APPLICATION OF AN ANALYTICAL GROUND WATER FLOW MODEL TO A PSEUDOKARST SETTING IN A SURFACE COAL MINE SPOIL[1]

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Abstract: Attempts were made to apply an analytical groundwater flow model (MINEFLO) to a reclaimed surface coal mine spoil in West Virginia, U.S.A., that exhibited characteristics of both a conventional porous medium and pseudokarst flow. The model utilizes the method of analytic elements to derive a steady-state solution to the ground water flow equation for a single aquifer. Two simulations were performed, using hydrologic features and parameter values determined from field observations, slug withdrawal tests (1989) and slug injection tests (1990). Simulated heads at base-flow conditions for 1989 were about 12% different than measured values, with a root-mean-square (RMS) error of 0.82 m. A similar simulation for 1990 produced a somewhat better match, with an average head difference of less than 10% (RMS error of 0.66 m). However, in both cases, the simulated flow rate at the toe-of-spoil seep was over 75% less than the measured rate. This suggested that the hydraulic conductivity values obtained from the slug tests may have underestimated the overall hydraulic conductivity of the aquifer materials, perhaps because of the influence of pseudokarst and/or fracture flow mechanisms. It was concluded that the model could predict (within 10%) the base-flow water levels at a spoil site where recharge is known to occur primarily from adjacent unmined strata. The use of the model's only transient feature (pumping well) at the study site is doubtful due to the large RMS error in the steady-state simulation.

Additional Key Words: Acid mine drainage, aquifer testing.

Introduction

Previous studies (Hawkins and Aljoe, 1990; 1992) showed that the ground water flow system within a surface coal-mine spoil in central West Virginia, U.S.A., exhibits characteristics of both conventional porous-media flow and pseudokarst flow. Pseudokarst flow involves ground water storage and rapid movement through relatively large, open conduits; porous-media flow is characterized by slower water movement around the solid particles and through minute fractures in the medium. In mine spoil, conduit formation is facilitated by differences in spoil particle size and is caused by piping of the finer spoil material or differential settling (Groenewold and Bailey, 1979). Water levels in spoil monitoring wells suggest that porous-media flow is dominant under steady-state (low-flow) conditions, when the spoil appears to possess a single water table with gradual hydraulic gradients. Irregularities in the water table appear to be caused by permeability contrasts within the spoil and the existence of a discrete, preferred recharge area where the spoil intercepts a large natural fracture. However, indicators of pseudokarst flow are observed under transient conditions, such as during aquifer testing and single-event, high-recharge periods lasting only several days. These indicators include: (1) erratic response of observation wells to slug and pumping tests; (2) temporary changes in local ground water flow direction; (3) steepening of water table gradients; (4) artesian flow from a spoil monitoring well; and (5) rapid disappearance of channeled surface runoff into a swallet in the outslope area of the spoil and re-emergence near the toe-of-spoil seep.

The U.S. Bureau of Mines is currently conducting research to determine whether hydrologically complex spoils can be adequately characterized on a local scale by a ground water computer model. However, the most commonly-used and well-documented models, whether analytical or numerical, have been derived from porous-media flow principles. The applicability of such models to spoils with some pseudokarst characteristics is therefore uncertain. To determine the applicability of a model, it is first necessary to calibrate the model at steady-state conditions at a site where ample field data are available, use it to predict the effects of transient events or different steady-state conditions at that site, then check the predictions with field data. The study described in this paper was directed toward the first part of this procedure, i.e., steady-state calibration at a mine spoil site that is as closely monitored as could be expected in practice. The site also receives most of its recharge from the surrounding undisturbed material rather than from direct infiltration through the spoil, a characteristic that is common to many spoil aquifers. The ability of a model to accurately simulate the important aspects of the flow system at this site will help determine the general applicability of porous-media flow models in the analysis of other surface mine spoils with similar flow systems but less field data.

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Previous Modeling Efforts

Modeling of ground water flow through and around surface mine spoils has been attempted in the past; however, none of the previous efforts have focused on lateral head variations within a single mine spoil, as the current study has attempted to do. Studies by Wilson and Hamilton (1978) and Schwartz and Crowe (1985) simulated the effects of surface mining on ground water levels in the undisturbed material surrounding a spoil in the Northern Great Plains region of North America during and after a hypothetical mining event. A later study by Schwartz and Crowe (1987) looked at the spoil on a smaller scale to examine the rates at which the spoil would resaturate following cessation of mining. In these studies, the spoil was considered to be a homogeneous mass within a large regional aquifer, and two-dimensional, finite-element numerical models were applied to vertical cross-sections through the mined area. Rogowski and Weinrich (1977) also examined spoil resaturation, using both a numerical solution of a one-dimensional moisture flow equation and a layered water-budget technique to model vertical percolation through topsoiled and non-topsoiled spoil material. The models were calibrated using data from 3-m-deep spoil profiles that had been reconstructed in the laboratory. Neither the cross-sectional modeling efforts nor the vertical infiltration studies considered lateral head variations or permeability contrasts within the spoil.

Bair and Parizek (1981) modeled the hydrologic effects of a proposed open pit mine in the anthracite coal district of eastern Pennsylvania (USA). The emphasis in this study was placed on the flow system in the undisturbed material around the mine rather than within the mine spoil. The hydrostratigraphic unit around the proposed mine was modeled as a single, unconfined, anisotropic aquifer. The pre-mining potentiometric surface in this aquifer was simulated with a finite-difference numerical model, and existing head data were used to calibrate the model. The hydrologic effects of various stages of mining were then simulated by placing constant-head nodes at the mine floor level. The potentiometric surfaces, mine inflow rates, and other simulation results could not be verified because the mine had not yet been developed.

Phelps (1984) performed a finite-element modeling study in which lateral flow through a heterogeneous spoil cross section was considered. The intent of this investigation was to analyze the flow patterns through and around a low-permeability "toxic package" placed within the saturated zone of the spoil, with a view toward minimizing the percentage of flow moving through the package. Although the water table configurations and vertical head distributions resulting from these simulations appeared to be reasonable, no attempt was made to compute areal head distributions or to relate the model to a field situation.

Description of Computer Model (MINEFLO)

The MINEFLO computer model used in the current study was developed by R. D. Schmidt of the U. S. Bureau of Mines' Twin Cities Research Center in Minnesota[3]. MINEFLO is a two-dimensional aquifer model that formulates steady-state analytical solutions to basic ground water flow equations. The starting point of a MINEFLO simulation is a single, confined aquifer of infinite lateral extent and user-defined thickness, porosity, and permeability. The user identifies all hydrologic features impacting this idealized system, inserting them into the simulation on the basis of their spatial coordinates. These features include: (1) vertical planes of constant head, discharge, or recharge within the aquifer (termed "line sources" in the model); (2) areal zones or vertical cracks within the aquifer whose permeabilities differ from that of the base aquifer; (3) wells that can add or withdraw water from the aquifer at any point; (3) zones of continuous recharge (infiltration) or discharge (leakage) above or below the aquifer; and (4) vertical (planar) hydrologic barriers that occupy the entire aquifer thickness. A "reference point" that is beyond the area of influence of the hydrologic features must also be specified. The model can be used to simulate a wide variety of hydrologic conditions (Schmidt, 1985; 1989), but this is the first known application of the model to a surface mine spoil and its surroundings.

MINEFLO uses the method of analytic elements (Strack, 1987) to create mathematical expressions for representing each of the hydrologic features. These expressions are combined to form a large matrix that is solved by the model to yield equations for the discharge potential (head) and its complex conjugate, the stream function, at any point (x,y) in the aquifer. The Dupuit-Forchheimer assumptions are used to simulate unconfined flow near a seepage face. Flow-related characteristics of hydrologic features in the aquifer, such as heads in wells and flow rates through constant-head planes, are also computed as part of the matrix solution. The computed values can then be compared to measured field data at key points in the flow system (e.g., heads in wells, discharge from springs) to check the accuracy of the simulation. Subroutines for gridding and contouring the values of the head and stream function and for tracing streamlines are included in the MINEFLO package.

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[3]A manual describing MINEFLO is currently being prepared. For information contact R. D. Schmidt, U. S. Bureau of Mines, 5629 Minnehaha Ave. South, Minneapolis, MN 55417.

Two advantages of MINEFLO over other hydrologic models are its speed and ease of use. Since the solution technique is entirely analytical, it does not employ the discretization and iteration procedures inherent in numerical models. Solutions can thus be obtained quickly on a microcomputer. MINEFLO is menu driven, from data entry through contouring of results, thereby eliminating the need for external software; however, MINEFLO data files can be created, read, and modified via most common word processing packages. Changes in the flow simulation can be made easily, and the effects of these changes can be assessed almost immediately. In this study, a version of MINEFLO for the Macintosh[4] was used, which allowed model outputs to be exported immediately to other Macintosh applications.

The primary disadvantage of MINEFLO is its limited capability for performing transient simulations. The only transient process supported by the model is that of a pumping or injection well, in which the Theis (1935) equation for drawdown due to pumping is superimposed on a previous steady-state solution. The effects of such transient wells can be examined at specified time periods, provided that the pumping does not change the head and flow conditions of the previously-specified steady-state features. Separate simulations, involving complete analytical solutions for the entire flow system, must be run for each time period being considered. Transient recharge events cannot be simulated. Therefore, emphasis in this paper is placed on model calibration in the steady-state case.

Description of Study Site

The study site is a 3.24 ha parcel of a 33 ha reclaimed surface mine that removed a sinuous strip of the lower and middle Kittanning coal seams along a hillside coal outcrop in Upshur County, WV (figures 1 and 2). Hawkins and Aljoe (1992) provide a description of the site geology, lithology, and mining history. The spoil was terrace backfilled and not returned to the contour of the original hillslope. As a result, most of the spoil surface slopes gently northwestward toward the buried highwall. Despite the presence of a surface drainage ditch, surface runoff becomes impounded on the spoil during and after precipitation events; however, heads in monitoring wells completed in the spoil beneath the impounded water indicated that vertical infiltration in this area was not a primary source of recharge to the spoil aquifer. Ground water inflow through fractures in the buried highwall appears to be the primary spoil recharge source (Hawkins and Aljoe, 1990). The slope of the water table appears to be controlled primarily by the slope of the original bedrock and/or land surface, which forms a low-permeability layer beneath the spoil (figure 2). The spoil outslope is steep and continues down to the interface with undisturbed ground, where a closely-spaced line of seeps is present. Flow from the seep line is channeled to a common collection point for gaging and sampling.

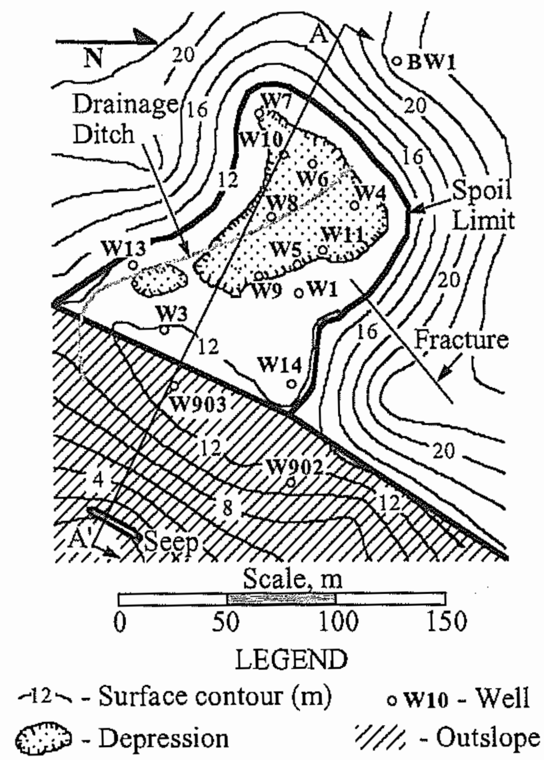

Figure 1. Surface features of mine spoil study site.

Wells 1 through 14 (figure 1) were drilled to the pit floor in the main spoil, while BW1 was drilled to a depth of about 20 m in undisturbed strata behind the final highwall. These wells were installed in the early 1980's and were used to calibrate the model. Wells 902 and 903 were drilled to the pit floor in the outslope during February 1990; these proved to be unsuitable for use in model calibration because their water elevations suggested that they penetrated localized pockets of water in the outslope rather than the continuous aquifer that comprised the main spoil wells. All wells were 5.1 cm in diameter and were finished with 3-m long slotted well screens. The study focused on the years 1989 and 1990, when monthly measurements of well water levels and discharge

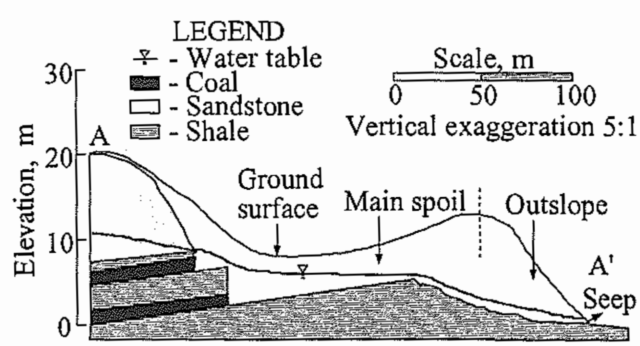

Figure 2. Cross-section of mine spoil study site.

[4]Reference to specific products does not imply endorsement by the Bureau of Mines

rates were obtained. During this period, the flow from the seep line ranged from 61 to 375 L/min with a median of 83 L/min.

Model Calibration

In order to clarify the discussion of model calibration, it is important to define the terms hydrologic features and model parameters as employed by the MINEFLO model. As stated earlier, a MINEFLO simulation starts with a base aquifer of infinite areal extent and constant thickness, porosity, and hydraulic conductivity. A hydrologic feature is defined as a deviation from the specified base aquifer, and is characterized by the type of feature (e.g., line source, permeability zone, well, crack, barrier) and its location (x,y) within the plane of the base aquifer. Model parameters are the numerical values of head, hydraulic conductivity, recharge, or discharge assigned to the base aquifer and each hydrologic feature, depending on the type of feature and its expected role in the field setting. The goal of model calibration is to configure the base aquifer and hydrologic features and adjust the model parameters, in a manner consistent with field observations, such that the simulated heads in monitoring wells and flow rates at discharge points match the field-measured values as closely as possible.

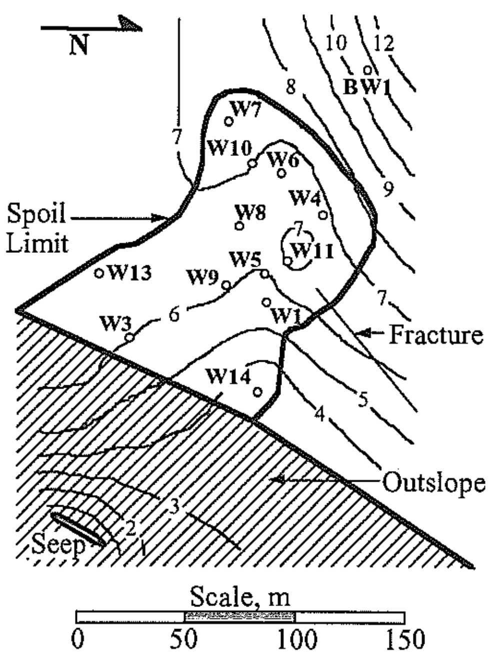

Figure 3. Water table contours (m) at steady-state (low-flow) conditions, August 29, 1990.

Calibration of a steady-state model is often performed by matching it to a low-flow period, when steady-state conditions usually prevail in the field. Figure 3 shows the water table contours for the low-flow period of 1990 (August 29); the water table map for the low-flow period of 1989 (July 26) was very similar. Flow originates mainly from the buried highwall and moves toward the seep. Irregularities in the contours in the main spoil (note the 7 m contours in figure 3) appear to be related to permeability contrasts within the spoil and/or the influence of a large natural fracture that intersects the spoil near well 11 (Hawkins and Aljoe, 1990). MINEFLO is capable of simulating these features (using line sources, permeability zones and cracks), so calibration to low-flow conditions appeared to be feasible. Although the calibration process described below would suggest that the base aquifer and hydrologic features were rigidly defined, and only the parameters were adjusted to achieve the desired match, this was far from the case. Many other sets of base aquifer conditions and hydrologic feature boundaries were examined, but only the final, "best match" configurations and parameter values are presented here. For this study, the "best match" was defined as the scenario that produced the minimum RMS (root-mean-square) error between the measured and simulated heads in monitoring wells, defined as:

$$\text{RMS error} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (h_{si} - h_{mi})^2} \qquad (1)$$

where n is the number of wells, and h_{si} and h_{mi} are the simulated and measured heads, respectively, in the ith well.

Configuration of Base Aquifer and Hydrologic Features

The base aquifer defined for this study had a thickness of 12.5 m, which was slightly greater than the maximum saturated thickness of the conceptual aquifer (maximum measured head in the monitoring wells). Since the base aquifer is horizontal, it comprises both the spoil material and the undisturbed strata beneath and around the spoil. This obvious simplification in the definition of the aquifer was acceptable for the purpose of comparing steady-state heads in wells and total seep discharge, because these parameters are independent of the flow distribution within any vertical cross-section of the aquifer. Steady-state heads and flows are also independent of the aquifer porosity; therefore, although MINEFLO requires that a porosity be specified, the porosity value had no effect on the desired results. However, ground water velocities computed by the model would definitely be erroneous, since the calculations would assume uniform flow through a homogeneous vertical cross-section of the aquifer at its stated porosity. In reality, the strata beneath the spoil are probably much less permeable than the spoil (note the location of the seep in figure 2), so most of the flow through spoil-covered cross-sections would occur through the spoil. This study therefore made no attempt to use the stream function generated by the model to analyze ground water velocities or to track water particle movement.

In order to simulate lateral (as opposed to vertical) permeability contrasts between the undisturbed material, mine spoil, and subregions within the spoil, "permeability zones" were constructed within the base aquifer. The boundaries of the permeability zones were estimated from: (1) field observations of the spoil limits; and (2) hydraulic conductivity contour maps generated from the results of two sets of slug tests conducted in the monitoring wells. Slug withdrawal tests were performed in November 1989, and slug injection tests were performed in June 1990, after a subsurface grouting project was conducted at the site. Table 1 compares the hydraulic conductivity values obtained from these tests. The differences between the hydraulic conductivity values in table 1 were determined by Hawkins, et al. (1991) to be related more closely to the test method and instrumentation used than to the effects of grouting, with the 1990 values being somewhat more accurate. However, in order to assess the sensitivity of the model to the results of the field data collection efforts, calibrations were performed for both the 1989 (slug withdrawal) and 1990 (slug injection) periods, using the low-flow heads and discharge values for the two years as calibration goals.

Table 1. Hydraulic conductivity values (m/sec) measured in slug tests.

Well #	Well Location	Slug Withdrawal 1989 (m/sec)	Slug Injection 1990 (m/sec)
1	Outer spoil	2.07E-07	9.37E-07
3	Inner spoil	8.94E-06	1.34E-04
4	Outer spoil	6.90E-06	6.76E-06
5	Inner spoil	1.93E-05	1.24E-05
6	Inner spoil	1.30E-05	3.14E-05
7	Inner spoil	5.10E-06	5.34E-05
8	Inner spoil	4.66E-06	8.23E-05
9	Inner spoil	5.69E-05	2.32E-05
10	Inner spoil	1.26E-06	1.01E-06
11	Outer spoil	9.14E-07	3.89E-06
13	Outer spoil	9.61E-07	8.56E-07
14	Outer spoil	4.93E-06	3.34E-07
BW1	Unmined area	4.12E-07	ND
902	Outslope	ND	2.85E-08
903	Outslope	ND	1.73E-08

ND = Not Determined

In both cases, the portion of the spoil closest to the highwall (outer spoil) constituted one permeability zone, whose hydraulic conductivity was greater than that of the base aquifer (undisturbed material) but less than that of the interior spoil, which constituted a second permeability zone. The primary difference between the two aquifer configurations was the relative size of the two spoil zones, as shown in figures 4a (1989 simulation) and 4b (1990 simulation).

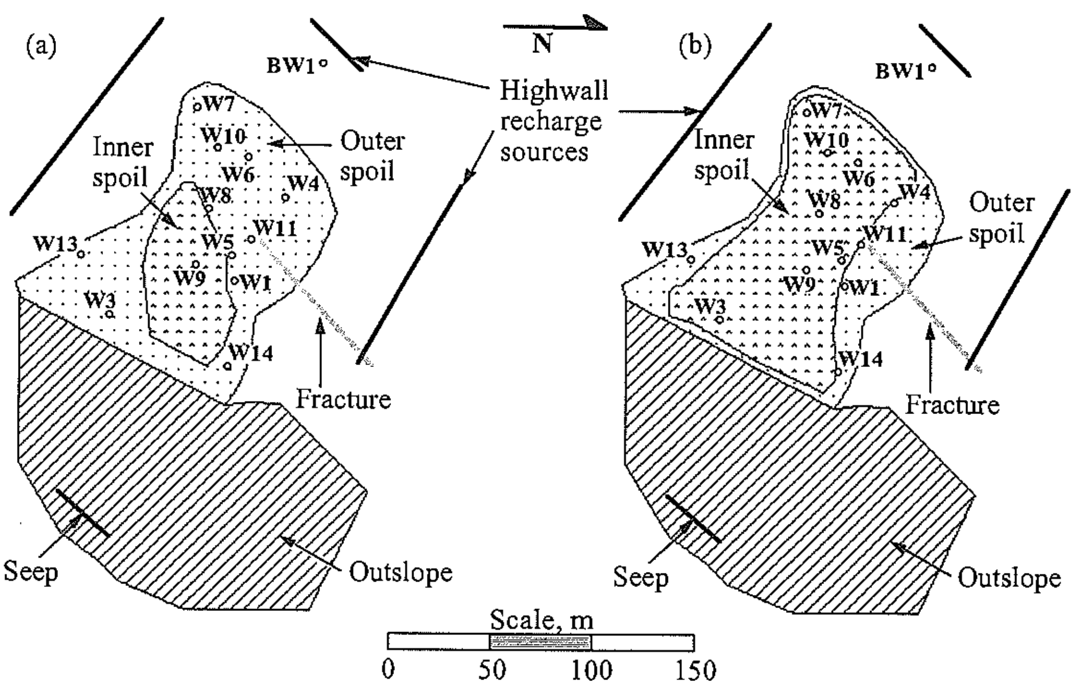

Figure 4. Hydrologic features of MINEFLO model: (a) 1989 simulation; (b) 1990 simulation.

A third important permeability zone is the outslope, which comprises the area between the spoil wells and the seep area, including the seep. The outslope was created by casting overburden material over the natural terrain downslope from the mined area . The blocky, heterogeneous nature of the outslope material lends itself easily to the development of conduits and localized, discrete, high-permeability channels; evidence of this was found during field investigations (Hawkins and Aljoe, 1990). The lateral (north-south) extent of the outslope area was not readily discernible in the field, so these boundaries were not as easily defined as those of the spoil-highwall and spoil-outslope interfaces. For consistency, the outslope boundaries were kept the same in both the 1989 and 1990 simulations (figures 4 and 5). The hydraulic conductivities measured in the two outslope wells (902 and 903 in table 1) were not used to help define the outslope boundaries because their extremely low values suggested that they were screened in relatively impermeable zones between conduits, and thus did not represent the bulk hydraulic conductivity of the outslope material. Static water levels in the two outslope wells were also inconsistent with those of the rest of the spoil, again suggesting that the spoil wells and outslope wells were not screened in the same aquifer.

A "crack" was used in both simulations to represent the effect of the large natural fracture that intersects the spoil near well 11. In MINEFLO, a crack is equivalent to a very narrow permeability zone; its location in the aquifer is defined by specifying its endpoints and its width rather than a closed areal boundary. The location of the crack in figures 4 and 5 and its width (5.0 cm) were specified on the basis of field observations.

In both simulations, three line sources of constant head were used to represent steady-state recharge to the spoil from the unmined material on the north, west, and south. The positions of these line sources corresponded to topographic highs in the undisturbed material. Since surface topography would be expected to determine ground water flow direction in the undisturbed material (unlike the bedrock-controlled flow direction in the spoil), topographic highs would generally correspond to ground water divides in the undisturbed material. A fourth line source in the outslope area was used to represent the seep; it served as the only means of removing water from the aquifer system.

Adjustment of Model Parameters

Table 2 summarizes the hydraulic conductivity values that resulted in the "best match" between the simulated and measured heads in monitoring wells, along with the rationale used to justify the parameter values. In the 1989 simulation, the hydraulic conductivity of the base aquifer was specified at 4.12 x 10^{-7} m/sec on the basis of the results of the slug withdrawal test in well BW1, the only well in undisturbed material. The boundary of the inner, high-conductivity spoil zone in the 1989 simulation and its associated hydraulic conductivity were obtained directly from a contour map of spoil hydraulic conductivity (i.e., the 2.50 x 10^{-5} m/sec contour). The hydraulic conductivity of the outer spoil zone (between the inner zone and the highwall) was specified at 3.24 x 10^{-6} m/sec, the geometric average of all spoil wells except well 9 (i.e., well 9 was contained within the inner zone). The outslope hydraulic conductivity in the 1989 simulation was adjusted until the best match was achieved (at 3.00 x 10^{-5} m/sec), and thus is designated as a "calibration parameter" in table 2. In the 1990 simulation, the inner spoil zone was much larger and the outer zone much smaller than in the 1989 simulation, and the hydraulic conductivities in table 2 were specified as the geometric averages of the wells contained in each zone. With this specification, the hydraulic conductivities of the base aquifer and outslope zone had to be adjusted to approximately twice their 1989 values to maintain an acceptable head match. However, these adjustments are not considered to be radical in view of the measured differences in hydraulic conductivities (table 1). The hydraulic conductivity of the crack was set at 3.00 x 10^{-3} m/sec in both simulations; however, it was found that as long as the hydraulic conductivity of the crack was at least one order of magnitude greater than that of the outer spoil, further increases in crack permeability had very little effect on the simulated results.

Table 2. Hydraulic conductivity values in "best match" simulations, MINEFLO model.

	1989 Simulation - Slug withdrawal		1990 Simulation - Slug injection	
Hydrologic feature	Hydraulic conductivity (m/sec)	Rationale	Hydraulic conductivity (m/sec)	Rationale
Base aquifer	4.12E-07	Measured Value in BW1	7.62E-07	Calibration Parameter
Inner spoil	2.50E-05	Hydraulic conductivity map; zone around well #9	2.45E-05	Geometric mean, wells #3, 5, 6, 7, 8, 9, 10
Outer spoil	3.24E-06	Geometric average of all spoil wells except #9	1.48E-06	Geometric mean, wells #1, 4, 11, 13, 14
Outslope	3.00E-05	Calibration Parameter	5.50E-05	Calibration Parameter
Fracture	1.00E-03	Calibration Parameter	1.00E-03	Calibration Parameter

Table 3 summarizes the "best match" values of reference head for the line sources shown in figure 4. Except for the seep, whose head was set at zero by definition, all the reference heads were considered to be calibration parameters. The minor differences in reference heads between the 1989 and 1990 simulations resulted from the fact that in most of the wells, the calibration goals (measured heads) were slightly lower in 1990 than in 1989. The relative strengths of the three highwall sources were the same (south >west >north) in both simulations.

Table 3. Reference heads of line sources in "best match" simulations, MINEFLO model.

Hydrologic feature	1989 Simulation - Slug withdrawal		1990 Simulation - Slug injection	
	Reference head (m)	Rationale	Reference head (m)	Rationale
Seep	0	Seep location defined at base of aquifer	0	Seep location defined at base of aquifer
West highwall	12.25	Calibration Parameter	11.75	Calibration Parameter
South highwall	12.50	Calibration Parameter	12.00	Calibration Parameter
North highwall	11.00	Calibration Parameter	10.75	Calibration Parameter

Discussion of Model Results

Table 4 compares the "best match" simulations to the measured values for both the 1989 and 1990 modeling exercises. Simulated heads at base-flow conditions for 1989 were about 12% different than measured values (RMS error 0.82 m); the 1990 simulation was somewhat better, with an average head difference of less than 10% (RMS error 0.66 m). This may reflect the previously-stated conclusion of Hawkins, et al. (1991) that the slug injection tests yielded somewhat more accurate values of hydraulic conductivity. In both simulations, some of the largest errors occurred in the two wells closest to the outslope (wells 3 and 14) and in well 11, which was close to the point where the spoil intercepted the large fracture. Field observations suggested that these areas would be more prone to non-Darcian flow conditions than other areas, and this may partially explain the large errors associated with these wells. Note in table 4 that the errors are approximately halved when wells 3, 11, and 14 are not included in the analysis; however, the average error without these wells was still about 5% (RMS errors 0.36 to 0.5 m).

Table 4. Comparison between measured and simulated data, MINEFLO model.

Well #	1989 Simulation - Slug Withdrawal				1990 Simulation - Slug Injection			
	Measured head (m)	MINEFLO heads (m)	Error (m)	% Error	Measured head (m)	MINEFLO heads (m)	Error (m)	% Error
1	5.35	5.84	0.49	9.2%	5.43	6.01	0.58	10.7%
3	6.10	4.63	-1.47	-24.0%	6.01	5.25	-0.76	-12.7%
4	7.46	7.25	-0.21	-2.8%	6.78	6.83	0.05	0.8%
5	5.80	5.99	0.19	3.2%	5.74	6.22	0.48	8.3%
6	6.59	7.38	0.79	12.0%	6.48	6.85	0.37	5.8%
7	8.21	8.12	-0.09	-1.0%	7.39	7.08	-0.31	-4.1%
8	6.37	6.20	-0.17	-2.7%	6.49	6.47	-0.02	-0.3%
9	6.13	5.75	-0.38	-6.2%	6.27	5.96	-0.31	-5.0%
10	6.96	7.42	0.46	6.6%	7.21	6.87	-0.34	-4.7%
11	7.44	6.58	-0.86	-11.6%	7.43	6.47	-0.96	-12.9%
13	6.41	5.42	-0.99	-15.5%	6.45	5.94	-0.51	-7.9%
14	3.01	4.86	1.85	61.7%	3.26	4.96	1.70	52.4%
BW1	11.34	11.15	-0.19	-1.7%	10.61	10.62	0.01	0.1%
Head error analysis	Mean error (absolute):	All wells -	0.63	12.2%	Mean error (absolute):	All wells -	0.49	9.7%
		w/o 3,14,11 -	0.40	6.1%		w/o 3,14,11 -	0.30	4.8%
	RMS error:	All wells -	0.82		RMS error:	All wells -	0.66	
		w/o 3,14,11 -	0.49			w/o 3,14,11 -	0.36	
Seep discharge	Measured flow (L/min)	MINEFLO flow (L/min)	Error (L/min)	% Error	Measured flow (L/min)	MINEFLO flow (L/min)	Error (L/min)	% Error
	61.80	11.652	-50.15	-81%	83.40	20.82	-62.58	-75%

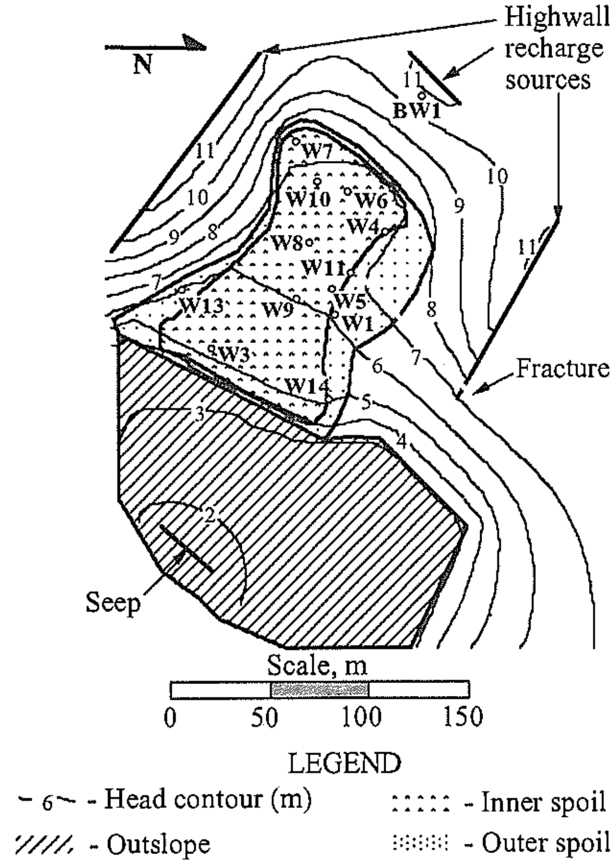

Figure 5. Head contours generated from MINEFLO model, 1990 simulation.

Figure 5 shows the water table contours generated by the model for the 1990 simulation; the map for the 1989 simulation was very similar in appearance, suggesting that the differences in the permeability zones did not have a dramatic effect on the simulation results. Note that the irregularities in the actual 7m water table contour (figure 3) did not appear in the simulated results (figure 5). Thus, field inferences and slug test results alone did not provide the information necessary to simulate the actual irregularities.

The most important problem with both simulations was that simulated seep discharge rates were 75% to 80% less than measured values (table 4). In order to make the simulated discharge rates match the measured values, while keeping the simulated heads in table 4 the same, the hydraulic conductivities of the base aquifer and all hydrologic features would have to be increased uniformly by a factor of 4 to 5. If the configurations of the base aquifer and hydrologic features are reasonably accurate, it can be inferred that the hydraulic conductivities measured in the slug tests are 4 to 5 times less than the effective hydraulic conductivity of the actual materials. This inference was supported by the fact that the recovery patterns of some of the wells during slug tests suggested the presence of discrete, highly permeable zones within the spoil (Hawkins and Aljoe, 1992). It is also possible that the fractures and bedding plane separations intercepted by well BW1 were relatively small in magnitude and extent compared to the actual fractures and bedding plane separations providing recharge to the spoil through the highwall. These conditions would cause slug test results to underestimate the overall hydraulic conductivities in both types of material.

The magnitude of the RMS errors shown in table 4, even without considering wells 3, 11, and 14, effectively precludes the practical application of the only transient capability of the MINEFLO model, that of a pumping or recharging well. Such a well can be superimposed on a steady-state solution in MINEFLO only if its inclusion does not significantly impact the previously-defined steady-state features -- in this case, the flow rates at the four constant-head line sources. This effectively places an upper bound on the stress (pumping rate and duration) that can be simulated. Furthermore, the drawdown achieved in a simulated pumping test will have practical validity only if it exceeds the RMS error between simulated and measured heads. This places a lower bound on the simulated stress. The practical difficulty in achieving these conditions can be illustrated by considering pumping simulations involving the most closely-spaced well pair (wells 6 and 10, separation 15 m) that would result in a drawdown exceeding the lowest RMS error in table 4 (0.36 m). The Theis (1935) equation that is employed by MINEFLO for transient pumping analysis can be used independently of the model; for calculation purposes, the average hydraulic conductivity of the inner spoil in the 1990 simulation (table 2) can be multiplied by the average aquifer thickness at wells 6 and 10 (6.86 m) to yield a transmissivity value of 1.68×10^{-4} m^2/sec. Since the aquifer is unconfined, aquifer porosity can be used to estimate its storativity; the porosity of the spoil aquifer at this site was estimated to be 20% (Hawkins, 1993), thus storativity was estimated at 0.2. Using these parameters, pumping in well 6 or 10 at a constant rate of 4 L/min (20 % of the 1990 simulated steady-state flow rate at the seep) would have to continue for more than 100 years before the simulated drawdown exceeded 0.36 m in the other well. Conversely, a more reasonable pumping duration, 3 days, would require a pumping rate of about 28 L/min -- greater than the 1990 simulated seep flow rate -- for the drawdown to exceed 0.36 m. Clearly, a pumping test that could be simulated with validity by the model would be nearly impossible to perform.

Conclusions

The MINEFLO model was used to predict, within 10%, the base-flow water levels in wells at a spoil sites where recharge is known to occur primarily from adjacent unmined strata. If premining ground water data on the adjacent unmined strata are available, it may be usable for the same purpose on other sites with similar recharge patterns. Field inferences and slug test results alone are not likely to provide the information necessary to simulate water table irregularities within the spoil. If slug tests are used to derive hydraulic conductivities for use in the model, the test values may underestimate the overall hydraulic conductivity of the aquifer materials if pseudokarst and/or fracture flow mechanisms are evident. This may cause the simulated flow rates at the spoil discharge to underestimate the measured flows by as much as 80%. The practical use of the model's only transient feature (pumping well) at the study site is doubtful due to the large RMS error in the steady-state simulation. The primary advantage of MINEFLO is that simulations are quick and easy to set up, perform, and evaluate. Numerical models which are capable of modeling hydrologic features within the spoil and are less restrictive in terms of modeling transient phenomena should be investigated to determine their advantages and disadvantages compared to MINEFLO.

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