DIGITAL MODEL ANALYSIS OF THE EFFECTS OF STRIP MINING FOR COAL ON LOCALIZED GROUND-WATER FLOW SYSTEMS IN EASTERN OHIO

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by
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INTRODUCTION

The increasing use of coal as an energy source has prompted the need for a better understanding of the effects of strip mining for coal on ground-water flow in the associated rocks. The U. S. Bureau of Mines has sponsored a detailed investigation of the hydrology of several small watersheds mined for experimental purposes in eastern Ohio (U. S. Bureau of Mines, 1978, 1982). The study began before mining and continued during mining and reclamation. The U. S. Geological Survey has investigated the ground-water components of the system and has reported on premining and during mining conditions (Helgesen and Weiss, 1978; Helgesen and Razem, 1980, 1981). This report describes the results of the postmining investigation, and makes comparisons with premining systems for the experimental watershed in Muskingum County. The data presented herein are part of the data collected in the overall investigation, all of which is not duplicated in this report. The interested reader is referred to the annual data reports of the U. S. Geological Survey (1976-81).

Digital ground-water flow models have been used extensively during this study. The models have helped determine values of hydraulic properties, identified the sensitivity of input parameters, and provided quantitative descriptions of the ground-water budget. The first section
of this report presents a synopsis of the premining investigation and is largely compiled from the existing literature. However, insights gained during the postmining analysis indicated modifications were necessary to the premining model. The simulation used in this report for final comparisons has not before been presented in the literature. The second section of this report describes postmining conditions and the postmining model. Comparisons of the premining and postmining model budgets are made in the third section, and allow a quantitative analysis of the effects of mining on the flow systems. Ground-water chemical data are utilized in this section in support of the flow concepts presented.

This report is intended as a description of the effects of strip mining on the ground-water hydrology of the study watershed. The results pertain only to this study area and do not necessarily apply to all strip-mined areas. However, the principles described herein have widespread application, because the effects of mining under similar conditions can be ascertained, and the consequences of mining activities in general can be better understood.
I. PREMINING GROUND-WATER CONDITIONS

A. GEOLOGY

The study area is in Muskingum County in eastern Ohio (fig. 1). The experimental watershed covered 43 acres prior to mining in the unglaciated region of the Appalachian Plateau province. Stratified sedimentary rocks of the Pennsylvanian System occur near the surface of the watershed and consist predominantly of interbedded limestone, shale, sandstone, and several coal seams. The rock sequence indicates a shallow marine and shoreline depositional environment. Crustal uplifting has caused fracturing of the rocks and has created a gentle regional dip towards the southeast. Erosional processes have created the hilly topography characteristic of this region today.

The generalized lithology and approximate thickness of the near-surface section is shown in figure 2. The highest part of the section in the watershed is part of the Monongahela Formation and includes two major coal beds. The Meigs Creek (Sewickley) No. 9 coal seam outcrops about midway down the watershed and was mined during the course of this study (fig. 3). The Pittsburgh No. 8 coal seam outcrops just below the mouth of the watershed and was left undisturbed during this study. Rocks of the Conemaugh Formation occur below the No. 8 coal bed and are near the
Figure 1.---Location of study watershed (adapted from Helgesen and Razem, 1980).
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Figure 2.—Stratigraphic column (from U.S. Bureau of Mines, 1978).
Figure 3.—Top aquifer premining potentiometric surface map (modified from U.S. Bureau of Mines, 1978).
surface at the mouth of the watershed. Several feet of weathered rock and soil cover the bedrock over almost the entire area.

B. PREMINING HYDROLOGY

Ground water within the study watershed is stored and transmitted within intergranular pore spaces, through fractures, and along bedding planes of the bedrock. Relatively impermeable underclay beneath the two major coal seams impedes the vertical movement of water. Each of the underclays forms a base for a perched zone, creating three separate saturated zones (fig. 4). The saturated zones are referred to as aquifers, although they yield very small quantities of water to wells. The top aquifer occurs above the clay underlying the Meigs Creek No. 9 coal bed. The middle aquifer occurs above the clay underlying the Pittsburgh No. 8 coal bed. The deep aquifer is part of a regional flow system larger than the confines of this study area.

Observation wells were installed into each of the three aquifers. The wells were cased so that each was open to only one aquifer. The wells are identified by a letter and a
EXPLANATION

B—B' Cross section
Coal
Saturated zone
Direction of water movement

Figure 4.—Cross-section illustrating ground-water occurrence and flow (from U.S. Bureau of Mines, 1978).
two-digit hyphenated number. The letter indicates the phase of the study during which the well was installed ("W" indicates premining; "P" indicates postmining). The first digit of the hyphenated number is a sequence number. The second digit refers to the aquifer into which the well was completed ("1" refers to the top aquifer; "2" refers to the middle aquifer; and "3" refers to the deep aquifer). The locations of the wells are shown on the potentiometric surface maps for respective sections of this report (figs. 3, 5, 11, and 15).

The configuration of the potentiometric surface of the top aquifer shows that the top aquifer ground-water divide coincides with the surface drainage divide (fig. 3). Recharge of the top aquifer occurs by infiltration of precipitation within the watershed. Discharge occurs laterally as springflow where the underclay intersects the land surface, as downward leakage through the underlying clay to the middle aquifer, and by evapotranspiration. The middle aquifer receives recharge as leakage from the top aquifer and by precipitation where the aquifer is exposed to the atmosphere. Springflow from the top aquifer also provides recharge by seepage where it crosses the middle aquifer unsaturated zone. Discharge from the middle aquifer occurs laterally as base-flow to the stream, by downward leakage through the underlying clay to the deep aquifer, and by evapotranspiration. In addition, underflow
passes across the middle aquifer from the western to the eastern boundary, as illustrated by arrows on the middle aquifer potentiometric surface map (fig. 5). This occurrence has created a ground-water divide in the middle aquifer in the southeast portion of the watershed, separating flow towards the stream from underflow leaving the watershed.

The deep aquifer receives some recharge as leakage from the middle aquifer but most of its recharge and discharge occurs outside of this watershed.

C. MODEL DEVELOPMENT

The numerical model used for simulation of the ground-water flow systems is a modified version (Helgesen and others, 1982) of the U.S. Geological Survey's three-dimensional finite difference model described by Trescott (1975) and Trescott and Larson (1976). Horizontal flow within the confining beds was considered negligible, thereby allowing usage of the quasi three-dimensional option. The model simulates horizontal flow within each layer, and vertical flow between layers by leakage through the confining beds.
Figure 5.—Middle aquifer premining potentiometric surface map (from U.S. Bureau of Mines, 1978).
The original version of the model calculates vertical leakage as a function of the head difference between two layers. In the case of perched aquifers, as found in the study watershed, the rate of leakage should be calculated using the head difference between the upper layer water table and the bottom of the confining bed. This modification was necessary for simulating leakage from the upper to the middle layer. The bottom layer is included in the model as a sink bed for receiving downward leakage, and was properly simulated by setting it at a constant head equal to the elevation of the overlying confining bed.

The original version of the model only allows the upper layer to be input as a water-table unit. The model calculates transmissivity for the water-table unit by multiplying the hydraulic conductivity times the saturated thickness. However, water-table conditions also exist in the middle and deep layers. Since the water-level fluctuations of the middle and deep layers were considered minor relative to their saturated thickness, only a negligible change in the transmissivity would occur. It was therefore determined unnecessary to further modify the model for simulating water-table conditions in each layer.

The original version of the model only allowed recharge by precipitation to the top layer. However, recharge by this mechanism also occurs where the middle layer is exposed. A modification was therefore necessary to allow the
application of recharge to any layer.

Additional improvements from the original model were found necessary for implementation of a head-dependent function for simulating springflow and streamflow, and for calculating water budgets for each layer. The necessary modifications and computer listing for proper simulation of hydrologic conditions at the study watershed are presented and described in further detail by Helgesen and others (1982).

D. MODEL CONSTRUCTION

A uniform grid of 23 rows and 15 columns with 100-foot spacing was overlain on a plan view of the study watershed (fig. 6). The schematic diagram (fig. 7) illustrates the various components of the model. The stream and springs were incorporated at each grid block for the corresponding layer in which they were located in the field. Constant head boundary conditions were assigned to portions of the east and west boundaries of the middle layer for simulating underflow across the the watershed. The entire bottom layer was set at constant heads equal to the elevation of the
Figure 6.—Premining model grid.

S: spring node
R: river node
Figure 7.—Schematic diagram of components of ground-water flow model (from U.S. Bureau of Mines, 1978).
bottom of the overlying clay.

Aquifer tests in the watershed indicated a fairly uniform hydraulic conductivity between and within layers. Best steady-state simulations were performed using a hydraulic conductivity of 3.5 \times 10^{-7} \text{ ft/s}, which is in agreement with the field test results. Representative transmissivity values required for the other layers were hand-calculated by multiplying hydraulic conductivity times the saturated thickness at each grid block.

Confining bed leakance is required input when using the quasi three-dimensional model, and is equal to the vertical hydraulic conductivity of the confining bed divided by its thickness (Lohman, 1972). Underclay leakance was determined from the model during calibration and was given a uniform value within each layer but varied for each layer as a function of lithology and thickness. Best simulations indicated a top layer underclay leakance of 8.1 \times 10^{-10} / \text{s} and a middle layer underclay leakance of 2.5 \times 10^{-10} / \text{s}. These values are within the range of laboratory determinations (George Hall, written commun., 1980).

A recharge rate of 7 inches/yr was assigned to the top layer and to the exposed portions of the middle layer. This value was based primarily on long-term percolation data from lysimeter measurements on similar soils in eastern Ohio, and from climatological data from an on-site weather station (U. S. Department of Agriculture, written commun., 1978).
E. MODEL BUDGET

The hydrologic budget for the study watershed for premining conditions, as determined by steady-state model simulation, is shown in figure 8. The slight discrepancy in the budget balance is due to computer round-off error and is considered insignificant. Evapotranspiration has been estimated to be a negligible component of the overall ground-water budget at this watershed. However, some water is lost by evapotranspiration at the zone of springs in the top aquifer and near the stream in the middle aquifer.

The amount of water discharged from the top and middle aquifers by downward leakage greatly exceeds the amounts discharged laterally by springflow and streamflow. The top aquifer, which receives all of its recharge from precipitation, discharges 85 percent of its water by downward leakage and 15 percent as springflow.

The middle aquifer receives recharge from several sources. Leakage from the top aquifer accounts for 66 percent of the recharge; 30 percent occurs from precipitation where the middle aquifer is exposed; and 4 percent occurs as regional underflow entering the western boundary of the watershed. Of the total recharge waters, 83 percent is discharged as downward leakage to the deep aquifer; 10 percent contributes to stream base-flow; and 6 percent leaves the eastern boundary of the watershed as
Top layer

- Recharge from precipitation: 0.0305 ft$^3$/s
- Discharge as downward leakage: 0.0260
- Discharge laterally to springs: 0.0045

Middle layer

- Recharge from precipitation: 0.0116
- Recharge from leakage above: 0.0260
- Recharge from regional underflow: 0.0017
- Discharge as downward leakage: 0.0327
- Discharge laterally to streams: 0.0040
- Discharge as regional underflow: 0.0025

Figure 8.-- Premining model budget.
regional underflow. The underflow out of the middle aquifer was 47 percent greater than underflow into the watershed, indicating a net deficit of water into the middle aquifer flow system.

A budget for the deep aquifer was not determined because it encompasses flow components not included in this study.
II. POSTMINING GROUND-WATER CONDITIONS

A. MINING AND RECLAMATION

Mining started at the watershed in January 1977 by the contour-area surface mining technique and is described by the U. S. Bureau of Mines (1982) and Helgesen and Razem (1981). Mining of the Meigs Creek (Sewickley) No. 9 coal bed began along the coal outcrop and proceeded towards the watershed divide. After topsoil removal and blasting, overburden materials were removed and placed downslope (fig. 9). As stripping operations continued, the position of the highwall migrated and additional ridges of overburden materials were formed with continuing mining. The mining operations totally disrupted the top aquifer supported on the coal underclay. Although not intended, the underclay was probably disturbed during blasting, by exposure to the atmosphere for extended periods of time, and by scraping of minor quantities during mining. Reclamation included grading of spoils, replacement of topsoil, and seeding for revegetation.

When reclamation was completed in September 1978 the watershed had a changed shape (fig. 10) and had been reduced in size by 15 percent to 37 acres. An additional portion of the top aquifer was constructed over areas where the middle aquifer had previously been exposed. This area amounts to
Figure 9.—Schematic sections illustrating strip-mining process (from Helgesen and Razem, 1981).
Figure 10.—Postmining watershed boundaries.
approximately the same amount of area that the entire watershed lost. Therefore, the size reduction of the watershed was largely at the expense of the exposed area of the middle aquifer. In addition, the surface relief was reduced by 37 percent from 233 feet to 146 feet, the stream channel length was reduced by more than 60 percent to 700 feet, and the springs were reduced to a zone of seeps.

B. POSTMINING HYDROLOGY

Mining and reclamation of the study watershed has changed the hydrologic characteristics of the top aquifer. As in premining conditions, the configuration of the potentiometric surface (fig. 11) indicates that the top aquifer ground-water divide coincides with the surface drainage divide, and all recharge occurs by percolation of precipitation. Comparison with the premining potentiometric surface map for the top aquifer (fig. 3) reveals that the water levels are at a much lower elevation than before mining. Resaturation of the spoils has proceeded slowly and is attributed to several factors: (1) increased hydraulic conductivity, (2) discontinuity of the underclay confining
Figure 11. -- Top aquifer postmining potentiometric surface map.
bed, (3) decreased recharge rate from precipitation, and (4) increased storage coefficient.

Alteration of the top aquifer from a consolidated overburden to unconsolidated spoil material has greatly increased the hydraulic conductivity. Aquifer tests in the spoils were performed by the slug-test method described by Cooper and others (1967). The tests indicate hydraulic conductivity values of $3.7 \times 10^{-6}$ ft/s at well P3-1, and $6.2 \times 10^{-5}$ ft/s at well P13-1. The values show considerable areal variability and indicate an increase since mining of more than two orders of magnitude. Variability in the texture of the spoils was also noticed during drilling of the postmining wells. Boulders and cobbles were encountered in the upper reaches of the watershed at well P12-1. The void spaces among this coarse material contributed to a higher hydraulic conductivity. In other areas, as at well P14-1, the spoils exhibited a much smaller grain size and have a lower hydraulic conductivity.

During reclamation, spoil material was laid directly on top of a portion of the premining land surface of the middle aquifer and covers an area that was previously exposed (fig 9). Hydrographs of paired wells (fig. 12) in the newly constructed area illustrate that an unsaturated zone still exists between the top and middle aquifers. The compacted topsoil of the old land surface acts as a confining bed in this area. However, the confining bed leakance is higher.
Figure 12.—Water-level hydrographs for top and middle aquifers.
than where the underclay still exists and allows an increase in vertical flow. Ground water previously discharged as springs is intercepted as leakage into the middle aquifer, thereby reducing the springs to a zone of seeps. In addition, disturbance of the underclay above the middle aquifer probably changed the leakance properties unevenly across the watershed.

A decrease in the recharge rate also contributed to lower top aquifer water levels. This was caused by a lack of vegetation and soil structure, and is responsible for lower stream base-flow and higher surface runoff volumes. The flow-duration curve illustrates the frequency of occurrence of different rates of flow. Flow-duration curves for the study watershed for the years 1977 through 1980 are presented in figure 13. The lower end of the duration curves indicates the general characteristics of the shallow ground-water bodies in the drainage basin (Cross and Hedges, 1959). The curves show a trend since mining toward lower base-flows, despite a general increase in precipitation throughout the period, and indicate a reduction in recharge to the ground-water system. This occurrence is similar to that described for a watershed in eastern Kentucky by Collier and others (1970). They described the spoil banks in their study area as having a relatively impervious clayey cover with little vegetation. The material offers little capacity for ground-water storage, contributes little to
Figure 13.--Flow-duration curves and precipitation (from U.S. Dept. of Agriculture, written commun., 1981).
long-term base-flow, and reduces the recharge of more porous materials at underlying levels. However, this is not the case in all strip-mined areas, as Grubb and Ryder (1972) describe higher base-flow levels at a watershed subjected to strip mining in western Kentucky. The type of overburden material, the degree of reclamation, and the length of time since mining are probably the important factors influencing the recharge rate. The recharge characteristics in the study watershed should change with continued vegetative growth and soil structure development, and might influence future hydrologic conditions.

Reliable quantitative information concerning the storage coefficient is generally unobtainable from aquifer testing by the slug-test method (Cooper and others, 1967). Transformation of the bedrock overburden to unconsolidated spoil material should increase the storage properties of the aquifer. The actual increase will depend largely upon the degree of fractures in the overburden before mining and the clay content of the spoil material. An increase in the storage coefficient will require larger volumes of water in order to reach the premining water-level elevation.

The middle aquifer has also shown some hydrologic changes, although not as pronounced as in the top aquifer. Well W5-2, which was not destroyed during mining, provides a continuous water-level record in the middle aquifer and indicates a rise during mining of approximately five feet
(fig. 14). The well is located downgradient of the area where the underclay is absent, and the rise is attributed to higher leakage. Although no continuous water-level record exists upgradient of the high leakance area, the water levels probably would have shown a decline due to lower leakage associated with the lower hydraulic head in the top aquifer. The middle aquifer potentiometric surface map (fig. 15) reflects this occurrence by the migration of the groundwater divide on the eastern side of the watershed. Comparison with the premining middle aquifer potentiometric surface map (fig. 5) indicates that the divide has shifted towards the "high leakance zone", and away from the area underlying lowered top aquifer hydraulic heads. Shifting of the potentiometric surface in the middle aquifer is not prominent on the west side of the watershed, and is attributed to the underflow entering the watershed from the west and subsequently balancing the deficit in leakage.

The deep aquifer has shown no discernible effects due to mining during this study. Well W10-3 (fig. 14), also undisturbed during mining, provides a continuous water-level record in the deep aquifer and indicates that no significant changes have occurred which can be attributed to the mining operations.
Figure 14.—Water-level hydrographs for middle and deep aquifers.
Figure 15.—Middle aquifer postmining potentiometric surface map.
C. MODEL DEVELOPMENT

The numerical model developed for simulating premining conditions was adapted for postmining conditions by making an additional modification. Model modifications made by Helgesen and others (1982) define the BOTTOM array as the altitude of the bottom of the confining bed, and utilizes it in two separate calculations. First, the middle layer is not fully saturated and the leakage it receives is a function of the head difference between the upper layer water table and the bottom of the underclay confining bed. In addition, the upper layer is unconfined and the transmissivity is calculated using the same head difference. This creates a potential source of error since the transmissivity should be calculated using the head difference between the upper layer water table and the top of the underclay. In premining conditions the underclay is thin compared to the upper layer saturated thickness and the error introduced is negligible. However, in postmining conditions the saturated thickness is greatly reduced and the error becomes significant. As an example, if the confining bed thickness is four feet and the upper layer saturated thickness is four feet, then the transmissivity is mistakenly doubled. It was therefore necessary to include an additional array to input the altitude of the top of the confining bed, or equivalently, the bottom of the water-table unit. This new array, called
TOP, is used for calculating the upper layer transmissivity, while the BOTTOM array is still correctly used for determining leakage between layers.

The necessary modifications to the computer program of Helgesen and others (1982) are listed in the appendix.

D. MODEL CONSTRUCTION

The premining model grid of 23 rows and 15 columns was overlain on the postmining watershed map (fig. 16). Modifications were made to the premining input data to simulate the new watershed shape. New locations were specified for the springs and stream, as identified in the field. Boundary conditions were left the same as for the premining model. Modifications to the input data were made to reflect the top layer changes in (1) hydraulic conductivity, (2) underclay leakance, and (3) recharge from precipitation. These parameters were interchanged until a close match against field measurements was achieved. Leakance and recharge proved to be the more sensitive parameters during model calibration.

Two zones of top layer hydraulic conductivity were
Figure 16.—Postmining model grid.
implemented to reflect the variable nature of the spoils. The upper portion of the watershed was assigned a value of $7 \times 10^{-5}$ ft/s, while $3.5 \times 10^{-6}$ ft/s was assigned to the lower portion (fig. 17). These represent increases since premining of 200 and 10 times, respectively, and closely approximate the results of the postmining slug tests.

Two zones of confining bed leakance were used in the best steady-state simulation (fig. 17). A value of $8.1 \times 10^{-10}$ /s was used for leakance where the underclay occurs between the top and middle layers, and is identical to the value used for premining conditions. Although this value might be higher in places due to underclay disturbance, not enough field evidence exists to support these changes. A value of $2.43 \times 10^{-9}$ /s was used where the underclay does not exist between the two layers, which amounts to three times the premining leakance value. The high leakance zone underlies approximately 15 percent of the top layer.

Model simulations indicate a decrease in the recharge rate from precipitation to the top layer on the order of one to two inches. The final calibration was performed using a recharge rate of 5.5 inches/yr, which amounts to a decrease since mining of approximately 20 percent. Precipitation increased during the project period (fig. 13), and under conditions similar to 1976 the recharge to the top layer from precipitation probably would have shown a greater decrease.
Figure 17.—Postmining distribution of top aquifer hydraulic conductivity (K) and confining bed leakage (TK).
All other hydrologic properties remained unchanged by mining and reclamation, and were input identical to the premining conditions.

E. MODEL BUDGET

The hydrologic budget for the study watershed for postmining conditions, as determined by steady-state model simulation, is shown in figure 18. Evapotranspiration is still considered to be a negligible component of the overall ground-water budget at this watershed. However, some water is lost by evapotranspiration at the zone of springs and seeps in the top aquifer and near the stream in the middle aquifer.

As in premining conditions, the amount of water discharged from the top and middle aquifers by downward leakage greatly exceeds the amounts discharged laterally by springflow and streamflow. The top aquifer, which receives all of its recharge from precipitation, discharges 93 percent of its water by downward leakage and only 7 percent as springflow. The value for downward leakage is a combined total for leakage through the underclay and for leakage where the underclay does not exist.
**Top layer**

- Recharge from precipitation: \(0.0218\ ft^3/s\)
- Discharge as downward leakage: \(0.0203\ ft^3/s\)
- Discharge laterally to seeps: \(0.0015\ ft^3/s\)

**Middle layer**

- Recharge from precipitation: \(0.0056\ ft^3/s\)
- Recharge from leakage above: \(0.0203\ ft^3/s\)
- Recharge from regional underflow: \(0.0037\ ft^3/s\)
- Discharge as downward leakage: \(0.0248\ ft^3/s\)
- Discharge laterally to streams: \(0.0027\ ft^3/s\)
- Discharge as regional underflow: \(0.0020\ ft^3/s\)

---

Figure 18.-- Postmining model budget.
The middle aquifer receives recharge from several sources. Leakage from the top aquifer accounts for 69 percent of the recharge; 19 percent occurs from precipitation where the middle aquifer is exposed; and 12 percent occurs as regional underflow entering the western boundary of the watershed. Of the total recharge waters, 84 percent is discharged as downward leakage to the deep aquifer; 9 percent contributes to stream base-flow; and 7 percent leaves the eastern boundary of the watershed as regional underflow. The underflow into the middle aquifer was 85 percent greater than underflow out of the watershed, indicating a net gain of water into the middle aquifer flow system.

Similar to the premining analysis, a budget for the deep aquifer was not determined because it encompasses flow components not included in this study.
III. COMPARISON OF PREMINING AND POSTMINING SYSTEMS

A. MODEL BUDGETS

Comparison of the premining and postmining budgets permits a quantitative description of the effects of mining on the ground-water flow systems. Total recharge to the top aquifer was reduced by 29 percent. This is mostly due to the decrease in the recharge rate but also partly due to the reduction in surface area of the top aquifer. Discharge from the top aquifer by downward leakage into the middle aquifer was reduced by 22 percent. In the upper reaches of the watershed, where the underclay occurs between the two aquifers, the leakance is identical to premining conditions. However, the downward leakage is greatly reduced because of the lower driving force associated with a lower hydraulic head in the top aquifer. In the area where the underclay does not occur between the top and middle aquifers, the confining bed leakance is much higher. In this area, horizontal flow previously discharged as springs becomes intercepted as downward leakage. Consequently, the volume of water discharged laterally was reduced by 67 percent, the springs were transformed to a zone of seeps, and the volume of downward leakage has increased. However, when combined with the reduction in leakage over the rest of the top aquifer, a net reduction in downward leakage still occurs.
Despite this overall volume reduction, the percentage of the total discharge from the top aquifer occurring by leakage has increased since mining. If the top aquifer was reconstructed such that the occurrence of underclay was maintained between aquifers, then the total leakage to the middle aquifer would be reduced by a greater amount. Springflow would not have experienced as much of a reduction, but still would show a decline due to a reduced recharge rate and a lower hydraulic head in the top aquifer.

Total recharge to the middle aquifer from all sources was reduced by 25 percent. This incorporates a 22 percent reduction in recharge occurring as downward leakage from the top aquifer, and a 52 percent reduction in recharge occurring by precipitation. Because the middle aquifer recharge rate did not change as a result of mining, the latter reduction is entirely attributed to the decrease in the exposed area of the middle aquifer. The reduced recharge has induced additional underflow into the watershed from the western boundary. Recharge by underflow into the middle aquifer has more than doubled since mining. This has caused very little water-level difference north of the high leakage zone on the western side of the watershed, as indicated by comparison of observed postmining water levels with computer-generated premining water levels. The additional underflow could only balance part of the deficit.
from other recharge sources, and a reduction in total recharge still occurs. The decreased recharge caused a significant lowering of the water levels north of the high leakance zone on the eastern side of the watershed, also indicated by comparison of observed postmining water levels and computer-generated premining water levels. Consequently, underflow discharge out of the eastern boundary was reduced by 20 percent. These changes in middle aquifer underflow occurrences caused a net gain of water from the regional flow system, in contrast to the net loss of water occurring before mining.

Discharge from the middle aquifer as downward leakage was reduced by 24 percent, and is partly in response to the 15 percent decrease in area of the middle and deep aquifers within the study watershed. In the vicinity of well W5-2, water levels increased after mining, and leakage subsequently increased. However, computer analysis reveals that the water levels declined north of the high leakance zone, and leakage subsequently decreased. The cumulative effect is a net reduction in leakage per unit area. Lateral discharge from the middle aquifer as base-flow showed a reduction of 33 percent. This is partly due to the decrease in the contributing area caused by the shifted ground-water divide in the middle aquifer, and to the distribution of water-level declines in the middle aquifer after mining. Although a 25 percent reduction in total discharge occurred,
the percent discharging by each mechanism was almost identical to the pre-mining conditions. This indicates that the reduction in recharge to the middle aquifer had a proportional influence on all discharge outlets.

Although a detailed budget is not available for the deep aquifer, it is presumed that the reduction in recharge by downward leakage from the middle aquifer is negligible since the deficit can be balanced by additional underflow. This presumption is based on the lack of any significant changes in the observed water levels in the deep aquifer.

B. WATER QUALITY

Trilinear diagrams of water quality have been useful in this study as an aid in understanding the changes in the flow system as a result of mining. As described by Hem (1970), the composition of water with respect to cations is indicated by a point plotted on the lower-left triangle, and the composition with respect to anions by a point plotted on the lower-right triangle (fig. 19). The points are extended into the central diamond-shaped field by projecting them along lines parallel to the upper edges of the central
EXPLANATION

I  Premine top aquifer
II  Premine middle aquifer
III  Postmine top aquifer
IV  Postmine middle aquifer

↑ time

Figure 19.--Trilinear water-quality diagram.
field. The point of intersection of these projections represent the composition of the water with respect to the combination of ions. The resulting plot can be used for indicating similarities and differences in the composition of water from certain geologic and hydrologic units.

Water analyses from several locations in the top and middle aquifers are presented for premining and postmining in figure 18. Repetitive sampling indicated a fairly constant water quality before mining. However, continuation of sampling after mining has indicated changes in water quality with time. Therefore, "time" arrows have been included on the diagram for illustrative purposes.

Prior to mining, water in the top and middle aquifers was of substantially different water types. Water in the top aquifer was a calcium-magnesium bicarbonate type and plots to the left in the central plotting field. Water in the middle aquifer was more variable in nature, but was generally a sodium bicarbonate type and plots in the lower portion of the central plotting field. The abundance of sodium is a result of ion exchange as the water flows through the underclay. A sample from well W11-2, taken from the extreme upper reach of the watershed, plots towards the top aquifer calcium-magnesium bicarbonate zone and suggests a greater proportion of downward leakage. The premining top aquifer water levels were the highest in this part of the watershed and maximum leakage occurred before mining.
After mining, water quality of the top aquifer spoil material showed a considerable change from premining. The water is predominantly a calcium-magnesium sulfate type and has shifted to the upper corner of the central plotting field. This is a result of total disruption of the overburden, thereby exposing more surface area of the rock and leaving it more susceptible to solution, particularly the sulfide minerals.

Water in the middle aquifer changed from sodium-rich to calcium-rich, in addition to sulfate enrichment. The illustration clearly shows the water in the middle aquifer migrating with time towards the water type of the top aquifer, and suggests a greater degree of hydraulic connection between aquifers. The middle aquifer samples from well P11-2 plot directly among the top aquifer postmining samples, and samples from well P9-2 show the same trend. These samples were taken from the area where the underclay doesn't exist between the two aquifers (well locations on fig. 15). Greatest amounts of leakage occurs in this area without being subjected to ion exchange associated with the underclay. Recharge occurred by direct precipitation prior to mining, and was also unaffected by the clay minerals. The water flowing through this area after mining has migrated through the top aquifer and has acquired a water quality characteristic of the spoil material. The difference in the water type of P11-2 and P9-2 is attributed to the variable
nature of the spoils. The samples from wells W5-2 and P5-2a also indicate a shift with time, even though the wells lie in the area of direct recharge from precipitation. This location is immediately downgradient from the high leakance zone, and the recharge from precipitation shows little influence on water type. The samples from well P2-2 are also shifting toward the top aquifer water type, even though they appear to be upgradient of the high leakance zone. Although not apparent by the observation well density or by the mapped contour interval, the computer-generated water levels indicate a localized gradient reversal in the middle aquifer away from the high leakance zone, and explains the water-quality occurrence in the apparent upgradient direction. In addition, the lower head in the top aquifer and subsequent decreased leakage where the underclay does exist, also provides less influence of the clay minerals on the water type at P2-2.

Although the horizontal underflow into the middle aquifer was previously described as showing a substantial increase, the total volume is much less than the vertical leakage component and its significance on water type is not noticed.
SUMMARY

A small watershed in eastern Ohio was mined for experimental purposes in order to determine the hydrologic consequences of strip mining for coal. This report describes the effects on the ground-water components of the hydrologic system by utilizing digital modeling techniques for quantitative analyses.

The premining watershed was characterized by nearly flat-lying sedimentary rocks of the Pennsylvanian System. Clay beds beneath the two major coal seams formed bases for perched zones, creating three separate aquifers. The top aquifer is entirely a local flow system, and recharges and discharges within the study watershed. The middle aquifer is mostly a local flow system, although some underflow passes across the watershed boundaries. The deep aquifer is mostly a regional flow system, although it receives some leakage within the study watershed. Recharge to the ground-water system occurs mainly by infiltration of precipitation to the top aquifer and exposed portions of the middle aquifer. Most of the discharge from the top and middle aquifers occurs by downward leakage to the respective underlying aquifers. A lesser amount of discharge occurs as springflow or streamflow at the intersections of the underclay and land surface.

Mining at the watershed totally disrupted the top
aquifer, and has transformed the bedrock aquifer into spoil material. Water levels in the spoils have stabilized at a much lower elevation than existed before mining. Slow resaturation of the spoil material is attributed to (1) an increased hydraulic conductivity, (2) discontinuity of the underclay confining bed, (3) a decreased recharge rate from precipitation, and (4) an increased storage coefficient. During reclamation, spoil material was laid directly on top of a portion of the middle aquifer and covers an area that was previously exposed. The old land surface acts as the confining bed in this area, thereby creating a high leakance zone. Horizontal flow across this zone becomes intercepted as downward leakage, and reduces the springs to a zone of seeps. Covering of exposed portions of the middle aquifer and lowering of the hydraulic head in the top aquifer has reduced the recharge available to the middle aquifer. This reduction has induced additional underflow into the watershed and limited the underflow leaving the watershed. Reductions also occurred in discharge from the middle aquifer as downward leakage and streamflow.

Analysis of trilinear water-quality diagrams has allowed conclusions that are consistent with the digital flow model. Water in the top and middle aquifers were of different water types before mining. Water in the top aquifer was a calcium-magnesium bicarbonate type, and water in the middle aquifer was a sodium bicarbonate type. The
differences were attributed to ion exchange occurring as water flowed through the underclay separating the two aquifers. Water in the top aquifer changed to a calcium-magnesium sulfate type after mining, as a result of total disruption of the bedrock overburden. The water in the middle aquifer has acquired a water quality similar to the top aquifer water type, and is attributed to several reasons. The leakage in the high leakance zone occurs without flowing through an underclay confining bed. In addition, the decrease in leakage occurring where the underclay still exists has reduced the influence of the clay minerals on the water type of the middle aquifer.

The results of this investigation indicate that strip mining for coal has considerable effects on ground-water flow systems. The most pronounced effects occur in the overburden materials and associated aquifers. However, significant changes can also be noticed in underlying aquifers. The interactive nature of local and regional flow systems suggests that localized mining can also influence ground-water regimes outside of the mined area. Monitoring of ground-water conditions in adjacent watersheds would have provided additional insight into this study. Reclaimed areas are initially lacking in vegetation and soil structure. As these characteristics are susceptible to change, mined areas should be observed for future hydrologic conditions.
REFERENCES


Helgesen, J. O., and Razem, A. C., 1980, Preliminary observation of surface-mine impacts on ground water in two small watersheds in eastern Ohio: Proceedings of
the Symposium on Surface Mining Hydrology, Sedimentology, and Reclamation, University of Kentucky, Lexington, Kentucky, p.351-360.


The following modifications should be made to the computer code presented in Helgesen and others (1982).

**APPENDIX**

Lines to be changed:

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<thead>
<tr>
<th>Line</th>
<th>Original Code</th>
</tr>
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<tr>
<td>100</td>
<td><code>DIMENSION Y(40000), L(33), HEADING(33), NAME(48), INF(2,2), IOFT(9)</code></td>
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<td>230</td>
<td><code>2 *4H TK,4H HX,4H DX2,4H L1C,4H HOND,4H UX1,4H VTY,</code></td>
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<tr>
<td>240</td>
<td><code>34H *4HCONF,4H ININ,4H BE,4H BD,4H HTON,24H &gt;4H R,4H HCHA,</code></td>
</tr>
<tr>
<td>1470</td>
<td><code>3 Y(L(31)),Y(L(32)),Y(L(33)))</code></td>
</tr>
<tr>
<td>1550</td>
<td><code>4 ND,4HIV,X(L(24)),Y(L(33)))</code></td>
</tr>
<tr>
<td>1580</td>
<td><code>24),Y(L(25)),Y(L(33)))</code></td>
</tr>
<tr>
<td>2550</td>
<td><code>1 T+PERM+BOTTOM+ORE+IDL+ELD+IDR+RH+RB+TOP</code></td>
</tr>
<tr>
<td>2690</td>
<td><code>4 IDX(IO+J0+K0)+LX(1)+ELD(1)+IDR(IO+J0+K0)+RH(1)+RC(1)+RB(1)</code></td>
</tr>
<tr>
<td>6940</td>
<td><code>2 IRIV+BOT+TOP</code></td>
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<tr>
<td>10520</td>
<td><code>1+PERM+BOTTOM+ORE+TOP</code></td>
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<tr>
<td>10630</td>
<td><code>2TOK(IP+JP), ORE(IO+J0), TOP(IP+JP)</code></td>
</tr>
<tr>
<td>10800</td>
<td><code>T(I+J+K0)=PERM(I+J)+PHI(I+J+K0)+TOP(I+J)</code></td>
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</tbody>
</table>

Lines to be inserted:

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<tr>
<th>Line</th>
<th>New Code</th>
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<tbody>
<tr>
<td>241</td>
<td><code>44HSGE,4HRTX,4H HGT,4H AGU,4HIFER,4H BOT,4HTON</code></td>
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<tr>
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<td><code>ISU=ISUH1K1</code></td>
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<tr>
<td>942</td>
<td><code>L(33)=ISUM</code></td>
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<tr>
<td>1941</td>
<td><code>CALL ARRAY(Y(L(33)),INF(1,1),IOST(1,1),NAME(43),IRH,BUR)</code></td>
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<tr>
<td>2691</td>
<td><code>TOP(IP+JP)</code></td>
</tr>
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</table>
The following modifications should be made to the Group III array data:

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<th>DATA SET</th>
<th>COLUMNS</th>
<th>FORMAT</th>
<th>VARIABLE</th>
<th>DEFINITION</th>
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</thead>
<tbody>
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<td>1-80</td>
<td>20F4.0</td>
<td>TOP(I,J)</td>
<td>Elevation of top of confining bed (L)</td>
</tr>
<tr>
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<td>1-80</td>
<td>20F4.0</td>
<td>BOTTOM(I,J)</td>
<td>Elevation of bottom of confining bed (L)</td>
</tr>
</tbody>
</table>

Note: These data sets are required input for the uppermost hydrologic unit. Data set 6A is required only when simulating unconfined conditions in the uppermost hydrologic unit. See Appendix B of Helgesen and others (1982) for additional instructions.