Ground-Water Flow Model of Drawdown and Recovery Near an Underground Mine

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ABSTRACT

The U.S. Geological Survey's modular code (McDonald and Harbaugh, 1984) was used to reconstruct past ground-water flow paths and make predictions of future flow patterns to understand movement of sulfate-contaminated ground water through a carbonate aquifer near an underground mine. The abandoned mine is in the zinc-lead district near the town of Shullsburg in southwestern Wisconsin. The model predicts observed hydraulic head distributions and ground-water discharge rates with fair accuracy. Instantaneous dewatering rates are underestimated, but long-term rates can be estimated with the model. The persistence of a cone of depression at present and in the future allows uncontaminated water from surrounding areas to dilute the sulfate, as confirmed by chemical sampling. The model predicts radial flow will persist near the Shullsburg mines until approximately 1988.

The model represents a significant test of the ability of a ground-water flow model to predict the impacts of underground mining on ground-water systems. The method used required field data collected before, during, and after mining. A model calibrated to just one or two of these data sets is likely to have larger associated uncertainties.

INTRODUCTION

Computerized ground-water flow models have been used to simulate dewatering and recovery of ground water around mine workings (Cook, 1982; Schwartz and Crowe, 1987). Construction of such models requires information about the aquifer system and mining project. This paper describes the development and use of a model to reconstruct past ground-water flow paths and aid predictions of future flow patterns around the underground Shullsburg zinc-lead mines, in southwestern Wisconsin (Figure 1).

Purpose

The model increases understanding of the hydrogeology of the Shullsburg mines. Using the model to reconstruct known ground-water head distributions and flow rates identifies which hydrogeologic parameters most influence ground-water flow paths and is a first step in making predictions about future flow paths. This understanding helps interpretation of observed ground-water chemistry in the area. An understanding of both the hydrogeologic and geochemical processes associated with mine dewatering and recovery is necessary to predict potential ground-water contamination. Local well owners want to know whether contamination will spread or dissipate. The results of the geochemical aspects of the problem are reported elsewhere (Toran and Bradbury, 1985; Toran, 1987). Here, the results of calibration and prediction using a two-dimensional ground-water flow model are described.

The model differs from others because of the availability of data for validation and thus provides a test of the validity of using a numerical model to predict subsurface mining impacts. Most previous studies (e.g., Weeks *et al.,* 1974; Bair and Parizek, 1981; Voorhees and Prickett, 1982; Bair and O'Donnell, 1983; Winter *et al.,* 1983; Wang and Williams, 1984; Weiss and Razem, 1984; Schwartz and Crowe, 1985) have developed only predictive models of proposed mines because the mining impacts will take place many years in the future, and there are few or no data for model calibration. In the Shullsburg area, data from before, during, and after mining constrain the model and allow predictions with greater knowledge of model limitations than is usually possible.

Background

The zinc-lead mines near Shullsburg, Wisconsin (Figure 1) operated from the 1920's until 1979 when they were shut down for economic reasons. The host rock is a carbonate aquifer that was

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Received July 1987, revised November 1987 and March 1988, accepted April 1988.

Discussion open until May 1, 1989.

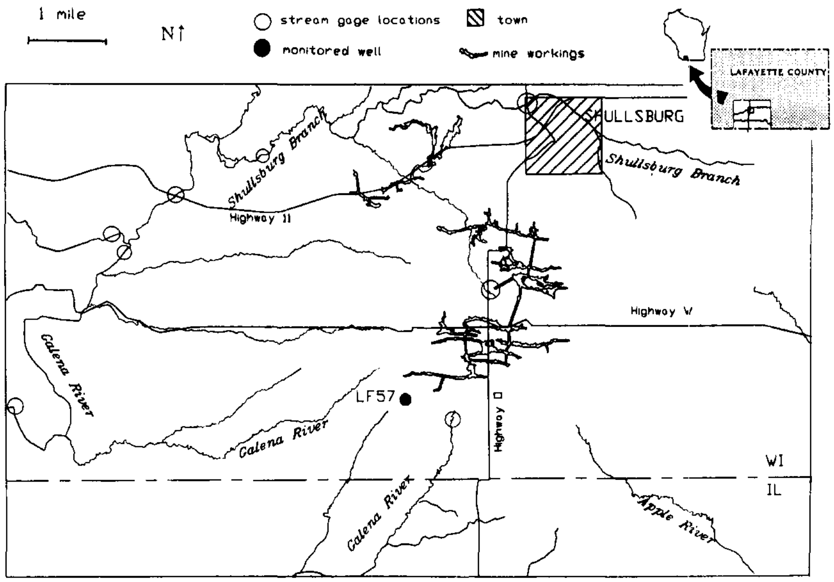

Fig. 1. Location of the mine workings and drainage patterns near Shullsburg, Wisconsin. Outline of figure shows model grid outline (Figure 2).

dewatered during mining. While the rock was exposed to air, sulfide minerals were oxidized to sulfate. This reaction produces iron, sulfate, and hydrogen ions, commonly referred to as acid mine drainage. However, in carbonate rocks, the pH is buffered.

Within a year after the mines shut down, local well owners began complaining about poor water quality, and a dairly farmer suffered a significant drop in milk production. A preliminary study (Evans and Cieslik, 1985) documented sulfate levels as high as 40 mmol/l (3800 ppm) in some domestic wells near the mines. The EPA safe drinking water standard (U.S. EPA, 1979) is 2.6 mmol/l (250 ppm). Because elevated sulfate levels can cause diarrhea in humans and poor milk production in cows, 11 local wells were abandoned.

Local well owners faced two threats to their water supply when sulfate contamination was discovered. First, although the abandoned wells were within one-half mile of the mine workings, other wells would be at risk if contamination spread. Second, a deeper confined aquifer provided an alternative supply for water, but there was concern that contamination might breach the thin aquitard and threaten deeper wells.

MODELING METHODOLOGY

Computer Code

The modular, saturated ground-water flow code developed by McDonald and Harbaugh (1984) was used in a two-dimensional mode, as further explained below. The code uses a block-centered finite-difference grid and is separated into modules which simulate various features of the hydrogeologic system. The packages used were the recharge package, drain package, and general head boundary package. Use of these packages is described in more detail below. The solution scheme is the strongly implicit procedure.

The modeling was done in three stages: steady-state premining, transient mining and dewatering, and transient recovery. The calculated heads from each stage were used as input to the next stage. Governing equations for each stage, respectively, are as follows:

$$\frac{\partial}{\partial x}(K_x b \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y b \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z b \frac{\partial h}{\partial z}) - W_1 - W_2 + R(x, y) = 0 \quad (1)$$

$$\frac{\partial}{\partial x}(K_x b \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y b \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z b \frac{\partial h}{\partial z}) - W_1 - W_2 - W_3 + R(x, y) = S\frac{\partial h}{\partial t} \quad (2)$$

$$\frac{\partial}{\partial x}(K_x b \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y b \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z b \frac{\partial h}{\partial z}) - W_1 - W_2 + R(x, y) = S\frac{\partial h}{\partial t} \quad (3)$$

where x, y = Cartesian coordinates aligned along the principal directions of the hydraulic conductivity tensor (L); K_X, K_Y (x, y, t) = components of the hydraulic conductivity tensor (L/T); b(x, y, t) = saturated layer thickness (L); h = potentiometric head (L); W_1 = discharge river drains (L/T); W_2 = discharge general head boundary nodes (L/T); W_3 = discharge mine nodes (L/T);

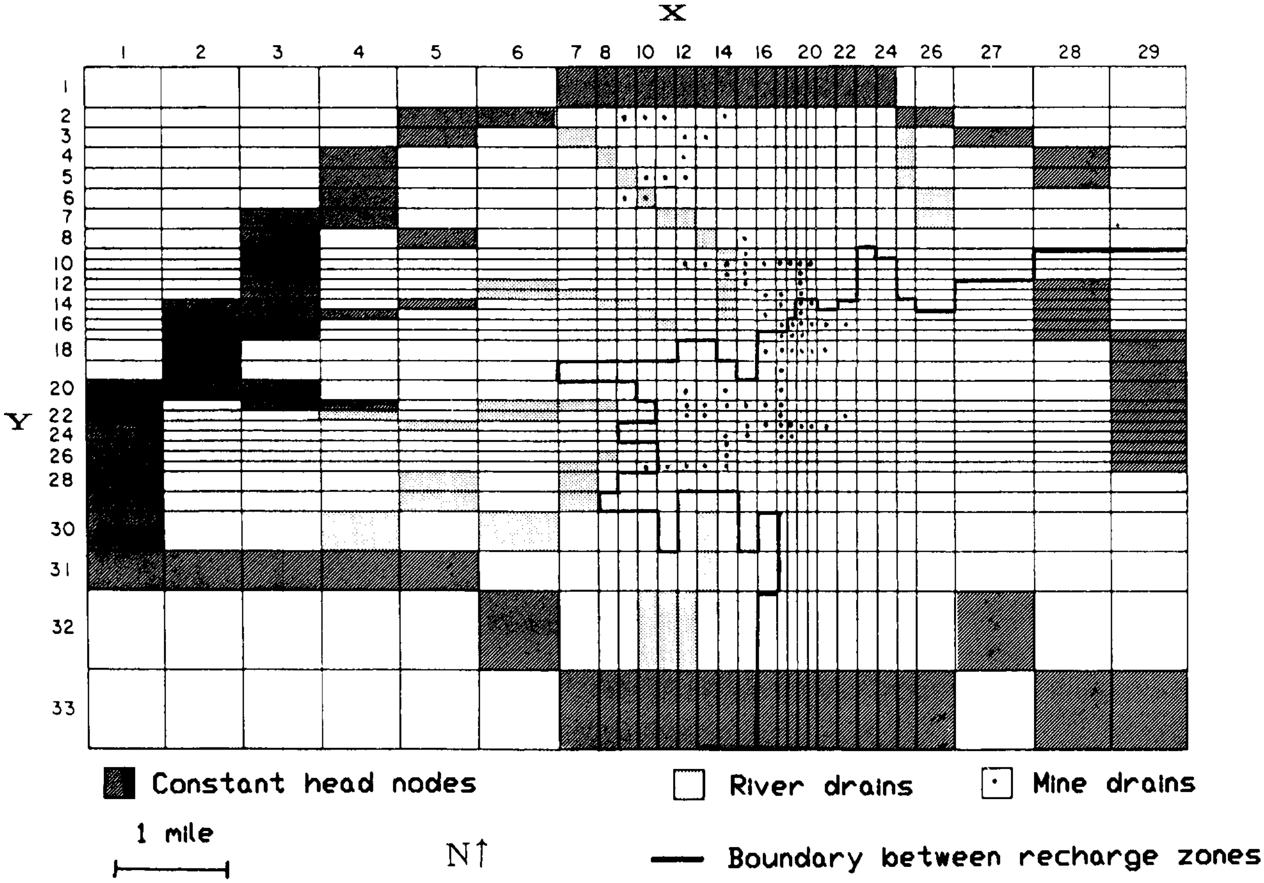

Fig. 2. Model grid showing constant-head nodes, drain nodes simulating rivers, drain nodes simulating mine workings, and boundary between recharge zones. The southeast zone of lower recharge is 1.5 in./yr; the rest of the model is 6 in./yr.

R(x, y) = recharge (L/T); S = storage coefficient (dimensionless); and t = time (T).

Grid Design

The study area is represented by a finite-difference grid consisting of 29 rows, 33 columns, and 1 layer, or 957 nodes of which about 778 are active (Figure 2). The grid is irregularly spaced, with a finer mesh near the mine workings. Node spacings range from 500 ft near the mines to 4000 ft near the model boundaries.

The study area is vertically divided into seven formations: Maquoketa Shale; Galena Dolomite (thickly bedded cherty dolomite); Decorah Formation (mixed dolomite, limestone and shale); Platteville Dolomite (thinly bedded dolomite and fractured ore deposits); Glenwood Shale; and St. Peter Sandstone (Figure 3). The Galena, Decorah, and Platteville Formations are compositely known as the Sinnipee aquifer. The model explicitly simulates the Sinnipee aquifer as a single model layer, corresponding to the three formations listed above, plus the mined layer at the top of the Platteville Formation. Thickness of the layer representing the Sinnipee aquifer varies in space corresponding to information obtained from mineral exploration

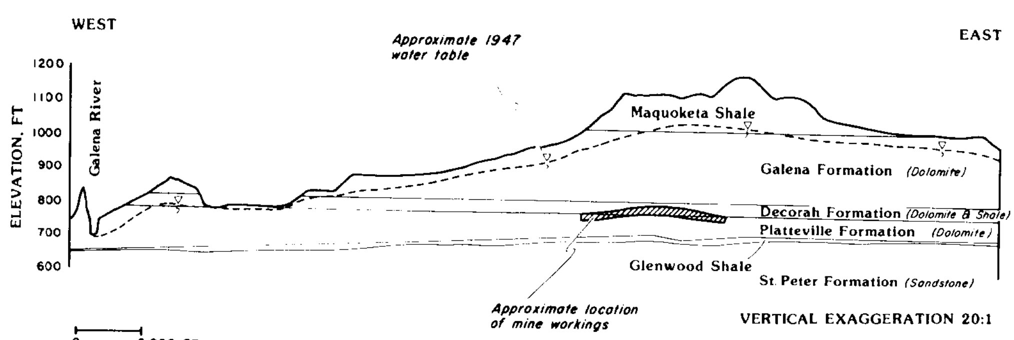

Fig. 3. Geologic cross section through the Shullsburg area showing the seven hydrostratigraphic units: Maquoketa Shale, Galena Dolomite, Decorah Formation, mine workings, Platteville Dolomite, Glenwood Shale, St. Peter Sandstone.

Table 1. Summary of Input Parameters for the Calibrated Model

Parameter	*Value*	*Reference*
K_X	2×10^{-5} ft/sec	Analysis of specific capacity tests.
Anisotropy ratio	0.5	Steady-state calibration.
S	0.02	Recovery calibration.
Recharge	6, 1.5 in./yr	Calibration to base flow (Stedfast, 1979).
K_X Mines	5.4×10^{-3} ft/sec	Pump tests (Holt, 1958).
K_Z Glenwood	2×10^{-10} ft/sec	Typical value for shale.
Mine conductances	0.25, 0.5, 1.0 ft^2/sec	Drawdown calibration.

records, water well logs, and geological maps of the region.

The model does not simulate flow in the Maquoketa Shale, but does assume that it limits vertical recharge where it occurs. The Glenwood Shale and the St. Peter Sandstone form a leakage boundary at the base of the model, as discussed later.

The primary axes for the hydraulic conductivity tensor were aligned in the N-S and E-W directions to follow faults measured in the area (Mullens, 1964, p. 523), and the trend of the mine workings (Figure 1).

Boundary Conditions

The upper boundary of the model is a recharge boundary, added to the fluctuating water table. The model contains two zones of uniform recharge. One zone of recharge of 6 in./yr (a little less than 30% of the annual precipitation in southwest Wisconsin) covers the surface outcrop of the Sinnipee aquifer. A second zone of lower recharge (1.5 in./yr) is used where the Maquoketa Shale covers the Sinnipee, in the southeast area (Figure 2). Field measurements of base flow in local streams were used to constrain estimates of ground-water recharge in steady-state simulations. Low-flow estimates at stream gages are available for six stream reaches along the Galena River and Shullsburg Branch in the western part of the study area (Stedfast, 1979).

The bottom boundary is described by the general head package using heads in the St. Peter Sandstone as constant heads, with leakage allowed through the Glenwood Shale. The vertical conductivity of this leakage boundary was varied from 2×10^{-10} to 2×10^{-8} ft/sec, which are typical values for low-conductivity shale, without increasing flow to the St. Peter Sandstone beyond small volumes.

The side boundaries are regional divides (no flow) or discharge to area rivers (constant head) such as the Galena River, Apple River, and Shullsburg Branch (Figure 1). The lateral boundaries are beyond the radius of influence of the measured cone of depression. Major tributaries of these rivers are included as drain nodes, which are discharge points in the interior of the model when they are not dried up by mine dewatering.

Input Parameters

The input parameters (Table 1) were derived from a combination of field measurements and calibration. The specific storage was obtained by calibration as discussed in the results section.

A bulk horizontal hydraulic conductivity (K_x) of 2×10^{-5} ft/sec (English units are used to be consistent with historic data sets) was selected for the Sinnipee aquifer based on 21 specific capacity tests reported on well logs. Although these data are not always reliable, the value obtained is a starting point for calibration and in this case, provides the appropriate order of magnitude for hydraulic conductivity consistent with recharge. The tests were corrected for partial penetration and well loss using the method of Bradbury and Rothschild (1985). In the nodes representing mine workings, a hydraulic conductivity of 5.4×10^{-3} ft/sec is used. This conductivity was measured by pumping tests in or near the mines (Holt, 1958), and is assumed to be characteristic of fractured ore bodies near Shullsburg.

An areal anisotropy ratio (K_x:K_y) of 0.5 was found to give the most distinct representation of V-shaped potentiometric contours across the streams, and improved the shape of the transient cone of depression. A slight anisotropy is justified on the grounds that the major mine workings trend in the E-W direction (Figure 1), and there are slightly more joints measured in the E-W trend, and the joints along that trend are reported to be more open and continuous (Mullens, 1964).

The heads in the bottom constant-head boundary were obtained from data on the St. Peter Sandstone in the U.S. Geological Survey (USGS) Ground Water Site Inventory. These data were supplemented by about 20 additional measurements from wells in the St. Peter Sandstone collected for this study.

Calibration Data

An extensive unpublished collection of hydrogeologic data (Holt, 1958) is available from the USGS. The historic database was supplemented by additional water-level measurements.

Holt (1958) constructed a series of maps of the potentiometric surface in the Sinnipee aquifer. The first was for premining conditions, before extensive underground mining and dewatering (Figure 4A). The historic records suggest the map is strongly based on topography, with a few wells for control. Holt collected water-level measurements at over 300 points during the period of mining, and produced potentiometric maps in 1954, 1955, 1957, and 1958 (Figure 5A). The latter was used for model calibration during the drawdown stage. Holt's (1958) history of mining was used to distinguish five stress periods during dewatering. The stress periods correspond to major mining developments, and simulate progressive opening of new drifts. The dewatering rates for three pumps were reported by Holt (1958) although it is not known whether the rates are daily averages or instantaneous measurements.

For this study, over 130 new measurements of total head over an 80 mi^2 area in the Sinnipee aquifer were collected four years after mining ceased (the Summer of 1983). Measurement points included household wells, prospect holes, an open mine shaft, springs, and seeps (Toran, 1986). Measurements were made at various depths and in wells with varying screen lengths, so it is difficult to quantify vertical flow. Therefore, the map (Figure 6A) of the 1983 potentiometric surface of the Sinnipee aquifer assumes horizontal flow.

Simulation of Mine Dewatering

The modular model drain package (McDonald and Harbaugh, 1984) was used to simulate mine dewatering. Drains are head-dependent boundaries which are active only when the head in the aquifer is greater than the elevation of the drain. Drain conductance describes the communication between the drain and the aquifer. The conductance is the hydraulic conductivity of the layer between the drain and the aquifer multiplied by the thickness of the layer. High drain conductances of 1.0, 0.5, and 0.25 ft^2/sec (depending on the cell size) simulate open mine workings. The drain head is assigned to be the reported base of the mine workings. The total flow to drains was compared with actual mine dewatering rates. Using the drain package rather than pumping wells for mine dewatering has several advantages. First, actual pumping rates during mining varied with time, and actual pumping rates at any particular time are unknown. The drain option allows constant variation of dewatering rates. Second, the drain option automatically "turns off" flow to a drain whenever the head in that cell falls below the drain head. This feature reduces the problem of node dry-up. Finally, the number and locations of drains can be varied between stress periods in a single run, allowing the sequential addition or reduction of drains as mining progresses.

Model Assumptions

The model is two-dimensional, and it assumes horizontal flow between nodes. Because many of the wells are open to several stratigraphic units, and maps of the potentiometric surface assume horizontal flow, no data were available for vertical calibration. Therefore, the model assumes head in a single layer can be used to calibrate the model. By using a single layer, large downward vertical gradients near the mines during drawdown are neglected, and thus head during calibration may be underestimated. Upward gradients occur near the mines during recovery. However, in runs made using a quasi-three-dimensional, four-layer model, vertical gradients were significant for only 10% of the model area. Use of the quasi-three-dimensional model did not significantly improve calibration.

An equivalent porous medium is assumed for the fractured dolomite, a reasonable assumption in view of the regional scale of the problem and the intensity of the fractures (Mullens, 1964). For example, in dolomite in eastern Wisconsin having similar fracture intensity to the rocks at Shullsburg, LaPoint and Hudson (1985) measured frequencies of between 0.3 and 1.1 fractures per meter of horizontal scan line. The smallest cell in the Shullsburg model is 250,000 ft^2; a node of this area would thus contain several thousand fractures. The assumption of equivalent porous medium has been used with success in numerical models of flow through other carbonate aquifers in the region (Bradbury, 1982; Winter *et al.,* 1983; Krohelski, 1986; Young *et al.,* 1986; Emmons, 1987).

The model is a saturated ground-water flow model, and thus does not include saturated/unsaturated wetting phenomena. While hysteresis effects might make recovery slower than drawdown, the fractures and mine drifts in the Shullsburg area are large enough that these effects should be minor on the scale of this model. This assumption affects the calibration to the storage coefficient in the recovery period, but not the recovery rate of the model since measured head data were used for recovery calibration.

In addition, the model assumes that Holt's premining water-table map and the potentiometric map for the St. Peter Sandstone represent steady-state conditions, and that the heads in the St. Peter and associated sandstones (several thousand feet of sediments) will be unaffected by hydrologic stress in the Sinnipee aquifer. There are only half a dozen water-level measurements reported in the St. Peter Sandstone during mining, but they are not consistently lower than the measurements made after the mines closed.

RESULTS

Model Calibration

The goal of model calibration was to find a set of parameters that would allow the model to reproduce field data, including both hydraulic head and boundary fluxes, during three different time periods. There is no point in time-stepping from one period to another, then on to future time periods, without first finding a match between modeled meads and measured heads at each available time period. Thus, the goal of this study was not to try to verify the calibration with the additional head data, but instead to use it to calibrate unmeasured parameters.

The model was calibrated by varying hydraulic conductivity, recharge, anisotropy, and specific storage until simulated heads and simulated flows agreed as nearly as possible with field data. Because the comparison was between maps rather than data points (owing to lack of historic records) and because the model simulates three different time periods, the fits are qualitative. Parameters used in the best-fit calibration are summarized in Table 1. While better matches might be obtained by varying parameters in more detail, calibration where there is no hydrogeologic data is somewhat arbitrary. The goal was not to obtain close reproduction of hydraulic heads, but instead to simulate observed gradients, flow directions, and ground-water divides in order to predict the spread of contamination.

The modeled heads for steady state provide a smoothed match to Holt's premining field map (Figure 4): the regional flow pattern and gradients in the model are similar, but stream incisions are not as sharply delineated since discretization causes some smoothing. Furthermore, Holt's map is based on limited data, and may exaggerate the local relief of the potentiometric surface.

Calculating fluxes to specified head and drain cells representing the Shullsburg Branch and the Galena River provides an additional check on the calibration of the steady-state model. These fluxes were compared to base flow calculated from data at stream gages (Table 2). Using the increase in base flow along each reach, and correcting for the topographic drainage area within the model boundaries, the steady-state ground-water discharge along the southwestern model boundary is about 4.6 ft³/sec, and along the northwestern model boundary it is about 2.8 ft³/sec. The simu-

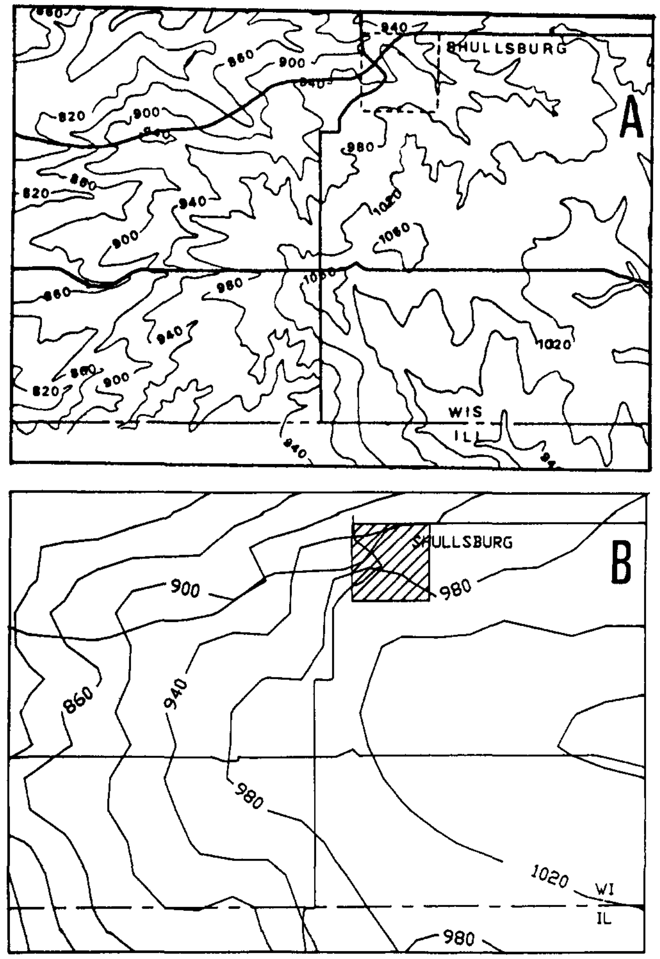

Fig. 4. Measured (A) and modeled (B) potentiometric surfaces of the Sinnipee aquifer prior to mining, 1948 (Holt, 1958). Contour intervals in feet above sea level. Mines are located near the intersection of Highway O and Highway W (Figure 1). Outline of town of Shullsburg gives scale of 1 mile.

Table 2. Flow Calibrations

Parameter	*Reference*	*Measured ft³/sec*	*Modeled ft³/sec*
SW streams	Stedfast, 1979	4.6	5.3
NW streams	Stedfast, 1979	2.8	2.9
Pumping high, measured	Holt, 1958	14	12.9
Pumping high, estimated	Holt, 1958	31	
Pumping ave.	Stedfast, 1979	5 to 8	4

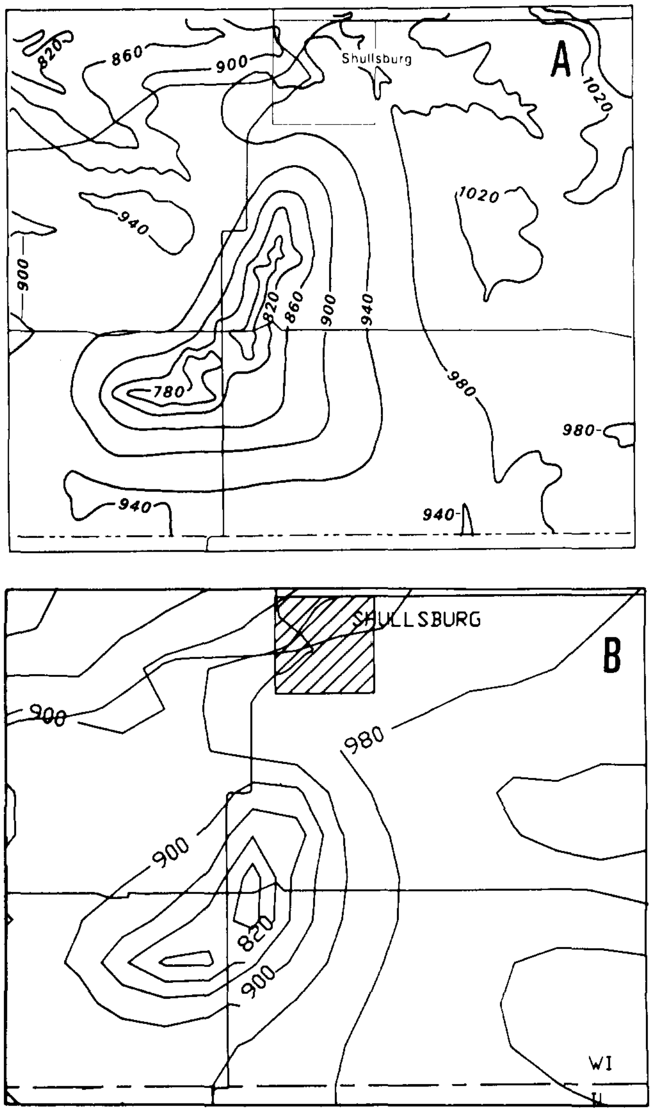

Fig. 5. Measured (A) and modeled (B) potentiometric surfaces of the Sinnipee aquifer during mining, 1958 (Holt, 1958). Contour intervals in feet above sea level. Mines are located near the intersection of Highway O and Highway W (Figure 1). Outline of town of Shullsburg gives scale of 1 mile.

lated base flow is 5.3 ft^3/sec vs 4.6 ft^3/sec calculated for southwestern streams, and simulated base flow in northwestern streams matched measured base flow almost exactly (2.9 vs 2.8 ft^3/sec). The total recharge to the model was 11.9 ft^3/sec vs 11 ft^3/sec calculated from stream fluxes.

The heads from these steady-state runs were used as initial conditions for the drawdown simulation. The drawdown period was matched to Holt's 1958 map, the last made during mining (Figure 5) which shows the Sinnipee aquifer becomes unconfined in the cone of depression. The contours match the steepness and the outer limits of the cone of depression, and the flow pattern of the two maps is generally the same. No adjustment of parameters was needed to obtain a match to the heads around the mines because the boundary conditions in the drains were set up to draw down heads throughout the model.

However, flux to the mine drains was sensitive to S and drain conductance. The final value of S selected was based on calibration to recovery heads, but was consistent with pumping rate data. Drain conductances between 0.25 and 1 ft^2/sec (depending on cell size) provided appropriate high and low pumping rates (Table 2). Order of magnitude shifts in the drain conductance changed the pumping rate less than 1 ft^3/sec. Holt (1958) measured mine dewatering rates up to 14 ft^3/sec and estimated dewatering rates up to 31 ft^3/sec for short periods. In contrast, the single highest dewatering rate predicted by the model is 12.9 ft^3/sec, and the average predicted long-term dewatering rate is about 4 ft^3/sec. This long-term value is in relatively good agreement with mine effluent measurements of 5 to 8 ft^3/sec made by Stedfast (1979) in 1975 during later stages of mine operation. Possibly, Holt measured instantaneous flow, which may not have been continuous over a long time or at night. The time discretization in the model may not accurately reflect these instantaneous values. Alternatively, the drains may underestimate mine dewatering rates. Nonetheless, the drain fluxes create a cone of depression with a similar shape to the one measured.

Simulated heads during the recovery period were compared to the map of the potentiometric surface made in 1983, four years after the mines closed. This time period was the most sensitive to the remaining calibration parameter, S. With the model calibrated only to the 1958 map, the 1983 modeled heads in the remnant cone of depression could vary from 40 ft lower to 40 ft higher than 1983 field measurements, using S values of 0.1 to 0.01. The best fit (Figure 6) was obtained for an S of 0.02, a value toward the low end of values typical of unconfined aquifers. This may not be the true S of the Sinnipee aquifer, but merely a calibration value for the two-dimensional model. However, values of S measured in similar dolomite in eastern Wisconsin have been as low as 0.002 (Sherrill, 1978).

Simulated water-level changes for a local monitoring well (LF57) shows dewatering and recovery trends parallel to field measurements available from 1950 to 1983 (Figure 7). The well is in the area influenced by mine dewatering (Figure 1), near the edge of the cone of depression. The modeled water levels for LF57 are averaged over a 1000 by 1000 ft block, so some smoothing of the water-level fluctuation is expected.

Verification was not provided by having three

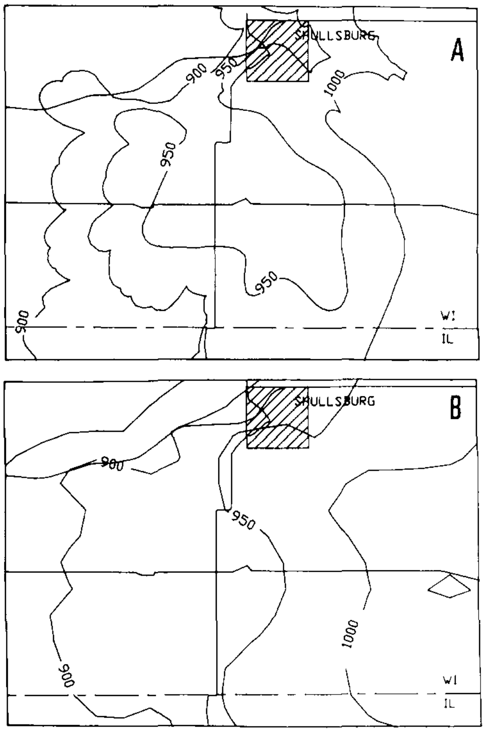

Fig. 6. Measured (A) and modeled (B) potentiometric surfaces of the Sinnipee aquifer post-mining, 1983 (Toran and Bradbury, 1985). Contour intervals in feet above sea level. Mines are located near the intersection of Highway O and Highway W (Figure 1). Outline of town of Shullsburg gives scale of 1 mile.

different time periods, but rather all three provided a point of calibration. Steady-state heads provided base flow calibration, R/K ratio, and anisotropy. The drawdown period provided pumping rate calibration for the drain conductances. The recovery period was sensitive to S.

The important point to note is that predictive modeling depends on matching both drawdown and recovery periods. The calibration during recovery is needed to help justify predictions about future water levels in the Shullsburg area. Without calibration to the recovery period the recovery rate can vary widely depending on the value of S. While S can be measured in pumping tests, it is a difficult parameter to measure accurately. Predictions carry along uncertainty of parameters and the inadequacies of calibration, and a steady-state or drawdown calibration alone is not necessarily adequate for predicting recovery. The difficulties reported here in matching both drawdown and recovery periods should be a warning to modelers with more limited data sets.

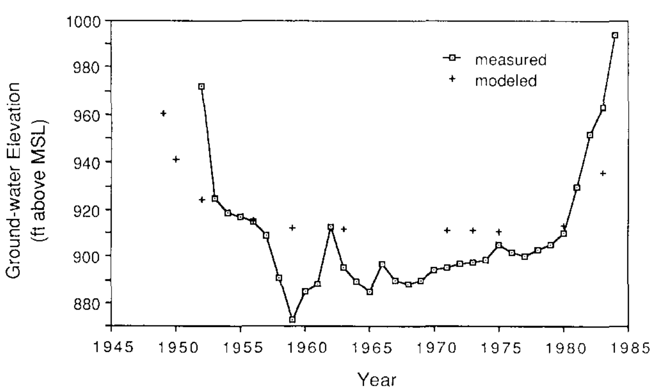

Fig. 7. Measured and modeled ground-water elevation in monitor well LF57 (see Figure 1 for location).

Predictions

The questions of future concern are: (1) What is the potential for contamination of the St. Peter aquifer beneath the mines? (2) When will ground water begin moving laterally in the Sinnipee aquifer away from the contaminated zone around the mine workings, and how long will radial flow persist? (3) Will mining create permanent changes in the potentiometric surface?

(1) Even using a relatively high conductivity (K_Z) in the Glenwood Shale, little water enters the St. Peter aquifer through the general head boundary. Over the 100 years of the recovery simulation, the total amount of simulated downward leakage to the St. Peter is less than 50,000 ft^3, or less than 0.1 ft^3/day. Chemical sampling of water from the St. Peter aquifer shows sulfate concentrations around 0.1 mmol/l as opposed to $>$ 10 mmol/l in nearby wells in the contaminated Sinnipee aquifer (Toran, 1986). The only wells with higher sulfate in the St. Peter have been adjacent to wells open to both formations, creating a conduit for contamination. Thus, contamination of the St. Peter aquifer would require a physical break in the Glenwood Shale.

(2) The model predicts that radial flow toward the mines should persist until about 1988. However, water should begin moving away from the contaminated zone around the mines between 1985 and 1988.

(3) One might expect the hydraulic conductivity in and around the mines to increase due to mining (Booth, 1986). The sensitivity to long-term change in the aquifer due to the creation of the mine drifts and the lack of drift reclamation is tested in the model by increasing the hydraulic conductivity of the mine nodes by two orders of magnitude (to 0.54 ft/sec). This increased hydraulic conductivity has little effect on the modeled heads at steady state. In fact, the steady-state potentiometric surface for recovery, shortly after model year 2030, is identical to the premining steady state. Thus, *on a regional scale,* the Shullsburg mines will not cause a permanent change in the

hydrogeologic system, and the system will eventually return to steady state in a premining configuration.

DISCUSSION

Implications for the Shullsburg Area

Sulfate contamination in the Shullsburg area has been localized because ground water flows toward the mines to fill the cone of depression. Modeling indicates radial flow will persist until approximately 1988. The use of this model in the predictive mode depends on calibration to premining, drawdown, and recovery periods.

The persistence of a cone of depression at present and in the future allows uncontaminated water from surrounding areas to dilute the sulfate. Evidence for dilution has already been observed as a recent decline in sulfate near the mines to less than 10 mmol/l in all wells (Toran, 1987). Some of this water is still above the drinking-water standard, but continued dilution may occur. Dilution is important, because when flow directions reverse and flow is away from the mines, the spread of sulfate will not lead to further well-closings.

The modeling shows that fluxes to the St. Peter aquifer are low which confirms evidence from chemical sampling that sulfate concentrations in this aquifer have remained low with few exceptions. The St. Peter aquifer is safeguarded provided there are no physical breaches in the Glenwood Shale by fractures or wells open to both formations.

The prognosis for dissipation of contamination must be qualified by warnings of potential future problems: (1) any undissolved sulfate present above the water table could act as a new source; (2) the tailings piles around the mines could leach additional sulfate; and (3) a breach in the Glenwood Shale could threaten the St. Peter aquifer locally. Although mining will not necessarily lead to long-term contamination in the Shullsburg area, recovery here depended on the physical hydrology. The extent and duration of the cone of depression was sufficient to dilute contaminants to a safe level. Ground-water flow modeling helped to describe the physical hydrology, but an understanding of the problem also depended on measurement of the past and present chemistry.

Implications for Other Mine Models

Hydrogeologists, mining engineers, and regulatory officials who use numerical ground-water models in assessing the impacts of underground mining on ground-water resources commonly are interested in predicting three aspects of mine hydrogeology: dewatering rates, drawdowns, and absolute hydraulic heads. In most circumstances these predictions cannot be checked because they refer to future events. The Shullsburg mine example provides an opportunity to assess the accuracy of a predictive model because most mining impacts at Shullsburg are already well-known. Obviously, recent observations since mining ceased have influenced both the conceptual and numerical model described here; thus, this study differs from the more usual one of modelers who predict future mining impacts based solely on base line data. Nevertheless, this study examines the ability to predict the three variables listed above, gives some measure of the viability of this and similar models, and suggests model limitations.

The use of drain nodes in this model generally underestimates absolute mine dewatering rates in the short term. Head and drawdown patterns for dewatering and recovery can be simulated, and absolute head values match with fair accuracy. Much of the differences between modeled and measured values can be attributed to the assumption of two-dimensional flow and the coarse time and space discretization. However, the methods here are not atypical of model discretization (owing to limitations in running time and file size), and the errors to be expected can be seen by examining the maps shown in this paper. For the purposes discussed here, these differences did not prohibit use of the model to make an estimate of future recovery rates.

In summary, a relatively simple ground-water model based on a widely available finite-difference code simulates ground-water changes associated with the development and abandonment of underground mines. On the regional scale of this model, the assumption of equivalent porous media for fractured rock and mine workings was adequate for model calibration. While the simulations and predictions of this model are not abolutely accurate, they may be accurate enough to be of use to mine planners and regulatory officials who need to make decisions regarding mine operations and ground-water quality.

However, the method of creating a boundary condition in the mine workings for the drawdown period made it necessary to have a recovery period for calibration and prediction of future heads. The availability of data collected before, during, and after mining demonstrates the errors associated with assuming two-dimensional flow and the uncertainty in model predictions when a model is calibrated to just one or two of these points in time.

ACKNOWLEDGMENTS

This research was supported by the Wisconsin Water Resources Center and the U.S. Geological Survey as authorized by the Water Resources Research Act of 1984, by the Wisconsin Geological and Natural History Survey, and by the University of Wisconsin graduate school fellowship program.

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