

ASSESSMENT OF ACID MINE DRAINAGE REMEDIATION SCHEMES ON GROUND WATER FLOW REGIMES AT A RECLAIMED MINE SITE¹

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Abstract: Ground water modeling and a field monitoring program were conducted for a 35-acre (150,000 m²) reclaimed surface mine site that continues to produce acid drainage (AMD). The modeling effort was focused on predicting the effectiveness of various remedial measures implemented at the site for the abatement of AMD production. The field work included surface surveys and monitoring of ground water levels with time, seepage areas, and sedimentation ponds located on the site. The surveys provided the physical and topographic characteristics of the site. Pump tests conducted at the site provided general hydraulic conductivities (k) for two major areas of the site; undisturbed area ($k \approx 2.9 \times 10^{-5}$ ft/s or 8.7×10^{-6} m/s) and disturbed area ($k \approx 3.3 \times 10^{-4}$ ft/s (1×10^{-4} m/s) to 2.0×10^{-3} ft/s (6.2×10^{-4} m/s)). The monitored ground water data indicated rapid change in ground water levels during recharge events. Such behavior is indicative of flow regime that is dominated by fracture flow. Modeling of an approximately 700 ft by 1500 ft (213 m x 457 m) area of the site was achieved using the US Geological Survey code MODFLOW, and ground water field measurements were used to calibrate the model. A hydraulic conductivity of approximately 1.15×10^{-3} ft/s (3.5×10^{-4} m/s) was estimated for the undisturbed area and 1.15×10^{-2} ft/s (3.5×10^{-3} m/s) was estimated for the reclaimed area. Remedial measures for diverting the ground water away from the areas of spoil included the use of a subsurface seepage cutoff wall and discrete sealing techniques. Modeling results indicated that the most effective remedial technique for this site is the use of a subsurface seepage cutoff wall installed at the interface (highwall) between the disturbed and undisturbed zones. Using this scheme caused a dewatering effect in the reclaimed area and therefore reduction in the volume of the AMD generated at the site.

Additional Key Words: acid mine drainage, coal refuse, ground water, grouting

Introduction

AMD poses a serious environmental problem in the United States. Kleinmann (1989) estimated that abandoned coal and metal mines and the mine waste that accompanies them adversely affect water quality in 12,000 miles of streams and rivers and 180,000 acres of lakes and reservoirs. AMD forms due to the oxidation of sulfide minerals and subsequent hydrolysis during and after the mining process. Chemical reactions associated with the production of AMD were presented by Stumm and Morgan (1970). The presence of pyrite material (FeS_2), water, and air is required for generation of AMD. The AMD pollution leads to low pH values, increased turbidity, and increased concentration of metals such as iron, and manganese and elements such as sulfates. The advent of clean water standards mandated by Federal laws such as the National Pollutant Discharge Elimination System (NPDES) and Wetlands Mitigation necessitates the development of cost effective and innovative remedial measures for regulatory compliance.

One of the emerging remedial techniques for abatement of AMD is the use of subsurface grouts to encapsulate and divert ground water from areas containing the pyrite material. Harshberger (1991), Almes (1991), and Baker (1993) investigated the development of grout mixtures for formation of subsurface low permeability hydraulic

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barriers. In general, the function of these barriers is twofold; (1) control of AMD migration to stream reaches and rivers and (2) encapsulation of the spoil material to minimize exposure to water and air and therefore to minimize AMD production. As part of the ongoing research program for development of low permeability subsurface barriers, a 35 acres test site near Waynesburg, PA, was selected for field demonstration. Application of subsurface grout mixes to this test site was performed by US Bureau of Mine, Pittsburgh Research Cneter, in cooperation with the authors.

The research presented in this paper includes the modeling of the ground water flow regime before and after subsurface grouting. The simulation model is developed using the computer code MODFLOW by the US Geological Survey (USGS). Monitored ground water wells installed at the site were used to calibrate the computer model. Various modeling scenarios for simulating the placement of low-permeability grouts were conducted. Recommendations regarding the various grouting schemes and the most effective one for abatement of AMD are presented.

Research Site

The study site is located in Greene County, PA. The site encompasses 35 acres of reclaimed surface mine that currently produces approximately 20 gal/min of AMD under steady-state conditions. Figure 1 shows an overview of site area.

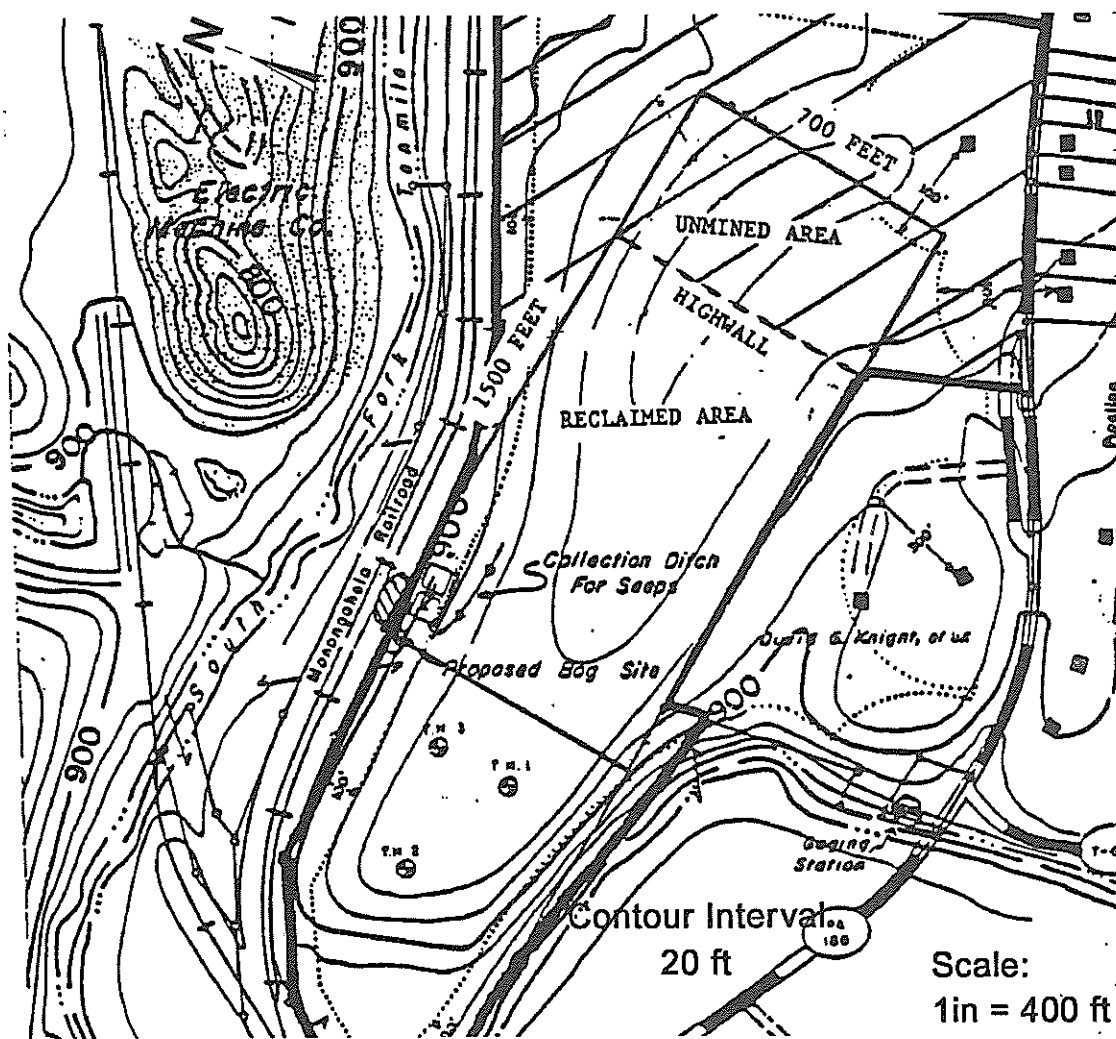


Figure 1. General overview and surface elevations of the study site

The AMD discharge exits the site in the form of seeps at several locations. These seeps are routed to aeration and sedimentation ponds and then pumped to a central location for lime treatment. The main coal seam on the site is the Waynesburg Coal. The coal seam is overlain by the Cassville Shale and approximately 30 to 60 ft of Waynesburg Sandstone.

Fourteen monitoring wells were installed in the disturbed and undisturbed areas at the site. The general hydraulic conductivities (k) of the site were established using slug tests that were conducted by researchers at the U.S. Bureau of Mines. The results of the slug tests indicated that k values are approximately 2.85×10^{-5} ft/s for the undisturbed area and range from 3.3×10^{-4} to 2.0×10^{-3} ft/s for the disturbed area. These values are localized in nature, and variability in the hydraulic conductivities for both the disturbed and undisturbed areas should be expected. As discussed by Hawkins and Aljoe (1991) the hydraulic conductivity for disturbed areas can vary several orders of magnitude throughout the mine site.

As described by Harshberger (1991), magnetometry and conductivity surveys were performed at the site. Based on the results of these surveys, four separate areas were delineated as having material with high potential for producing AMD. However, subsurface exploration conducted during the installation of the monitoring wells indicated that the spoil material is randomly located over the whole site.

Monitored ground water levels indicated that the average ground water head difference between the undisturbed and reclaimed areas is approximately 8 ft with the higher heads within the undisturbed area. This head difference induces flow gradient across the site and results in recharge across the highwall from the undisturbed area to the reclaimed area. A second source of recharge to the reclaimed area is leakage from three AMD aeration and settling ponds. These ponds are lined with the sludge produced during the treatment process. The recharge rate from each pond was estimated by measuring the water depth and sludge thickness along with the permeability of the sludge material. Laboratory tests on the sludge material indicated that the average permeability of the sludge material is approximately 4.9×10^{-7} ft/s.

The estimated recharge rates from the treatment ponds are presented in table 1. Recharge from precipitation was minimal on the site. The greater portion of the reclaimed area is steeply sloped, and runoff trenches were installed. Water ponded in the runoff trenches after storm events is routed underground away from the site. Field data from monitoring wells around the run-off trenches indicated that these wells exhibit a significant increase in water levels after precipitation events.

Table 1. Recharge rates from the three treatment ponds at the site

Pond	Water depth, ft	Sludge thickness, ft	Permeability of sludge, ft/day	Hydraulic gradient	Discharge per unit area ft/day
1	1.0	4.2	2.8×10^{-2}	0.24	6.7×10^{-3}
2	3.0	1.0	2.8×10^{-2}	3.00	8.4×10^{-2}
3	7.7	0.6	2.8×10^{-2}	13.00	3.6×10^{-1}

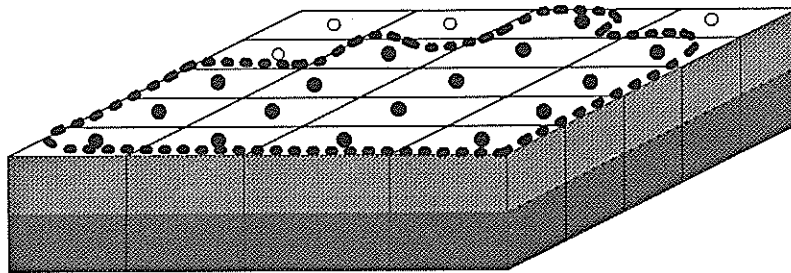
Analysis Model

The computer program MODFLOW by McDonald and Harbaugh (1988) was used in this study. The flow regime is modeled as a 3-D nonhomogeneous media using the following steady-state governing differential equation:

$$\frac{\delta}{\delta x} (k_{xx} \frac{\delta \phi}{\delta x}) + \frac{\delta}{\delta y} (k_{yy} \frac{\delta \phi}{\delta y}) + \frac{\delta}{\delta z} (k_{zz} \frac{\delta \phi}{\delta z}) - w = 0 \quad (1)$$

where: k_{xx} , k_{yy} , and k_{zz} = hydraulic conductivities along the x, y, and z axes,
 ϕ = piezometric head at any point, and, w = flux per unit volume representing source or sink.

Solution of equation 1 is obtained using a block-centered finite difference method. The flow domain representing the site aquifer system is discretized into node and elements as shown in figure 2. The program allows for the simulation of confined and unconfined aquifers or a combination. External stresses such as recharge events can be incorporated in the model. Solution of the finite difference scheme is achieved using implicit procedure with successive relaxation technique.



Key

- - Active cell
- - Inactive cell
- - Aquifer boundary

Figure 2. Representation of flow regime in MODFLOW

In general, the characterization of ground water flow through mine spoils is rather challenging. As discussed by Hawkins et al. (1991), ground water flow through mine spoil exhibits bimodal characteristics that include those similar to flow through porous media as well as pseudokarstic flow. The difference between the pseudokarstic flow and porous media flow is distinct. Conventional porous media flow is generally laminar and can be described by Darcy's law. Pseudokarstic flow is characterized by turbulent with multiple primary flow paths, extreme ranges of hydraulic conductivity, and rapid response to recharge events. The analysis model used in this study is based on assuming the dominance of porous media flow. Using this assumption, the hydrogeologic parameters of the site can be averaged over the flow domain and porous media flow can be simulated.

Site Characterization and Analysis Domain

The analysis domain for the research site is shown in figure 3. The modeled area of the site is approximately 700 ft wide and 1500 ft long. A part of the undisturbed area that is 300 ft long was incorporated in the model. This was necessary in order to simulate recharge events from this area and include into the model the presence of the highwall. The site was modeled as unconfined aquifer with the bottom of the aquifer at the elevation of the pavement. The bottom of the aquifer was estimated to be at El. 915.

Domain Discretization and Boundary Conditions

A grid measuring 18 cells by 25 cells was used to discretize the site as shown in figure 4. The cell width (in the y direction) ranged from 20 to 50 ft, and the length ranged from 25 to 100 ft. Boundary conditions for the flow model were selected in accordance with observed field conditions. A boundary located at the interface between the undisturbed and reclaimed area was modeled as a general constant head boundary with ground water flow allowed across it. The head levels for this border boundary were interpolated from the monitoring well data.

The north and south boundaries were set as no flow boundaries except where drains and ponds were located. The field location of the south boundary was set along the fence line at the edge of the mine site, as shown in figure 3. The field location of the north boundary was selected in the model to be off the reclaimed site such that its effect on the predicted ground water regimes is minimal. The simulated abatement techniques consisted of the installation of a 5-ft thick subsurface cutoff wall and the grouting of discrete spoil pockets as shown in figure 4. The permeability of the grout to form the wall was assumed equal to 3.3×10^{-8} ft/s. Seeps on the sites represented the primary source of discharge. Measurement of total seep volume indicated base flow of approximately 15 to 20

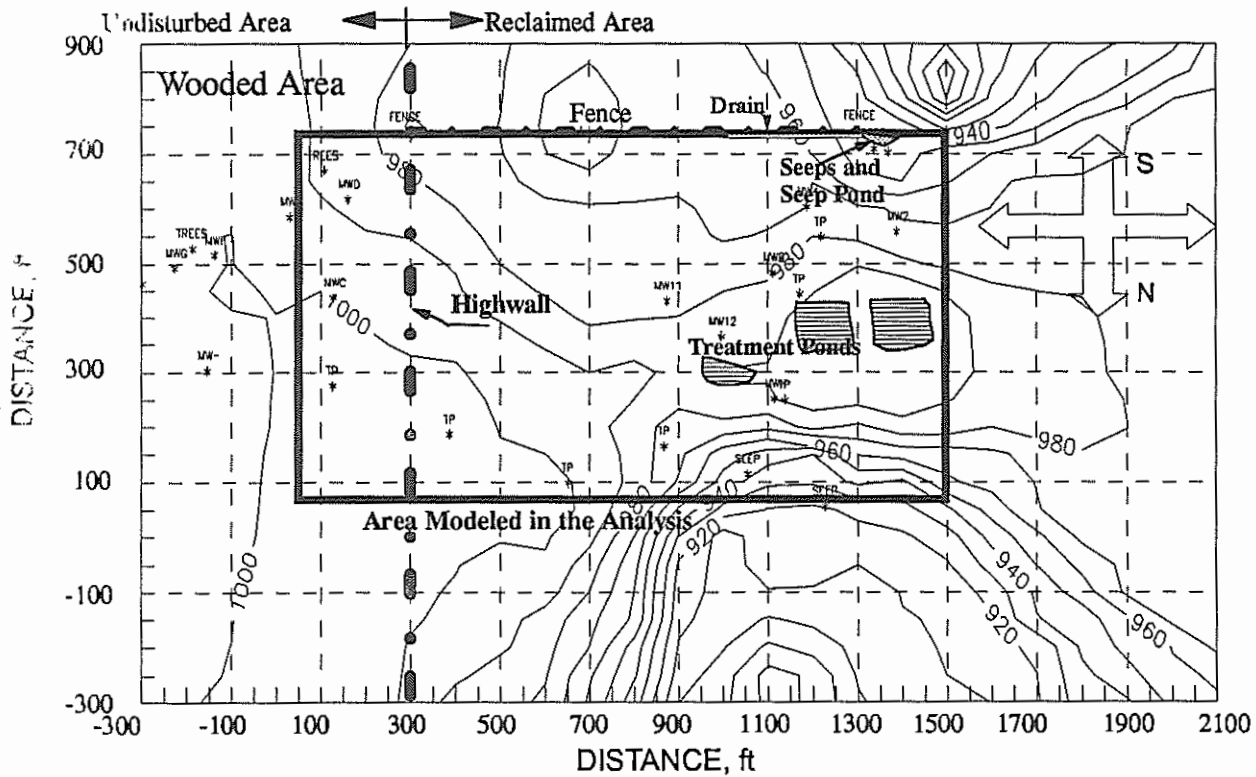


Figure 3. Area of the site used to model the ground water flow regime and remedial measures (North is Downward)

gallons per minute (gpm), or 2900 to 3900 ft³/day. The seeps on the site were modeled as drains. In addition, an existing interceptor drain on the south side of the site that was installed to prevent seeps from flowing to property adjacent to the mine was included in the model. The treatment ponds were represented as constant recharge nodes with the recharge rates as shown in table 1.

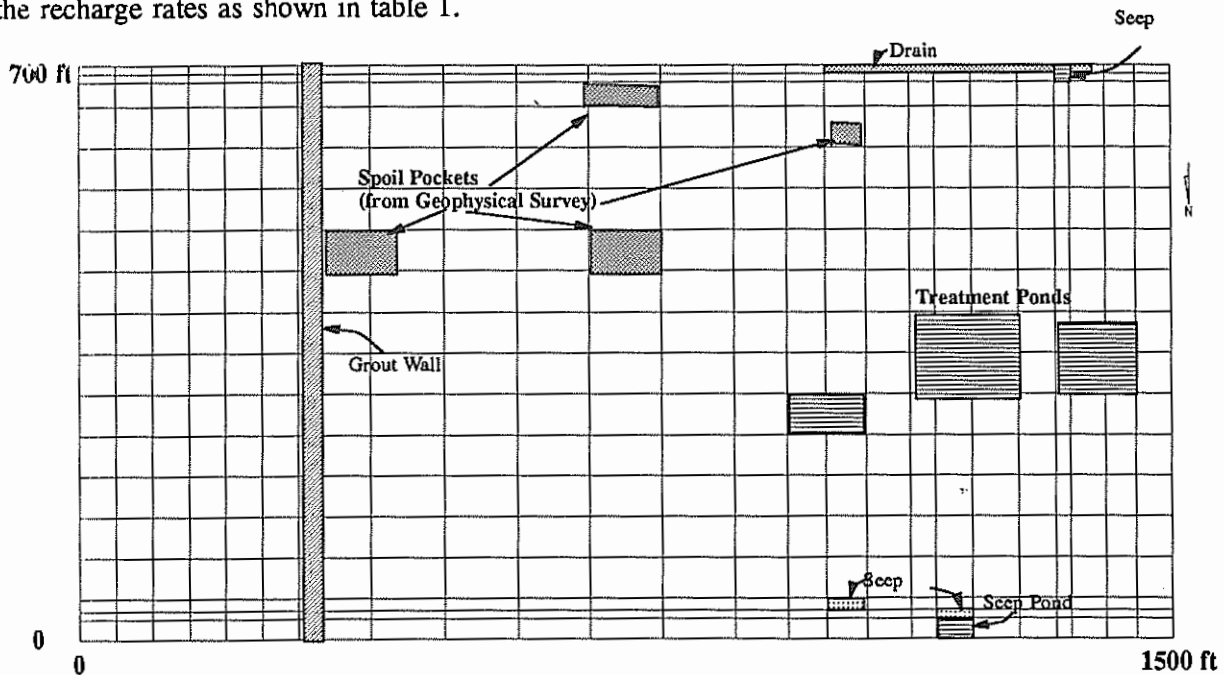


Figure 4. Domain discretization and boundary conditions

Model Calibration

A steady-state trial and error calibration study was performed using the monitored well data from measurements taken on June 24, March 5, and March 31, 1992. The June 24 data are representative of a time when seeps flow was minimum and precipitation did not occur for several days prior to that date. The March 31 data represent the highest water levels for the wells at the upgradient edge of the model as well as high-seep condition. The March 5 data were chosen to represent midlevel data between the low and high water levels.

The initial k values used for the model were those estimated from the slug tests as 2.85×10^{-5} ft/s for the undisturbed area and 3.3×10^{-4} ft/s to 2.0×10^{-3} ft/s for the disturbed area. Model simulations were conducted, and the predicted piezometric heads were compared with monitored well data. Adjustments were made to the k values until the differences between measured, and predicted piezometric heads in all wells were within 10% from each other. Figure 5 shows the results of the calibrated model and the difference in ft between measured and predicted heads.

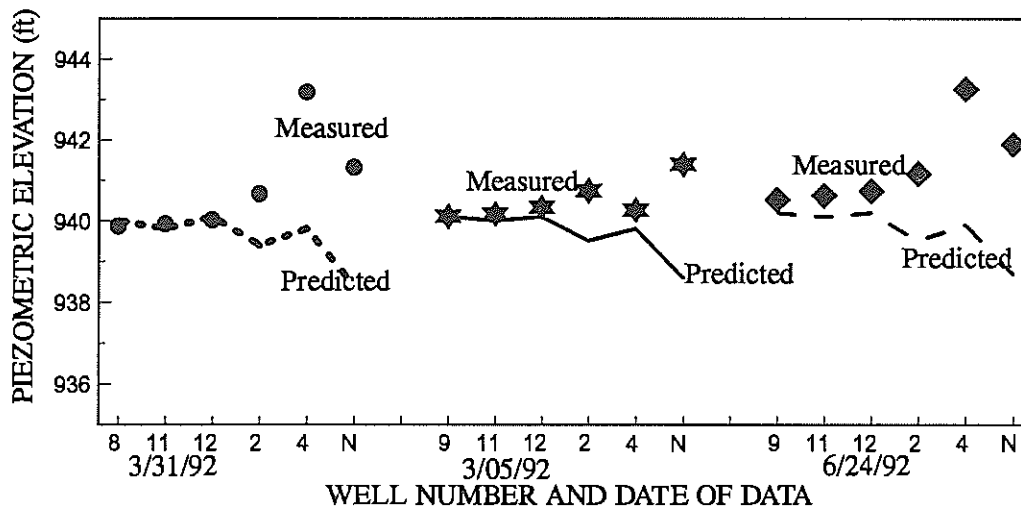


Figure 5. Measured and predicted piezometric levels from the calibration study.

Predicted piezometric heads at wells 2, 4, and N were consistently lower than the measured field values but within the 10% closure tolerance.

A possible explanation for the lower levels in these wells is the fact that the analysis did not account for rainfall recharge. The k -distribution shown in figure 6 was obtained such that these closure values were achieved. These permeabilities are 1 ft/day for the unmined area, and 10, 20, and 40 ft/day for zones in the reclaimed areas.

A volumetric budget generated for the site indicated a recharge flow of 785 ft³/day from the unmined area and 4517 ft³/day from the treatment ponds. Discharge from the reclaimed site was estimated at approximately 5290 ft³/day into the seeps, drains, and seep collection ponds. This value is 1.8 times the measured value from seeps based on June 24 data. However, it is possible that water on the site is discharged via other field means, such as evapotranspiration and possible vertical leakage, that were not represented in the analysis model. Based on the result of this analysis, approximately 85% of the seep water is from the treatment ponds.

Grout Wall: Simulation and Results

The use of subsurface grout wall is one of the most promising abatement techniques for AMD. In this study, the primary function of this wall is to block the inflow from the undisturbed area. The wall was extended along the length of the highwall with a thickness of 5 ft. The analysis was conducted for the days of June 24, March 5, and March 31. Two scenarios were assumed for the analysis. In the first scenario, the south seep pond remained at a constant head which artificially held the water level constant in this area.

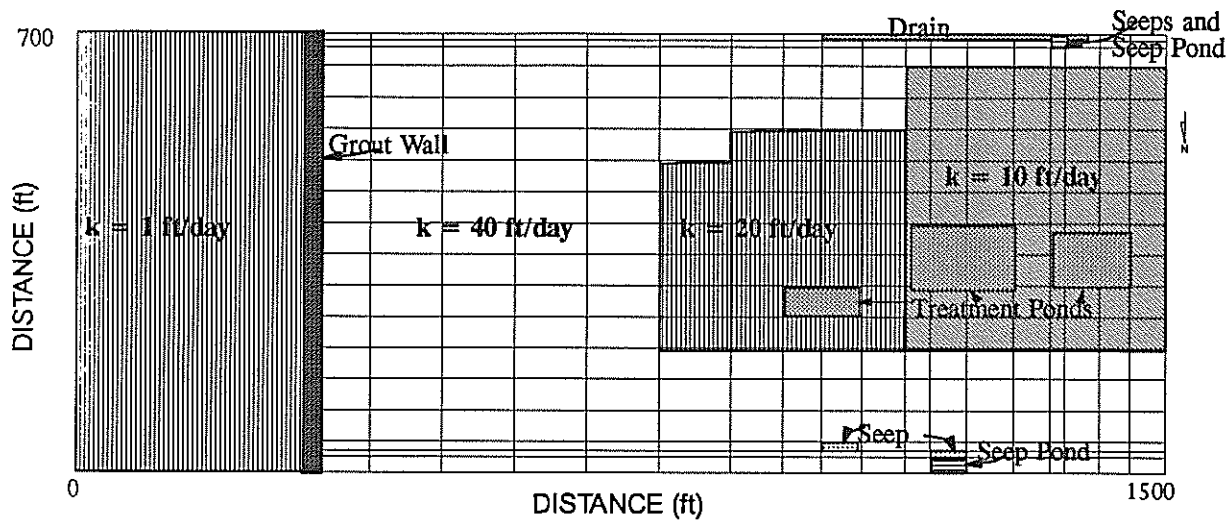


Figure 6. Distribution of permeabilities based on the results of the calibration study.

In the second scenario, the head at the south seep pond was set according to the initial conditions but was then allowed to vary in accordance with the analysis computations. As shown in figure 7A, the presence of constant head caused mounding of the ground water table.

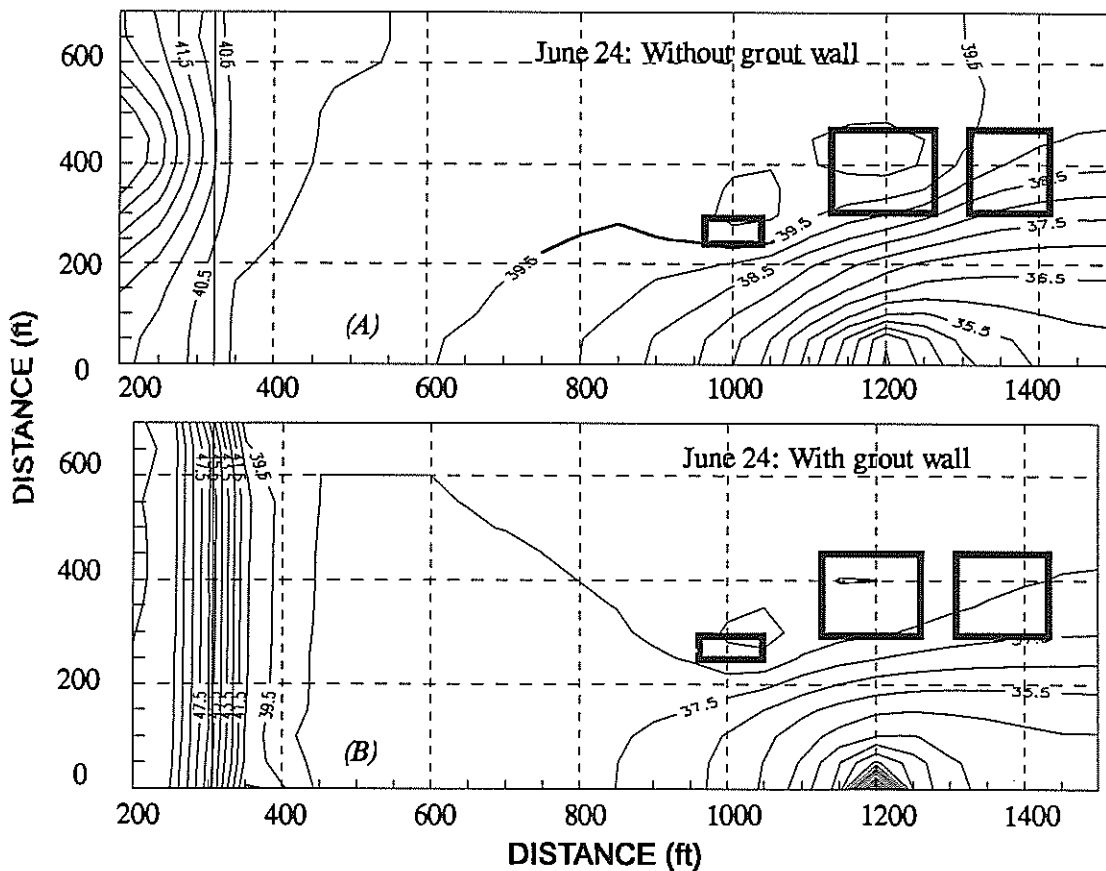


Figure 7. Piezometric contours (900+) from the ground water model : A, no grout wall; and B, grout wall installed.

This mounding dictated that the flow from the undisturbed area be routed around the south pond with the higher quantity flowing to the north boundary.

The installation of the grout cutoff wall caused a large head loss across the wall, as shown in figure 7B. The head loss occurred almost entirely within the grouted zone. As shown in figure 8 (section through the middle of the reclaimed area), the piezometric head drop across the grout wall is from El. 948 ft to El. 942 ft. Before the wall installation, the piezometric head was relatively constant and at about El. 940 at the edge of the reclaimed area.

After the installation of the grout wall the water level at the south seep collection pond was predicted below the initial level of El. 939.4 ft. As shown in figure 8, the piezometric level in the undisturbed area at the highwall boundary was predicted to increase from El. 941.9 without the wall to El. 951.9 (an increase of 10 ft) with the wall installed. In addition, a significant change was predicted in the direction of the flow in the reclaimed area as shown in figure 7. Before the installation of the wall, most of the flow from the unmined area was predicted to be around the treatment ponds. This flow was the result of the mounding effect induced from the recharge by the treatment ponds. The flow in this case was basically split between the north and south seeps. After the wall was installed, the piezometric head across the reclaimed area was reduced to an average of El. 939.5 with the entire flow routed to the location of the north seep. Accompanying this flow routing was a reduction of approximately 1.5 ft in the water level within the reclaimed area and therefore a reduction in the amount of saturated material. Results using the March 5 and the March 31 data were similar to those obtained using the June 24 data.

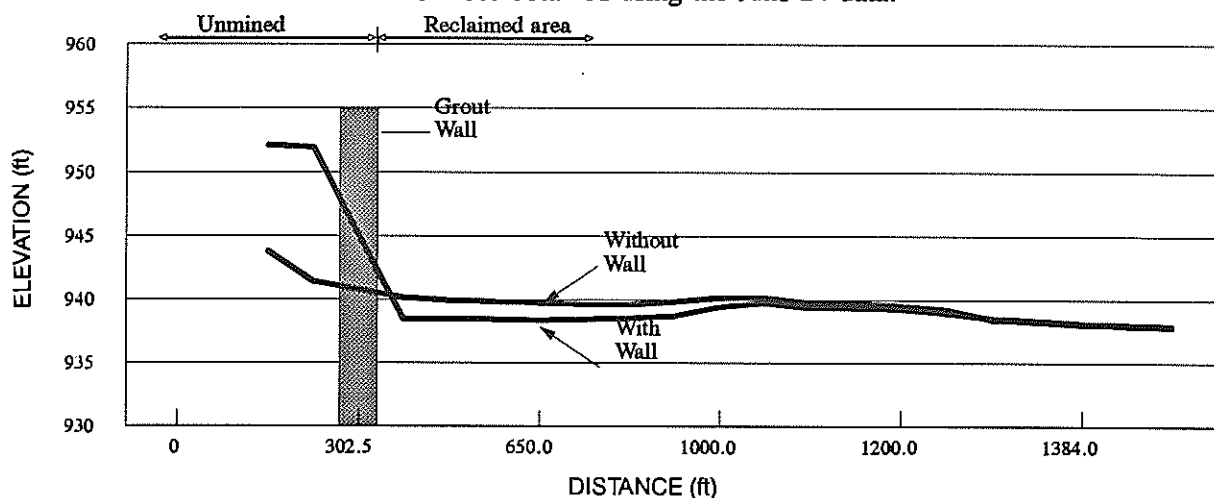


Figure 8. Profile of predicted piezometric heads based on June 24 data.

The volumetric budget for the grout wall simulation indicated that recharge from the unmined area was reduced to approximately 170 ft³/day. The total recharge from the aquifer was estimated to be approximately 4700 ft³/day. These discharge values correspond to 80% reduction in the amount of recharge from the undisturbed area and 10% reduction in the overall discharge from the aquifer. Based on the assumption used to formulate the model and the analysis conditions, approximately 97% of the amount of recharge to the reclaimed area was predicted to be from the treatment ponds after the cutoff grout wall was installed.

Grouted Pockets: Simulation and Results

The second abatement technique that was suggested for the site consisted of grouting isolated pockets of mine spoil that were identified from the geophysical surveys. The merit of this technique is to encapsulate the spoil material within the grout matrix and therefore minimize the generation of AMD. Ground water analysis was conducted with the spoil locations, shown on figure 4, grouted and thereby the cells were assigned a k value of 3.3x10⁻⁸ ft/s. The June 24 data were used to conduct the simulation. In general the grouting of pockets resulted in a slight increase in the predicted water levels (figure 9).

The increase in water levels ranged from 0.2 to 0.4 ft with the highest increase observed at the north side of the treatment ponds. In addition, and because of the location of the grouted pockets on the south side of the

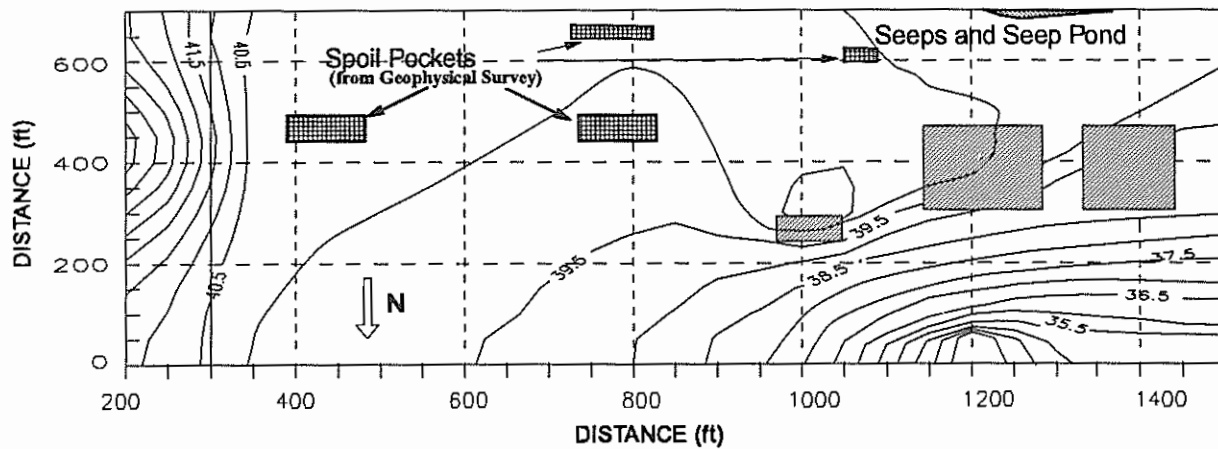


Figure 9. Ground water flow regime and discrete grouted spoil pockets

treatment ponds, increase in the flow to the north seeps was noted due to the routed recharge from the treatment ponds.

As mentioned earlier, the comprehensive subsurface investigation of the site indicated that the spoil material is randomly distributed across the site. Grouting of discrete pockets, although it may improve the quality of the discharge, did not significantly affect the ground water flow regime and magnitude at the site.

Summary and Conclusion

Modeling of the ground water flow regime at a reclaimed mine site was accomplished. The model was developed using the USGS computer code MODFLOW. The analysis model was used to predict the general ground water flow regime at the site and to evaluate the effectiveness of AMD abatement techniques. These techniques included the installation of subsurface grout wall at the location of the highwall and the grouting of discrete spoil pockets on the site. The developed model was calibrated using ground water elevations from monitoring wells. Closure between measured and predicted piezometric heads was approximately 10%. Modifications to measured permeability values were introduced to obtain close agreement with the monitored ground water heads. Based on the results of this study the, following conclusions can be advanced:

1. Installation of a grout wall at the location of the highwall provided for a significant reduction in the amount of recharge from the undisturbed area. A reduction of approximately 80% was predicted from the developed model.
2. After the installation of the wall, the main source of recharge to the reclaimed area, without accounting for precipitation, was the treatment ponds. The predicted flow pattern after the wall installation was radially outward from these ponds.
3. Due to the installation of the grout wall, the water levels near the south seep dropped to a level below the elevation of the south seep. This may cause the flow at the location of this seep to cease and therefore limit flow from the seeps to those on the north side of the site.
4. Grouting of discrete spoil pockets did not significantly affect the ground water flow regime. However, this area needs further investigation to evaluate whether improvements in the water quality may be realized due to encapsulating the spoil material within the grout matrix.

5. The most effective means for reducing the quantity of water flowing into the acidic spoil at this site is the use of subsurface grout wall. Predictions from this study indicated that this technique may eliminate the south seeps and therefore lead to a reduction in the volume of AMD. Consequently this reduction will lead to the downsizing of the treatment ponds which, after the installation of the grout wall, are the main source of recharge.

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