HYDROLOGIC MODELING OF RECLAIMED STRIP MINE SPOIL

by

Kenneth B. Edwards, Mary W. Stoertz, and Douglas C. Turney

Abstract. A numerical groundwater flow model (MODFLOW) of a surface coal mine in southeast Ohio was calibrated under steady state conditions to match measured heads by varying hydraulic conductivity (K) and recharge (R). Sensitivity studies indicated that K was not largely dependent on the poorly quantified underclay elevation or on the lake boundary condition. The baseflow recharge was determined to be between 8 and 60 mm/yr (1 to 6% of annual rainfall) and K between 0.004 and 0.01 cm/s for the spoil aquifer.

Additional Key Words: groundwater flow modeling, coal mine hydrology, MODFLOW

Introduction

The Surface Mining Control and Reclamation Act (SMCRA) of 1977 requires that pre-mining hydrologic status be determined, and that post-mining hydrologic changes be predicted, before permits are issued. Considerable efforts have been made to aid coal operators in determining probable hydrologic consequences, which might include changes in recharge, baseflow, permeability, groundwater storage, flow gradient, and water quality (Eberle and Razem 1985). These efforts have met with limited success (Caruccio 1988), mainly due to the hydrogeochemical complexity of mined areas. However, as Wilson and Hamilton (1978) point out, "The flow field must be described prior to any serious attempt at quality analysis."

This study investigates and models the movement of groundwater through mine spoil, emphasizing the determination of hydraulic conductivity (K) and groundwater recharge (R). In the process, some of the difficulties in modeling spoils, including handling boundary conditions and the non-unique relationship between K and R, are addressed.

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Site Description

Howard Williams Lake is a 0.14 km^2 reservoir in Perry County, southeast Ohio. Draining a hilly area of 5 km^2, the lake was dammed in 1950 to provide water to a coal-washing plant down-valley. Blasting and subsequent removal of the overburden to expose and remove the Middle Kittanning coal in the 1960s resulted in the pyritic sandstone and shale overburden materials being highly mixed. The resulting material is termed "spoil." Reclamation in 1990 on the lake's north side involved regrading the spoil to eliminate the highwall and revegetating the site (Figure 1). Only this 0.5 km^2 northern region has been reclaimed. The lake has a pH of 3 and contains 200-300 mg/l $CaCO_3$ equivalent acidity. Monthly stream flow and water table data were collected from August 1995 through June 1996 as part of our investigation. Additional investigations at Howard Williams Lake can be

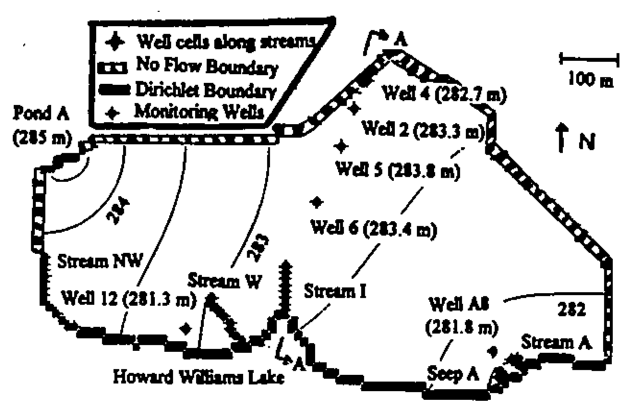

Figure 1. Site Plan of Model Domain
Water table contours for Scenario #2 with R=38 mm/yr, K=0.005 cm/s.
Measured heads on 12/3/95 in (). Units are m.

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found in Edwards and Turney (1997), Turney et al. (1996), and Edwards and Grube (1995).

Hydrologic Modeling

Numerical simulations of groundwater flow are normally based on a simplified conceptual model of the system. At the Howard Williams Lake site, water is believed to enter the spoil as recharge from rainfall infiltration and, to a lesser extent, from an unmined coal seam adjacent to the site. Water flows laterally through the spoil above an underclay which lies slightly above the lake level, and seeps out above the clay outcrop. Channels lined with limestone rock transmit the flow to the lake. Our conceptual model of the spoil water-table system is diagramed in Figure 2.

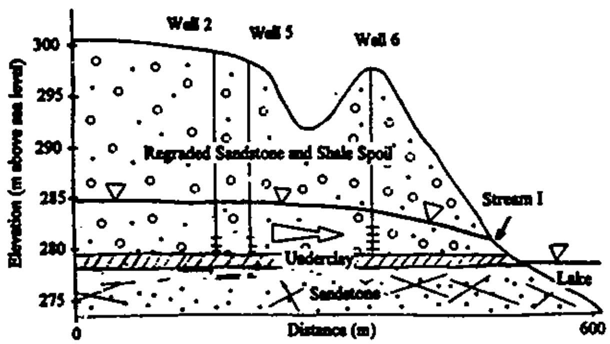

Figure 2. Cross-Section A-A and Conceptual Flow Model (exaggerated vertical scale)

Steady state flow provides the simplest conditions for model calibration of R and K. The 11 month record of well water levels and stream flow data indicated a period of minimum change around December 3, 1995, corresponding to a period of minimum precipitation and the most nearly steady state (or baseflow) conditions.

For a homogeneous unconfined aquifer with an impervious bottom base, steady horizontal groundwater flow is governed by Poisson's equation:

$$\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\frac{\partial h}{\partial y}\right) + \frac{R}{K} = 0 \quad \textbf{(1)}$$

where h is hydraulic head [L]; K is hydraulic conductivity [L/T]; R is recharge [L/T]; and x and y are spatial coordinates [L]. Due to the complex boundary conditions at the site, numerical solution of (1) is required. Visual MODFLOW (Waterloo 1996), an implementation of the U.S. Geological Survey numerical finite-difference groundwater flow model MODFLOW (McDonald and Harbaugh 1988), was used for this study. In modeling, either R or K can be used to calibrate a model to minimize head residuals, so the problem is ill-posed mathematically in the absence of flow constraints (Stoertz 1989).

The groundwater flow domain at the study site was represented by a 91x57 grid (Figure 1). Each grid is 12m x 12m. The domain is bounded by the physical boundaries of the lake, streams, Seep A, Pond A, and flow divides. Corresponding mathematical boundaries are a Dirichlet boundary (constant head) at the pond, and Neumann boundaries at the streams (specified flow) and divides (no flow). Whether the lake is best represented by a Neumann or Dirichlet boundary is investigated in this paper. Seeps and streams were modeled as line discharges (Neumann boundaries) by invoking a series of fully-penetrating wells, with the measured baseflow discharge apportioned equally to cells along the stream or seep. The boundary conditions are summarized in Table 1 for the baseflow conditions on December 3, 1995.

Table 1. Boundary Conditions

Location	Discharge (m^3/day)	# Cells
Stream A	16.3	4
Seep A	29.4	4
Stream I	9.80	9
Stream W	17.4	9
Stream NW	2.72	14
	Head (m)	
Pond A	285	4

While the stream and pond boundaries were accurately known, the lake boundary and underclay boundary were not as well defined. The underclay elevations determined from borings conducted during this study were 3m higher than underclay elevations found on a pre-lake underclay map of the coal seam. Scenarios were developed for both cases. Further, it was unclear whether the lake should be modeled as no flow or constant head. Since the lake resides below the top of the clay, nearly all water enters the lake through seeps, and this amount is small based on lake water budgets, especially during non-storm periods. However, the lake could be modeled as a Dirichlet boundary using, instead of the actual lake elevation, the elevation of the seepage face. When R and K were constrained within a reasonable range (discussed later), either the well levels predicted by the latter boundary were much too low compared to measured heads, or the groundwater flow into the lake exceeded by several times the amount predicted by water budgets. Therefore, it was postulated that the seepage face could consist of a low permeability strip (border) of unmined overburden, heaped clay, or low permeability iron coated oxidized spoil material along the lake perimeter at the seepage face. The four scenarios simulated are #1 (low clay, no flow lake boundary), #2 (low clay, lake boundary at 279m), #3 (high clay, no flow lake boundary), and #4 (high clay, 280m lake boundary). "Low" underclay means that the underclay elevations are 270, 273, 280, and 277m at the southeast, northeast, northwest, and southwest corners of the domain. "High" underclay means that the underclay elevations are 273, 276, 283, and 280m at the corners. The underclay is assumed to be planar at in-between locations.

Slug, pumping, and recovery tests were conducted on all wells except Well 4 to estimate spoil K. The results showed that K approaches a log-normal frequency distribution with mode of the order 10^{-3} cm/s. Because measured K varies from 10^{-5} to 1 cm/s based on well tests, a representative value of K for modeling the entire site is not known *a priori*. K is adjusted during calibration, along with recharge, until the best fit between predicted and measured well levels is found. K is bounded by the range of 10^{-5} to 10^{-1} cm/s since that is the range indicated by the majority of the field tests. As is the case with minespoil aquifers, well tests indicated significant heterogeneity. The homogeneous model presented here is a first approximation to understanding the regional groundwater system.

Results

Each of the four scenarios was investigated using MODFLOW to determine the combinations of R and K that provide the best fit to the measured monitoring well water levels. Twenty five combinations of R and K were simulated using MODFLOW for scenario #1, 42 for #2, 28 for #3, and 25 for #4. Rather than finding one combination of R and K that provided the best fit to the water levels, many combinations resulted in similarly good fits. Table 2 shows the combinations of R and K which provide the best fits for each scenario. Best fit was determined by minimizing the root mean square (RMS) error between the measured and modeled water levels.

Discussion

The results in Table 2 show that, regardless of the scenario, K for the spoil is between 0.004 and 0.01 cm/s since the RMS errors are least for this range of K. Due to the inter-relationship between R and K, there is not a single best combination of these parameters. Compared to K, R is more dependent on the boundary conditions. Scenario #1 indicates that R lies between 7.6 and 51 mm/yr. The run using R>51 mm/yr has too great an error to be considered realistic. R<7 mm/yr caused the groundwater to be unrealistically depleted in finite-difference cells near the streams. Scenario #3 requires larger recharge rates to

Table 2. Results (R in mm/yr, K in cm/s, RMS in m)

Scenario #1

R	K	RMS
7.6	0.01	0.98
18	0.008	0.97
28	0.006	0.97
33	0.005	0.98
41	0.004	0.94
51	0.002	1.00
58	0.001	1.40

Scenario #2

R	K	K_{border}	RMS
10	0.01	1e-6	0.98
38	0.005	1e-6	0.96
56	0.002	1e-6	0.98
61	0.001	1e-6	1.4

Scenario #3

R	K	RMS
33	0.01	0.95
38	0.008	0.96
46	0.006	0.93
51	0.004	0.92
56	0.002	1.17

Scenario #4

R	K	K_{border}	RMS
36	0.01	1e-6	0.95
51	0.009	1e-4	1.46
56	0.004	8e-6	0.97

match well levels. Since #3 has higher underclay than #1, greater recharge is required to compensate for the lower transmissivity. Scenario #3 indicates that the recharge lies between 33 and 51 mm/yr. Similar to scenario #1, cells unrealistically go dry for recharge less than 30 mm/yr and the well levels are poorly matched for recharge greater than 55 mm/yr.

Scenario #2 treats the lake as a Dirichlet boundary and inserts a low permeability zone on the lake's perimeter as discussed previously. A border K of 10^{-6} cm/s provides the smallest RMS errors. The best fit recharge rates and spoil K's are similar to scenario #1. The similarity is reasonable since the best fit R's and K's result in very little groundwater flow into the lake (relative to the stream flows), so the scenario is physically very similar to the no flow scenario. Scenario #4 was the most sensitive to R, spoil K, and border K trials. If K was less than 0.004 cm/s or R was less than 36 mm/yr, cells near the streams dried out. If K was greater than 0.01 cm/s or R was greater than 56 mm/yr, then the RMS was high. Scenario #4 has good fits for different border K's unlike #2 for which 10^{-5} cm/s always provided the best fits. Even though #4 was more sensitive to parameter variation, the best fit R and K are similar to #3 for the same reasons that #2 is similar to scenario #1.

Conclusions

Groundwater modeling of the coal mine spoil aquifer indicates the hydraulic conductivity of the spoil lies between 0.004 and 0.01 cm/s. Modeling indicates that, contrary to the conceptual model (Figure 2), flow is nearly perpendicular to the expected flow direction from highwall to lake. This occurs because Pond A has a high fixed head which controls the flow of groundwater in the model. The modeling also implies that the lake's acidity derives primarily from surface flow at discrete seeps and streams because these are the sources of highest flow. Lakes in surface-mined areas may be hydraulically disconnected from spoils by underclay, and the lake-spoil boundary may be modeled best as a no flow (as opposed to constant-head) boundary.

Acknowledgments

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