such as setting boundary conditions, initial heads, surficial recharge and discharge, and locating pumping or injection wells. MODFLOW permits the modeler to select only the modules required for each trial run and allows new modules to be created and added independently, without altering the existing modules.

At the start of modeling, it was determined that the model set up and data input had to be simplified from the conceptual characterization. A number of simplifying assumptions were made concerning the ground water flow characteristics: (1) The overall flow system was assumed to be a porous-medium type under steady-state conditions; (2) the hydraulic conductivity was assumed to be relatively consistent throughout the spoil; (3) all the outflow was assumed to exit through the known discharge point; and (4) most recharge was assumed to be from adjacent unmined areas. Analysis of field data collected indicates that these assumptions are valid. The objective of the model calibration was to simulate the heads and outflow within 10% of field conditions. Considering the known problems in characterizing spoil, this level of closure was assumed to be an adequate site approximation.

The spoil was simulated as an unconfined aquifer; therefore, the upper bound was unspecified and the cell thickness was variable, corresponding to changes in head. A confining layer (aquitard) simulated the stratum underlying the spoil. Any leakage through this layer was assumed to be insignificant. The elevation of the underlying layer cells was based on drill hole data. The model was set up as a 180 x 240 m horizontal grid divided into cells of 15 m^2 in two layers. The cells representing spoil were designated as variable-head cells. The cells located in unmined areas, where the highwall borders the spoil, were designated as constant-head cells, because of the limited fluctuation observed there. Cells in unmined areas above the highwall were designated as no-flow cells, because limited data exist for this area, the cells are outside the area of interest, and it is thought that they will not affect the modeling of the spoil. The discharge point (seep) was initially designated a constant-head cell.

The initial head levels for the spoil wells were set at 6.56 m above the discharge (datum), which is the estimated mean for the wells in the backfilled area under steady-state conditions (July 26, 1989). The head for the highwall cells (8.2 m) was determined by extrapolation from well BW-1 (in the unmined area) to the two nearest spoil wells (wells 6 and 7), because BW-1 was too far from the highwall-spoil interface to represent the water level at that point. The initial head for the seep (datum) was 0.01 (fig. 1).

The initial spoil hydraulic conductivity (K) value (0.22733 m/d) was the geometric average, assuming a lognormal distribution of K (Freeze and Cherry 1979), for the estimated values determined from the aquifer (slug) tests. The initial K value (0.03855 m/d) that was used for highwall cells was obtained from testing well BW-1. These values had to be modified (increased) several times during the calibration phase of the modeling to be able to match the known heads and outflow for steady-state conditions. Hawkins and Aljoe (1990) observed that the bulk K for spoil may be at least an order of magnitude higher than the geometric average for the wells. Because of the existence of large voids and conduits in the spoil, the effective K for the aquifer as a whole is substantially higher than the values determined by individual slug tests. Slug tests, by design, estimate the K for only a small area surrounding the well, not necessarily reflecting an average for the aquifer. Therefore, K values obtained from slug testing of wells that do not intersect voids may not necessarily represent the spoil as a whole. The K of conduits and large voids normally cannot be tested using conventional aquifer tests because the large openings permit rapid, turbulent nondarcian flow. Therefore, the results of slug tests performed on wells that intersect conduits may be in error. Given the darcian flow equation used to determine K, the calculated values may be artificially high, if the rapid displacement recovery can be recorded (Hawkins 1993). However, the early partial head recovery is often too rapid to be measured, but is followed by a slower darcian-type recovery. In these types of wells, the K is estimated from the later darcian-type recovery, which tends to underestimate the true K value.

For the first few simulations of the calibration phase, ground water tended to impound in the backfill. The K at the discharge cell was too low to accommodate the volume of water that was known to flow through it. The K of the discharge cell was increased to 1,000 m/d to allow higher flow through that cell. To increase the total outflow, the K of the outslope cells was raised by a factor of 10 to 2.272 m/d. No wells exist in this area, therefore the K value of the outslope is conjecture. However, field observations indicate that interconnected conduits are common in the outslope and that these conduits strongly influence the ground water flow (Hawkins and Aljoe 1990).

For the initial model-calibration runs, a surface recharge package was used. Based on experience, the recharge rate was established at 10% of the mean annual precipitation rate. After several runs, it was determined that the package was complicating the model and may not be required. During early runs using the recharge package, the output head levels and outflow were higher than measured values. The model results were improved when the majority of the aquifer recharge occurred laterally from unmined areas. Razem (1983) observed that following reclamation, surface recharge is significantly lower for spoil than for adjacent unmined areas, because of the lack of soil structure, high soil compaction, and low vegetative growth for mine cover material.

The relative importance of lateral recharge from unmined areas of this site was empirically determined during monitoring and testing (Hawkins and Aljoe 1990, 1991). Ground water enters the spoil primarily through fractures exposed in the buried highwall. Once the model simulations closed in on field conditions, the recharge package was reintroduced. It is not assumed that surface recharge does not occur, just that the rate is 10% of what occurs at unmined sites.

After the first few model calibration runs, the discharge cell was changed from a constant-head to a variable-head cell to accommodate changes in the discharge elevation with higher flow rates. With the increased k, the head remained consistently low (0.001 m) and the heads and the flow neared field conditions. However, this change caused some of the cells in the center of the backfill to dry up. To alleviate this problem, the K of these cells was increased by a factor of 10 and the K of the discharge cell was decreased to 100 m/d.

An injection well (module) was added at the northern fracture zone cell (fig. 1) to simulate the inflow from this recharge source. The injection rate (17.4 m^3/d) was set at one fifth the average discharge rate, based on experience with the site. At this rate, the injection well cell tended to dry up. The K value for the center spoil cells was again increased by 10. The well cell continued to dry up.

Rather than force water into the system via an injection well, it was decided that the model would work better if the outflow was better defined and controlled. Therefore, the well package was eliminated and a general-head boundary was created for the discharge cell. The general-head boundary package for the discharge was assigned a head of 0.01 m and a conductance of 5,000. A high conductivity value was used to ensure an adequate discharge rate. Conductance was not changed for the remainder of the model calibration. The initial head was later increased to 0.1 m to accommodate higher outflows.

These changes greatly improved the head simulation. However, the outflow was still too low. Therefore, the outslope K of the outslope wells was increased again by a factor of 10 to 22.73 m/d, based on the assumption that the outslope contained numerous highly conductive conduits. This change caused several spoil cells to dry up. The K of the outslope cells was reduced to 5 and then finally to 3 m/d. This brought the heads in the backfill to near actual levels, but the flow was almost a factor of 18 too low. At this point during the modeling, the recharge package was temporarily eliminated from the model. To account for the removal of the recharge, the K values for the highwall cells were increased to 0.3855 m/d. Because of unaccounted discrete fractures in the highwall, it is reasonable to assume that the overall K of the highwall rock is, in fact, significantly higher than the K of BW-1, which is not representative of fractured rock. The K for the northern fracture zone cell was also increased by two orders of magnitude, to 3.855 m/day.

Higher K values all along the length of the highwall yielded heads substantially above field conditions and outflow nearer the actual rate. Therefore, the K values for portions of the highwall where no fractures were known or could be inferred from the field observations and data were greatly reduced, by a factor of 2,000. This K value was based on the upper range of values for sandstone (Freeze and Cherry 1979). Where fracture zones were known to exist or were inferred from field data, the K was maintained at a higher level. For example, the K values were set at 3.855 m/d for an inferred fracture zone along the western edge of the highwall to augment the recharge from the northern fracture zone.

These model refinements brought the head levels and the discharge rate to near measured levels. Heads in the central spoil zone wells averaged 16.7% above the steady-state field values for 1989. The discharge flow was approximately 68% below the measured rate. The heads for the individual wells for the preliminary model are exhibited in table 1. Only wells that were screened in spoil to the pit floor and intersected the saturated zone were included. Wells W902, W903, and W905 were excluded because they were not installed until after 1989.

At this point, preliminary modeled heads were nearing field conditions. However, to improve simulated head values and increase the outflow, additional adjustments were made to the model input data. At this point, the recharge package was reintroduced to the model. Based on experience and trial and error, the recharge rate was set at 10% of the annual average precipitation, although this was below the anticipated recharge rate for unmined conditions.

Hawkins and Aljoe (1990) observed extreme differences in the K values for the wells in the interior spoil zone. A zone of high K was located in the center of the interior spoil zone, surrounding wells W3, W8, W9, and W13 (fig. 1). For this series of model runs, the K for this center area was based on the geometric average of these wells. A second area of elevated K values represents the spoil cells adjacent to the outslope area based on the geometric average of wells W2, W902, and W903. The K values for these two areas were at first established at the geometric average for each group of wells. Later, to

Table 1.–Summary of actual and modeled hydrologic data for steady-state conditions. Heads are in meters above datum (seep level), and flow is in liters per minute.

	Heads		
Well	July 26 1989	Preliminary model	Final model
1	5.35	7.93	7.22
3	6.10	7.37	6.62
4	7.46	8.13	7.52
5	5.80	7.99	6.83
6	6.59	8.13	7.59
7	8.21	8.17	8.28
8	6.37	8.00	6.86
9	6.13	7.83	6.87
10	6.96	8.12	7.33
11	7.44	8.05	7.39
13	6.41	7.81	6.66
Seep flow	62.10	20.10	58.50

lower the modeled heads and increase the flow, the values were increased by a factor of 10, and then 100 times the geometric average. The flow at this stage was about 2.5 times below the known outflow.

The K for the outslope was doubled, and the K of the discharge cell was increased by a factor of 20 in a continued effort to increase outflow. With these changes, the outflow was approximately one-half the measured flow rate, and the heads were similar to steady-state levels. To increase the outflow further, while not overly lowering the water level, the K for the entire site was multiplied by a factor of 2. This resulted in the final calibrated model.

The final steady-state model configuration is illustrated by figure 3. The actual steady-state head levels in the wells averaged 8.7% above the modeled head values with a range from 0.7% (well W11) to 34.9% (well W1). The root-mean-square error (standard error) for the calibrated model was 0.79 m. During the modeling, well W1 was consistently the most difficult well to match to the actual level. This may be related to the proximity of the fracture zone, which may impact the spoil ground water levels by rapid and high-volume recharge. Extreme water level differences are not unexpected in a pseudokarst system. The discharge rate of the final model was within 6% (5.7%) of the actual discharge rate (table 1). The head-contour map of the calibrated model (fig. 3) is very similar to actual site conditions (fig. 2). Additional calibration and refinement of the model may reduce the observed differences, but the possible improvement is not worth the required effort.

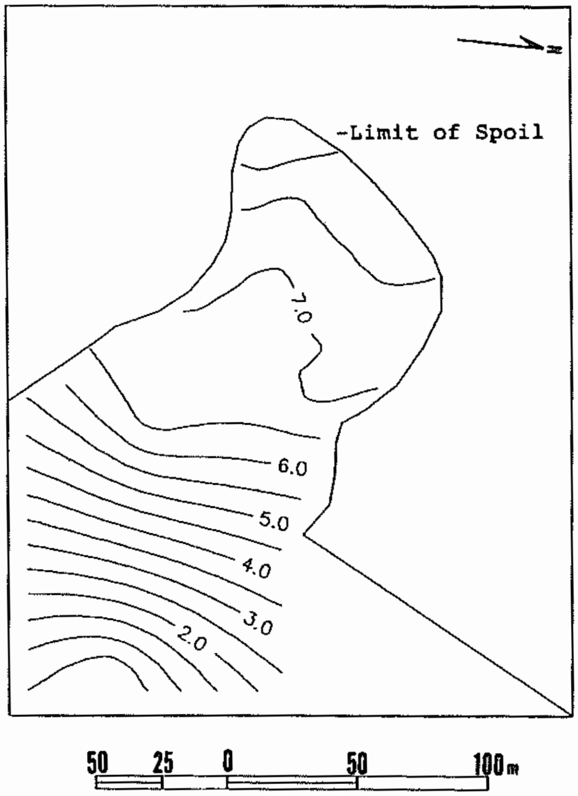

Figure 3. Final steady-state model configuration. Contour interval equals 0.5 m.

Stress Simulation

Once the steady-state model was satisfactorily calibrated, a simulated constant-discharge test was performed. This test was a simulation of an actual field test performed on June 28, 1990, when the head levels and hydrologic conditions were very similar to 1989 steady-state conditions. Well W6 was pumped at a rate of 6 l/min for 2 hours. The pumping rate was established based on the K determined from the slug test and the saturated thickness of the aquifer at well W6. Wells W8 and W10 were used as monitoring wells. At the end of the constant-discharge test performed in the field, drawdown for these wells was 0.05 and 0.04 m, respectively.

For the pumping test simulations, the initial heads were reset to the levels of the final heads from the steady-state simulation, and a well module was introduced. A pumping well was simulated at the cell containing well 6 and was pumped at the same rate and for the same length of time as in the field test. Several stress model runs were performed with the storage coefficient (storativity) value being varied. None of a series of model results satisfactorily simulated the drawdowns observed under field conditions. Initially, the storativity for the spoil was established at 0.2, which was based on calculations of effective porosity determined from tracer tests performed at this site. No drawdowns were observed at wells 8 and 10 using this value. The storativity was subsequently lowered to 0.05. However, no drawdown was produced at the monitoring wells with this simulation. The storativity was then lowered to 0.01, which is the lowest value of the range for storativity (specific yield) for unconfined aquifers suggested by Freeze and Cherry (1979). At this level, well 8 exhibited no drawdown, while well 10 exhibited a decline of 0.02 m.

The differences between the field-observed drawdowns and those from the simulated constant-discharge tests appear to be caused by the highly heterogeneous nature of spoil and the associated anisotropic ground water flow. Estimation of drawdown from a constant-discharge test is based on assumptions that the aquifer is a homogeneous material, that there is isotropic ground water flow, and that the cone-of-depression created during a constant-discharge test is relatively symmetrical. If preferred flow paths of relatively high conductivity exist in the spoil, the cone-of-depression will elongate in those directions. Monitoring wells not located along these elongation directions may exhibit lower drawdowns than predicted. However, monitoring wells located along these high conductivity zones may exhibit more drawdown than predicted.

The head differences may also be related to the potential incompatibility of the model and the ground water flow characteristics. Hawkins and Aljoe (1990) observed that under transient conditions or when a stress is applied, a spoil aquifer tends to exhibit pseudokarstic (nondarcian) characteristics. Pseudokarstic ground water flow is characterized by turbulent flow through voids or conduits. However, MODFLOW assumes ground water flow is laminar (darcian). The stress to the aquifer created by the constant-discharge test may have induced pseudokarstic ground water flow conditions in the area surrounding the pumping well, so that MODFLOW becomes incompatible to the site.

The lack of the model to simulate the constant-discharge test could also be related to the mean-root-error masking the drawdown. The mean-root-error is greater than the drawdowns observed during the field test. Therefore, some of the drawdown could be lost or hidden by lack of a closer fit during the calibration of the model.

Summary and Conclusions

Based on the modeling results, a mine spoil aquifer can be simulated for steady-state conditions using MODFLOW. The initial model setup was greatly simplified from known field conditions. For modeling steady-state conditions, the pseudokarst characteristics of mine spoil must be subordinate to the porous media characteristics. This is supported by aquifer testing and water table monitoring data. For calibration of the model, the spoil was divided into zones of equal hydraulic conductivity based on the geometric average of the wells within that portion of the site. To obtain a sufficient head and outflow match, the hydraulic conductivity determined from aquifer tests had to be increased by one to two orders of magnitude for spoil areas, a majority of the recharge was modeled flowing laterally from adjacent areas, and the recharge from precipitation was established at a rate well below conditions for unmined areas (10% of the annual precipitation rate). The K of the outslope area cells, although unknown, was set at a rate higher than that of the interior spoil cells. This increase in K was based on field observations of a network of interconnected voids and conduits in the outslope.

The steady-state model did not adequately simulate transient conditions of a constant-discharge test. Under conditions of stress, pseudokarst characteristics become more prominent and spoil heterogeneities are accentuated. The simulation, which was calibrated for steady-state conditions, did not simulate the anisotropic and nondarcian ground water flow through the spoil. MODFLOW can model anisotropic conditions. However, the magnitude and orientation of the anisotropies must be accurately known, which was not the case for this site. Because of difficulties in quantifying void hydraulic characteristics, it may not be possible to simulate a mine spoil aquifer under transient conditions using a steady-state model.

The results of the modeling effort indicate that many of the characteristics observed during field testing may not accurately represent the site. The modeling exercise also caused some rethinking and refinement of the original conceptual site characterization in terms of ground water flow and storage. To determine the widespread applicability of computer simulation of surface mine spoil aquifers, additional modeling and conceptual characterization are required. With improvements in spoil modeling, prediction of the postmining water table, ground water flow paths, and other hydrologic parameters prior to mining can be used to improve special handling of alkaline or acidic spoil and hydrologic engineering techniques, which may diminish or halt the production of AMD.

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