REDUCING WATER LEAKAGE INTO UNDERGROUND COAL MINES BY AQUIFER DEWATERING

Schubert, J. P.

ABSTRACT : Based on stratigraphic, structural, hydrogeologic, and mining data collected during a study in central Pennsylvania, a two-dimensional, finite-difference computer model was used to simulate groundwater flow in a sandstone unit (0.3 to 11 m thick) overlying an underground mine, and to evaluate the responses of the flow system and leakage rate into the mine when hypothetical dewatering wells are introduced into the system. Simulation of well dewatering, using 25 wells, showed that negligible reduction in leakage would occur if sandstone permeability was less than 0.30 m/day. When sandstone permeability equalled 3.0 m/day, 25 wells reduced leakage by 2.4 percent.

RESUME : On a utilisé un modèle bidimensionnel, de différences finies, pour simuler l'écoulement d'eau souterraine dans du grès (0,3 a 11 m d'épaisseur) qui recouvre une mine souterraine, et pour évaluer la dépendance du régime et la vitesse de drainance vers la mine, quand des puits hypothétiques de drainage s'introduisent dans le système. Ce modèle se base sur des données minières, hydrogéologiques, structurales y stratigraphiques. La simulation du drainage par puits, utilisant 25 d'entre eux, indique une réduction négligeable de drainance si la perméabilité du grès est inférieure à 0,30 m/jour. Pour des valeurs de 3 m/jour, 25 puits produiraient une réduction de drainance de 2,4 %.

RESUMEN : Se ha utilizado un modelo computacional bidimensional, de diferencias finitas, para simular el flujo de agua subterránea en una arenisca (0,3 a 11 m de espesor) que cubre una mina subterránea, y para evaluar la dependencia del caudal y la velocidad de los aportes hacia la mina, cuando se introducen en el sistema hipotéticos pozos de drenaje. Este modelo se basa en datos mineros, hidrogeológicos, estructurales y estratigráficos. La simulación del drenaje por pozos, usando 25 de ellos, muestra una reducción despreciable del aporte si la permeabilidad de la arenisca es menor de 0,30 m/día. Para valores de 3 m/día, 25 pozos producirían una reducción del aporte de 2,4 %.

Energy and Environmental Systems Division, Argonne National Laboratory
Argonne, Illinois 60439, U. S. A.

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Introduction

Pumping of water from wells has been used since the late 1920's to dewater ore-bearing rocks prior to and during the mining of iron ore, lead-zinc, and uranium deposits (Loofbourow, 1964). Well dewatering could also be a very useful means of reducing seepage of water into underground coal mines, thus reducing the flow of mine discharges. Several different dewatering schemes have been proposed (Ahmad, 1970; Parizek, 1970, 1971, 1972), but none have been tested or documented. Among the several proposed methods, gravity drainage, or connector, wells (Figure 1) appear to have the greatest potential for reducing seepage into active and abandoned underground mines for the least cost.

The purpose of connector wells is to reduce the hydraulic head and partially or completely dewater an aquifer above an active or abandoned underground mine. The wells would drain water away from the aquifer, allowing the uncontaminated water to flow by gravity past the mine and into a deeper aquifer (Fig. 1). By decreasing the hydraulic head in the upper aquifer, the leakage rate into the mine should also be reduced. Decreasing the flow rate from an abandoned underground mine will decrease the acidity and dissolved metal loading rates of the discharges (Schubert, 1978), thus reducing pollution problems. For an active mine, this would mean a reduction in costs of water handling and treatment. Connector well dewatering has many other desirable aspects as a mine drainage abatement technique (Parizek, 1970, 1972). Assuming the water being drained from the upper aquifer is good quality, it may serve to increase potable water supply yields from the lower aquifer. Only one aquifer above a mine needs to be dewatered (preferably the lowest one). Therefore, there should be little chance of depleting shallow domestic and farm groundwater supplies that occur commonly in coal mining regions. Pumping equipment is not used, so operating and maintenance costs are minimal. This is an important consideration because any abandoned mine drainage abatement program is a long-term endeavor. At any time in the future if local need for water became sufficient, wells could be converted to a water supply by installing pumps (assuming the quality of water in the wells is suitable for a desired use).

In 1973, the U.S. Environmental Protection Agency (U.S. EPA) approved and funded a demonstration project to test the engineering feasibility, evaluate the effectiveness as an acid drainage abatement technique, and develop cost estimates of connector well dewatering. Before drilling and installation of connector wells

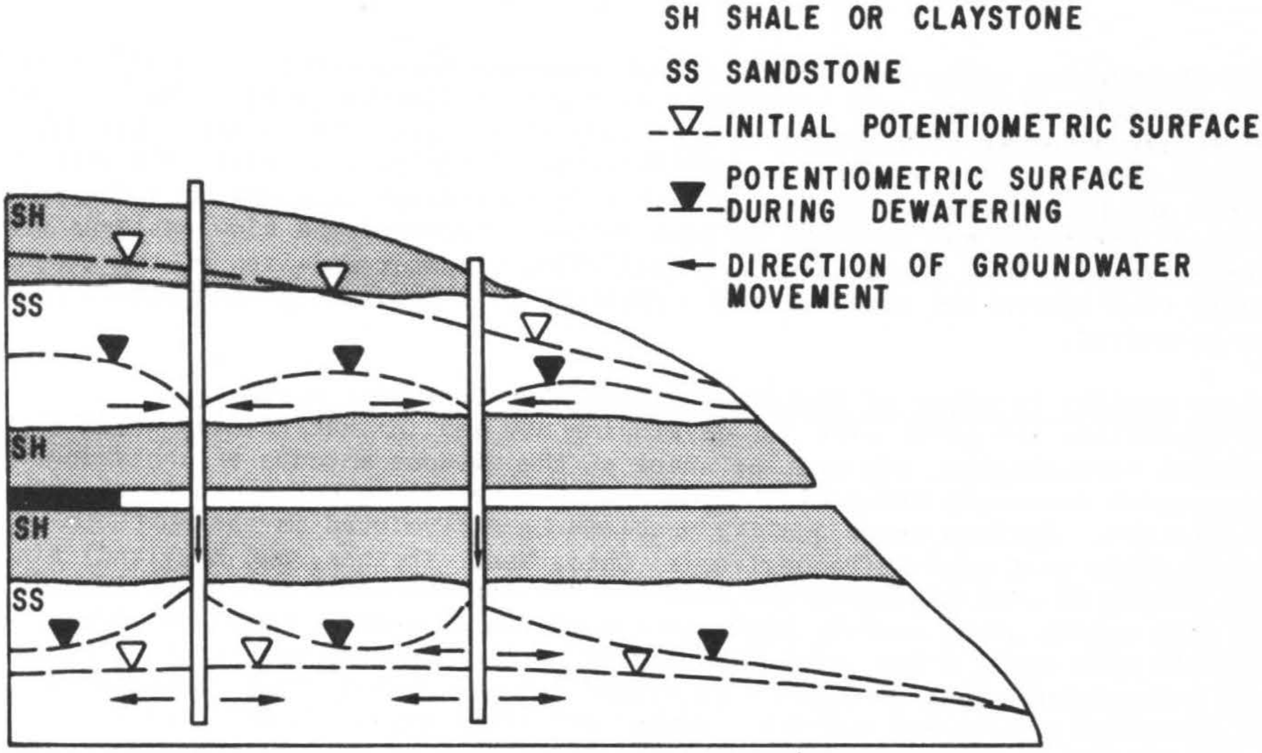

Figure I. GRAVITY WELLS DISCHARGE WATER INTO UNDERLYING AQUIFER

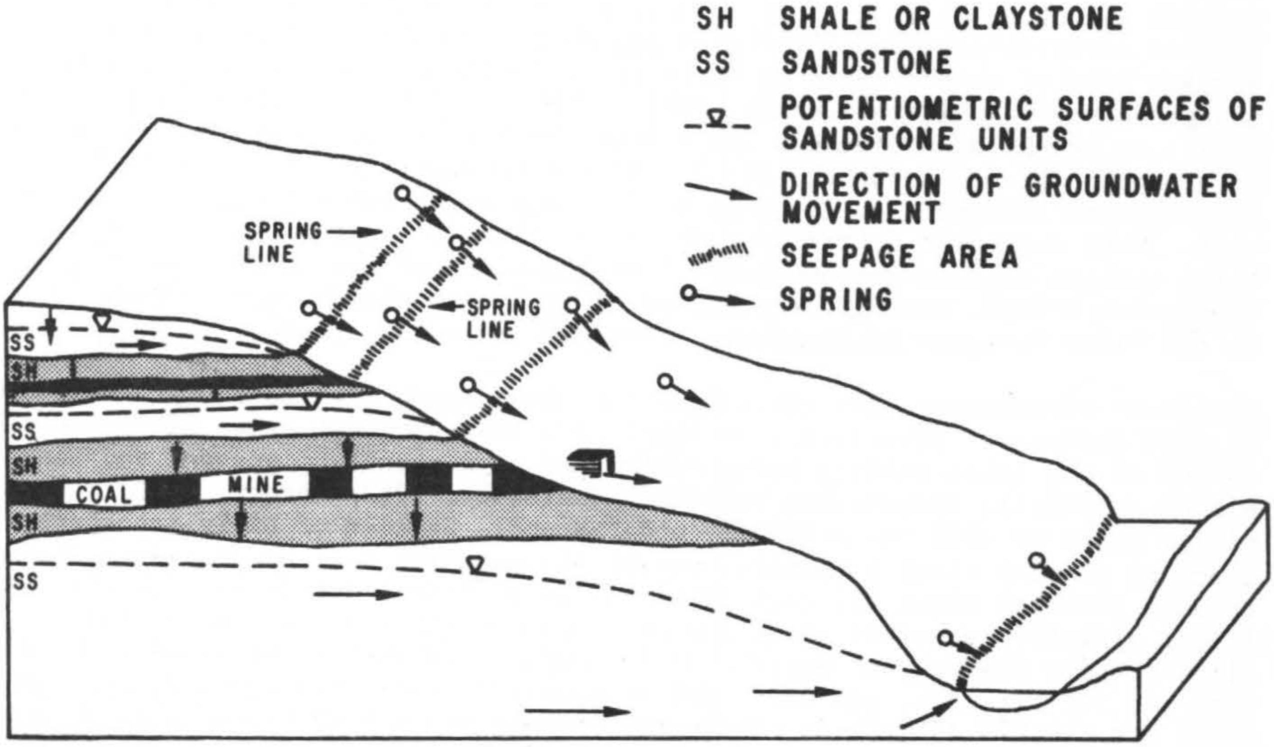

Figure 2. GENERALIZED GROUNDWATER FLOW SYSTEM OF THE APPALACHIAN BITUMINOUS COAL REGION (MODIFIED FROM PARIZEK, 1971)

and observation wells could begin at the proposed demonstration site in central Pennsylvania, geologic and hydrologic data were collected to determine the nature of the groundwater flow system in the study area. Areas of recharge and discharge, permeability and storage coefficients of lithologic units, the occurrence and potentiometric surface of water in individual aquifers, and the relation of fractures and jointing to groundwater occurrence and flow patterns were investigated. Once these data were available, computer modeling of the groundwater flow system and evaluation of connector well dewatering feasibility could be conducted.

Water Quality Problems of Abandoned Underground Coal Mine Discharges

To appreciate the great need for developing new and innovative mine-drainage control technologies, one must be aware of the awesome amounts of contaminated mine water currently being discharged, and the resulting consequences of such discharges. Serious water quality problems have developed in the northern Appalachian coal region (Pennsylvania, Ohio, West Virginia, and Maryland) since the advent of coal mining in the 1800's. Because the coals and overburden rock in this region often contain high concentrations of pyrite, water draining from surface mine spoil piles, coal refuse piles, slurry ponds, coal-washing plants, and underground mines is often very acidic and may contain high concentrations of dissolved metals and sulfate. Rivers and lakes seriously affected by acidic mine discharges can support only limited flora such as acid-tolerant molds and algae, and usually will not sustain fish. Ionic constituents from mine water, particularly dissolved metals, often occur in concentrations that are harmful or toxic to aquatic organisms. Streambeds can be coated with amorphous iron oxyhydroxide and other metal salt precipitates, which preclude the existence of benthic invertebrates and eliminates breeding areas for aquatic species. Subsurface flow of acidic water is known to seriously pollute springs, streams, and groundwater aquifers (Emrich, 1969; Schubert, 1978). In groundwater discharge areas, or seeps, mine drainage can destroy vegetation and cause the ruination of once productive soils (Brown, 1971). As the concentration level of mine drainage constituents increase, so do costs of treating water for potable or commercial uses. More extensive information on the biological, ecological, economic, and water quality impacts can be found in publications of the Appalachian Regional Commission (1969), the U.S. Army Corps of Engineers (1974), and references listed in the "Mine Drainage Bibliography 1910-1976" (Gleason, 1976).

Abandoned underground coal mines have long been recognized as the greatest source of acid drainage. Inventories in Appalachia indicate that these mines contribute 52-60% of the total acidity being discharged as a result of present and past coal mining activities (Appalachia Regional Commission, 1969; Warner, 1970). Coal mining prior to 1960 was primarily underground. Because of hilly topography and exposure of coal along hillsides, mining was normally done by placing mine entrances (drifts) along the coal outcrop. In addition, drifts were located at the lowest elevation possible along the outcrops and the coal was mined updip to allow gravity drainage of water from the mines. Because of high rates of rainfall and infiltration, and water tables generally near land surface, underground mines are usually subject to continuous seepage and act as groundwater drains. Subsequent surface mining and augering operations have intersected abandoned underground mines and thereby created new routes of infiltration into, and drainage from, underground mines. Acid water continues to flow from abandoned mines and will continue to be a significant economic and environmental problem unless steps are taken to remedy the situation.

Methods of Controlling Mine Drainage

For abandoned underground mines, several methods or combination of methods have been utilized in an attempt to reduce acid discharges. Various ways to reduce infiltration of surface water were reviewed by Lorenz (1962). These include stream rechanneling, construction of stream channel liners, wooden sluiceboxes, and canals. Grading surface mines to facilitate surface water runoff away from underground mines is also very important. By causing surface water to avoid major avenues of infiltration, these methods can reduce sources of water entering underground mines.

In the 1930's, the federal government funded extensive sealing of mines with "wet" and "dry" air seals to prevent entrance of oxygen into mine atmospheres. Although some mines showed improvement in water quality, overall the method proved to be relatively ineffective. In several more recent and better documented cases, air seals were unable to reduce air entrance or pyrite oxidation (Moebs, 1970; U.S. EPA, 1977). Even though air may be prevented from entering a mine through sealed passages, it may still gain entrance through subsidence holes and fractured overburden.

Another method of isolating pyritic material from atmospheric oxygen is to flood a mine. Vanzandt (1933), for example, reported some naturally flooded mines discharged alkaline water, whereas nearby operating mines had acidic discharges. Thompson and Emrich (1969), Koppe and Thompson (1972), and Miller and Thompson (1974) make several recommendations to successfully seal and flood a mine. These designs are intended to make a mine relatively "leakproof" after cessation of mining. Prior to 1966, when mining companies in Pennsylvania were not responsible for discharges, mines were not designed for effective flooding after closure. Shaft mines below regional water tables will naturally flood, and sealing of these mines is not difficult. In recent years, efforts have been made to seal drift mines that are located in zones of perched or semi-perched water tables above major surface water drainage. These sealing projects have proven to be more difficult. Significant leakage from a mine can occur through 1) thin or fractured roof rock or mine perimeter, 2) thin coal barriers between adjacent mines, 3) locations where past surface mining or augering has intersected an abandoned mine and later backfilled, or 4) numerous types of undiscovered mine features, such as air shafts, boreholes, or water drains. As a consequence, these mines are extremely leaky and seldom attain complete flooding when sealed (Foreman, 1972, 1974; U.S. EPA, 1977), thus allowing pyrite oxidation to continue in unflooded portions of a mine. If a drift is located at the lowest elevation of a coal mine and mining has proceeded updip, several hundred feet of hydrostatic head due to flooding would make a safe, effective seal almost impossible.

Since 1967, over $100 million has been spent by the state of Pennsylvania for acid mine drainage abatement, including surface mine reclamation, mine sealing, water treatment facilities, engineering designs, and administration costs. In addition, many millions of dollars of federal funds have also been spent for research, development, and demonstration projects. Despite this, Pennsylvania and other states of the Appalachian region are still plagued with mine water problems.

Groundwater Hydrology in the Appalachian Coal Basin

Coal-bearing strata in the Appalachian region generally consist of repetitious sequences of gently-dipping coal, shale, siltstone, sandstone, limestone, and clay of Pennsylvania age. The presence, thickness, and lateral continuity of these lithologic units, however, are quite variable. Many hydrogeologic investigations (Poth, 1963; Emrich, 1969; Brown, 1971; Schubert, 1978) have noted that sandstone and coal are the most permeable lithologic units; clay, shale, and siltstone are relatively impermeable. Groundwater flow systems are usually recharged in the upper and middle portions of hillsides, and discharge along streambanks at the base of the hills, thus contributing to base-flow of streams (Fig. 2). The presence of aquitards (e.g., clays, shale, and siltstones) at various levels within a hill, however, impedes downward flow of groundwater, thus causing some lateral flow through relatively permeable units, and surface discharge at springs located along hillsides where aquifers crop out. Each isolated hill has its own shallow groundwater flow system, which may or may not be linked to deeper regional groundwater flow.

Because groundwater can drain from a hillside by horizontal flow through a permeable stratigraphic unit or drift mine, confined aquifers are partially dewatered and several perched water tables may exist above the regional water table (Fig. 2). Observations by drillers and hydrogeologic investigators (Poth, 1963; Emrich, 1969; Brown, 1971) provide evidence that several free water surfaces may be present, and that large differences in hydraulic head can exist between upper and lower aquifers (Brown, 1971). The downward movement of water in these recharge areas is often enhanced by vertical faults or fracture zones. Fracturing and caving of shale roof rock in abandoned mines increase vertical permeability and vertical flow rates, and may significantly reduce groundwater storage and hydraulic head in the aquifer above the mines (Ward, 1968; Schubert, 1978).

Water may enter mine workings in several ways. Rapid infiltration of water can occur through boreholes, fracture zones, faults, and caved areas in the roof. The source of water may be surface water or an overlying aquifer. Methods of controlling surface-water infiltration are available (Lorenz, 1962), as discussed previously. Faults, fracture zones, and boreholes can be grouted, if accurately located. Most water entering a mine is usually due to slow, steady leakage through jointed shale roof rock from an overlying sandstone aquifer (Lovell, 1974). If a permeable sandstone is directly above a mine or if shale roof rock is thin, highly jointed, or extensively caved, then flow from the sandstone into the mine will be fairly rapid and the sandstone will be partially dewatered. If a shale roof is present and not extensively caved, then a difference in head will exist between the sandstone and the mine roof. Leakage into the mine will occur, according to the equation (Parizek, 1971):

$Q = k' \Delta h A / m'$, where

Q = leakage rate through the shale roof, in m^3/day,
k' = vertical permeability of shale roof, in m/day,
A = area of mine roof, in m^2,
m' = thickness of shale roof, in m,
Δh = head difference between overlying aquifer and the mine roof, in m.

A relationship has been shown to exist between mine roof areas and mine discharge rates for eighteen abandoned coal mines in western Maryland (Hollyday, 1973). This field evidence partially confirms the validity of the leakage equation.

The presence of large drift mines can drastically modify a groundwater flow system. The mine acts as an underdrain, intercepting most of the downward flow and discharging the water from drift entrances. Recharge to underlying aquifers is greatly reduced in the vicinity of the mine.

Hydrologic Considerations For Well Dewatering

Favorable hydrogeologic conditions are necessary to efficiently dewater an overlying aquifer (Parizek, 1971). For economic and practical reasons, it is desirable to have the least number of highly productive wells. A thin, very permeable aquifer, separated from the mine by a thin aquitard, and a high head difference between the aquifer and the mine roof are ideal conditions for connector well dewatering. Dewatering wells must significantly reduce the head in the aquifer over the entire area of the mine and eventually dewater the aquifer to some extent. If a highly desirable aquifer is not present above a mine, then effective dewatering may still be achieved by opening connector wells to more than one aquifer zone. Multiaquifer dewatering will be necessary where aquifers have low permeability and are not very productive; however, the potential success of dewatering becomes less if the permeability of the aquifers is low.

Fracture traces detected on aerial photographs are underlain by relatively narrow zones (3 to 13 m) of vertical fracture concentration, and permeabilities of these fracture zones have shown to be 100 to 1000 percent greater than adjacent unfractured rock (Lattmann, 1964; Koppe, 1972). For dewatering purposes, the most productive well sites should be located at fracture trace intersections.

The lower aquifer receiving water from the connector wells must be capable of transmitting maximum flows that could be drained from the upper aquifer (i.e., it must have adequate thickness and permeability), so that significant head build-up does not occur in the lower aquifer as a result of recharge. For downward flow through the wells to occur at all, the potentiometric level of water in the lower aquifer must be substantially less than the level in the upper aquifer; this conditions was shown to be the general case by Brown and Parizek (1971).

As with any mine drainage control method, problems may arise. The first concern is diversion of groundwater away from private wells and springs around the perimeter of the aquifer being dewatered. If a water supply is threatened, then the yield of connector wells could be reduced, one or more of the connector wells closest to the water supply could be plugged, or one of the connector wells could be converted to a water supply by installing a pump. The second concern would be to locate the wells so that they penetrate coal pillars. In the event that a mine void is encountered, grout columns (gravel piles stacked to the mine roof and injected with cement or other sealant) can be constructed to prevent roof settlement from destroying the well casing and protect the well casing from corrosive attack by acid mine water. The possibility of well plugging is the third potential problem. If ferrous iron is present in the overlying aquifer, then precipitation of iron oxyhydroxide and/or growth of filamentous iron-oxidizing bacteria in and around the lower portions of the wells could reduce permeability of the lower aquifer and well efficiency over a period of time. High concentrations of iron in groundwater above a mine are not typical unless caused by other mining activities at a higher elevation.

Geology, Hydrology, and Mining Conditions of the Study Area

The study area (approximately 65 km^2) in Clearfield County, Pennsylvania, is dissected into discrete, steeply-sloping hills by Clearfield Creek and its tributaries. Many gently-dipping coal seams crop out on the hillsides and have been subjected to mining since the late 1800's. Several large underground mines near Madera are the major sources of the acidity, dissolved metals, and sulfate being discharged in the watershed. The initial phase of this project was to collect geologic, mining, and hydrologic information necessary to the formulation of a groundwater flow model and dewatering simulation.

The Burgoon member of the Pocono Formation (Mississippian) is about 107 m thick and consists primarily of massive, cross-bedded, fine- to coarse-grained, fairly well sorted, micaceous sandstone. It is resistant to erosion and forms steep slopes rising above Clearfield Creek in the northern part of the study area. The top of the Burgoon Sandstone is an erosion surface (Mississippian-Pennsylvanian unconformity) which dips toward the south and southeast. Above the Burgoon Sandstone lies the Mercer Formation (Pennsylvanian), a 21 to 30 m complex sequence of coals, clays, dark shales, and sandstones. The Lower and Upper Mercer coals are thin and have not been mined.

The Clarion coal (with minor clay partings) ranges in thickness from 0.76 to 1.78 m and has been extensively mined. The largest underground mine is the Mid Penn No. 4 Mine which had numerous drift and shaft entrances (Fig. 3). In addition, a large portion of the Clarion coal outcrop around the hill has been surface mined in the past, often intersecting or closely approaching underground mine workings. The underground mine is roughly 5.15 km along a NNW-SSE direction, 2.17 km at its widest point, and covers an area of about 8.34 km^2. The mine dips to the south at an average slope of 14 m/km, and because the long axis of the mine is parallel to the maximum dip direction, a total of 70 m of structural relief occurs in the mine. According to the local residents who worked in these mines, the coal was continuous, but occasionally offset up to 0.6 m by faults. Most coal pillars were mined near the Bucher No. 7 and Betz drifts in the 1940's.

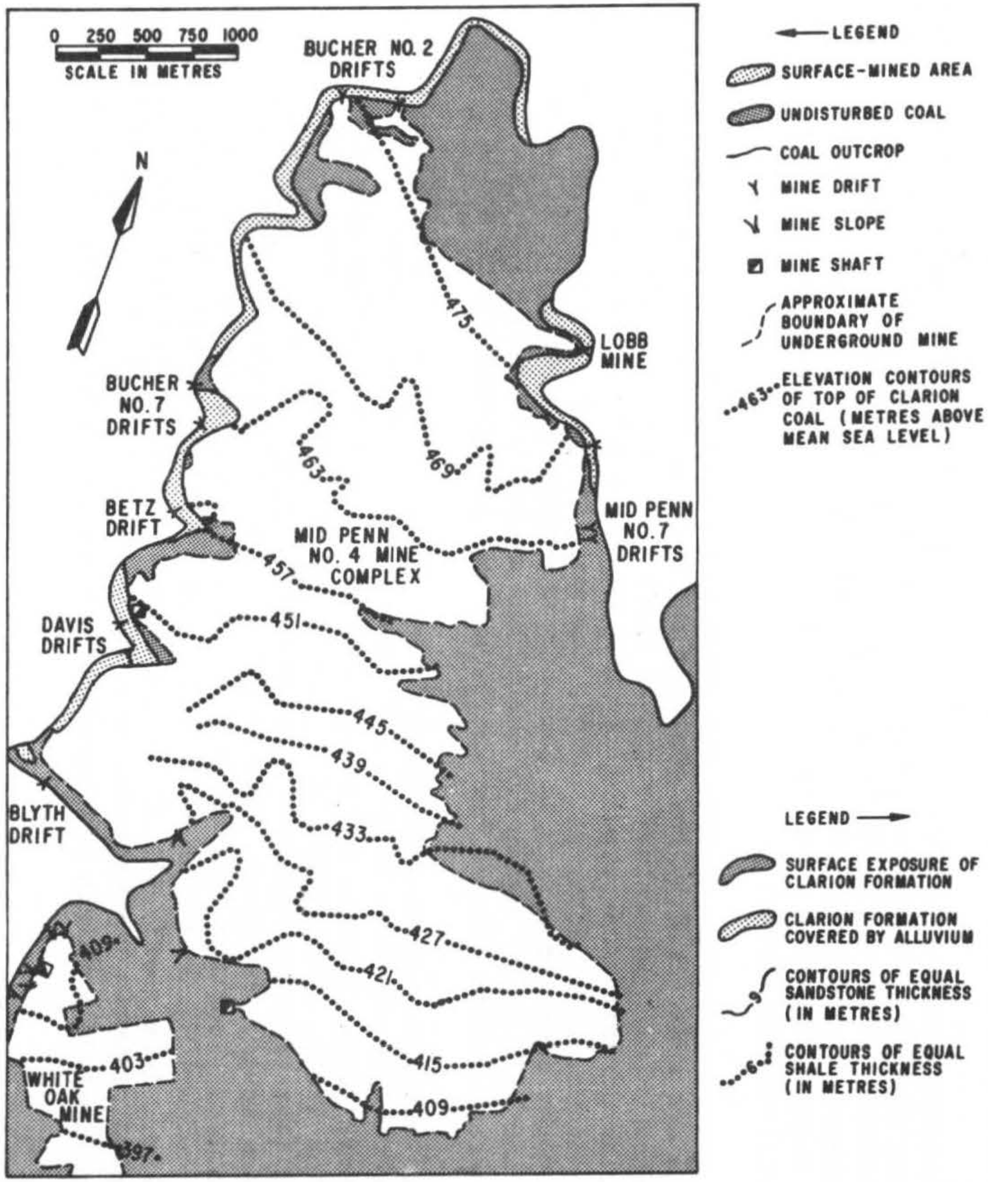

Figure 3. MINING AND STRUCTURAL GEOLOGY OF CLARION COAL

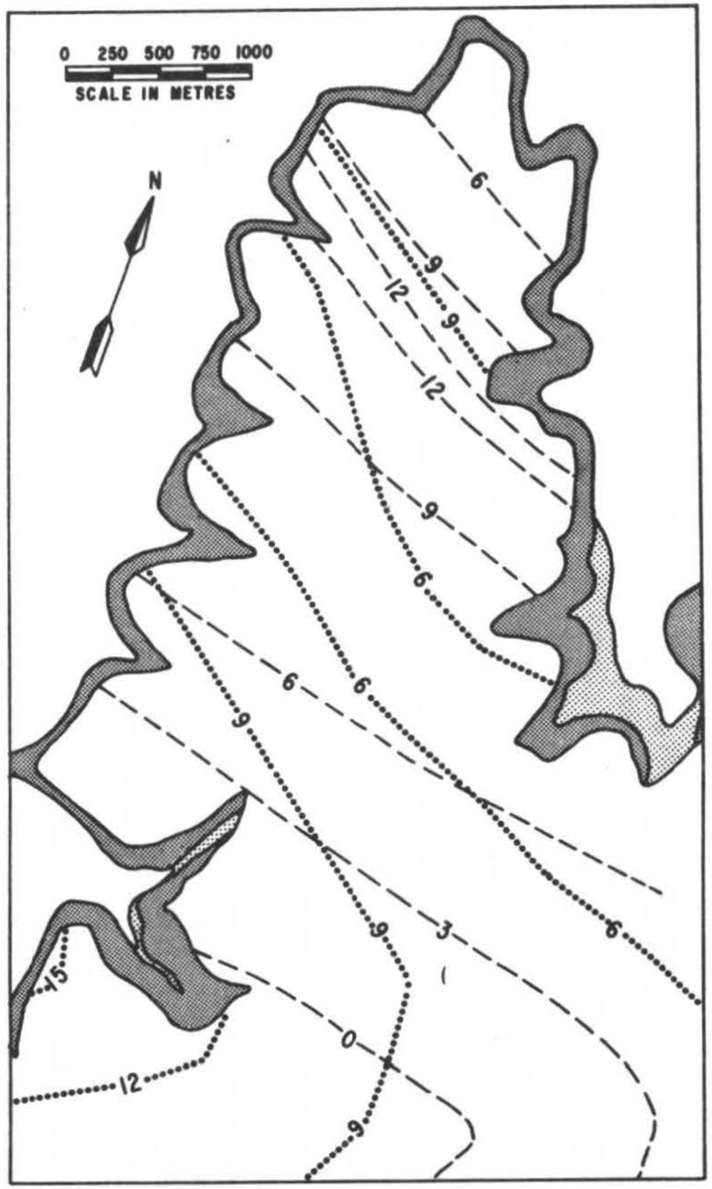

Figure 4. THICKNESS DISTRIBUTION OF CLARION SHALE AND SANDSTONE

Directly below the Clarion coal is 3 to 4.5 m of claystone. The Clarion coal is overlain, in ascending order, by variable thickness of 1) black, fissile, pyritic shale, 2) dark gray shale with siderite concretions, 3) silty shale, 4) fine- to coarse-grained sandstone, 5) siltstone, and 6) claystone. The combined thickness of the shales range from 6 to 12 m, with the thinnest shale roof occurring across the middle of the mine area (Fig. 4). The thickness is quite variable due to channeling prior to deposition of the overlying sandstone. In general, the sandstone thickness is inversely related to that of the shale, attaining a maximum thickness of approximately 12 m in the northern part of the mined area (Fig. 4).

Above the Clarion Formation is up to 107 m of additional coal-bearing strata, including the Lower Kittanning, Middle Kittanning, Upper Kittanning, and Freeport Formations. Small abandoned underground mines in the Lower Kittanning, Lower Freeport, and Upper Freeport coals, as well as surface mines in the Lower Kittanning, Middle Kittanning, and Freeport coals, overlie the Mid Penn No. 4 Mine. These mines have affected the hydrology in the hill to some extent. Surface mines, particulary Lower Kittanning and Lower Freeport contour mines, have impounded surface water and thereby increased groundwater recharge rate. Two Lower Freeport underground mines, located about 80 m above the Mid Penn No. 4, intercept some groundwater flow, resulting in small discharges to the surface.

The average annual precipitation in Madera is 1.04 m, with the greatest amounts falling from May through September. Using mean monthly temperatures, the annual evapotranspiration rate has been estimated to be 0.58 m, or 56 percent, using the Thornthwaite (1948) method. Studies (Reed, 1971) in coal basins of Pennsylvania have indicated that groundwater recharge may be in the range of 20 to 40 percent of total precipitation.

Once water enters the ground, its storage, flow rate, flow direction, and discharge are controlled by the geologic and hydraulic characteristics of the soil and rock units. Laboratory tests of small rock cores indicate that the intergranular porosity and permeability of coal-bearing strata are very low (Ward, 1968; Brown, 1971; Schubert, 1978); the porosities of shales, siltstones, and sandstones range from 5 to 11 percent and average permeability values are 4.82×10^{-5} and 4.15×10^{-5} m/day for shales and sandstones, respectively. Little difference exists between horizontal and vertical permeabilities.

Laboratory tests using rock cores do not reflect true field porosities and permeabilities because they do not taken into account all cracks, bedding planes, fracture zones, joints, and faults that occur in coal-bearing strata. Several studies (Poth, 1963; Ward, 1968; Brown, 1971; Koppe, 1972; Lovell, 1974) determined that fractures greatly influence the storage and flow of groundwater. Pumping tests, therefore, provide much better approximations of hydraulic characteristics. Fourteen drill holes in the study area were pumped at rates ranging from 6.3×10^{-5} to 37.9×10^{-5} m^3/s. Most drill holes were dewatered very quickly, since nearly all of the pumped water was derived from borehole storage. Residual drawdown was measured as a function of time after pumping each hole. The permeability values determined by the various recovery methods vary by two orders of magnitude between holes. Several lithologic units were present in the saturated intervals of each bore hole tested, and the calculated permeabilities, therefore, represent a composite permeability of the various lithologic units. For three drill holes where no sandstone was present, permeabilities ranged from 1.10×10^{-3} to 2.53×10^{-3} m/day. The other drill holes had various percentages of sandstone present and permeabilities ranged from 2.65×10^{-3} to 8.80×10^{-2} m/day, suggesting that sandstone might be more permeable than shale and siltstone.

During the drilling of piezometers, Brown and Parizek (1971) observed that fractured coals and sandstones yielded the largest amounts of water, an observation that has been confirmed by many drillers in central Pennsylvania. In most surface mine highwalls in the study area where groundwater seepage was occurring, the water almost always flowed from the base of a sandstone unit or from a coal seam. Most springs in the area also emanated from sandstone or coal. The largest springs in the area flow from the Burgoon Sandstone along Clearfield Creek. In addition, owners of wells in the Burgoon Sandstone report that their wells have high yield capabilities and never go dry, indicating that this stratigraphic unit has the greatest permeability in the area's shallow groundwater flow system.

Water level elevations in 31 ponds, 166 springs, 83 residential wells, and 93 coal exploration drill holes were measured during January through July, 1975. Water levels in the dug wells and drill holes were generally less than 15 m below the ground surface and the water-table configuration is very similar to the surface topography. Greater depths to water existed in a few deeper drilled wells. Because most of the wells and drill holes in the study area were shallow, aerial configuration of potentiometric surfaces for groundwater in each aquifer could not be established. Two generalizations can be made, however: 1) in each hill, the hydraulic potential decreased with increasing depth and 2) for individual aquifers, potential is greatest in the interior of a hill and diminishes toward the edges, resulting in flow towards outcrop areas.

<u>Digital Computer Model of Groundwater Flow</u>

One of the primary objectives of this study was to estimate the potential reduction of leakage into the Mid Penn No. 4 Mine that could be achieved by connector wells. To do this, a digital computer model was essential to simulate the groundwater flow system and to evaluate the responses of the flow system and leakage rate into the mine when hypothetical dewatering wells are introduced into the system. A dewatering project would be most effective in reducing leakage into an underground mine if dewatering of the nearest aquifer above the mine was attempted (Parizek, 1971). In the case of the Mid Penn No. 4 Mine, the Clarion sandstone lies 6 to 12 m above the mine, ranges in thickness from 0.3 to 12 m, and is at least partially saturated, as evidenced by a few springs emitting from the Clarion Formation where it crops out around the hillside. For these reasons, simulation of groundwater flow and well dewatering of the Clarion sandstone was deemed most useful.

The computer program used for simulation is a two-dimensional, finite-difference model developed by Trescott and Pinder (1975) and recently modified (Trescott, 1976). Because the model is two-dimensional, only water flow into and out of the Clarion sandstone could be simulated. A basic assumption of the model was that all water that flowed downward through connector wells could be adequately transmitted away from the wells by the receiving aquifer, the Burgoon Sandstone The capability of the Clarion sandstone to yield water to the connector wells is considered to be a much more critical factor affecting the usefulness of wel dewatering. To model a heterogeneous aquifer with irregular boundaries and boundary conditions, the model region was subdivided into a block-centered, finite-difference grid in which variable grid spacing is permissible (Fig. 5). Aquifer properties were assigned to each block based on actual or interpolated values available from field data collection. Assuming the coordinate axes of th grid are collinear with the principle components of the permeability tensor (when an aquifer is anisotropic), the partial differential equation governing groundwater flow in an aquifer in two dimensions may be expressed as:

$$\frac{\partial}{\partial x}\left\{k_{xx} b \frac{\partial h}{\partial x}\right\} + \frac{\partial}{\partial y}\left\{k_{yy} b \frac{\partial h}{\partial y}\right\} = S \frac{\partial h}{\partial t} + W(x,y,t), \text{ where}$$

k_{xx}, k_{yy} = are the principle components of the permeability tensor (L/T);
b = is the saturated thickness of the aquifer (L);
h = is the hydraulic head (L);
S = is storage coefficient for confined aquifers and specific yield for unconfined aquifers (dimensionless);
W(x,y,t) = is the volumetric flux of recharge or withdrawal per unit surface area of the aquifer (L/T);
L = constant unit of length;
T = constant unit of time.

Aquifer properties, aquifer boundary conditions, and initial head distribution in the aquifer are input data for the program. An equation of flow into and out of each aquifer block is calculated by the program using a finite-difference approximation of the above differential equation and the aquifer properties assigned to the nodes. An iterative equation-solving scheme then solves simultaneously the N unknowns (head values of the blocks) where N is the number of blocks representing the aquifer. The derivation and solution of the finite-difference equations and the theory of finite-difference aquifer models are discussed in more detail by Prickett and Lonnquist (1971) and Trescott et al. (1976).

The matrix of aquifer blocks is 35 (number of rows) by 51 (number of columns). The grid system is oriented so that it most efficiently fits the aquifer (and mine) boundaries within the grid, thus minimizing the number of blocks located outside the aquifer boundary (Fig. 5). The Δx and Δy dimensions of the individual blocks range from 122 to 427 m. Block sizes were generally made smaller near the boundaries of the aquifer and underground mine to better approximate their actual size and shape. Small block sizes were also arranged within the aquifer to help facilitate location of connector wells throughout the aquifer (accuracy of modeling is improved if wells are located in small blocks).

Data inputs that were fixed for all simulation studies were: aerial distribution of shale thickness, aerial distribution of the bottom elevation of the Clarion

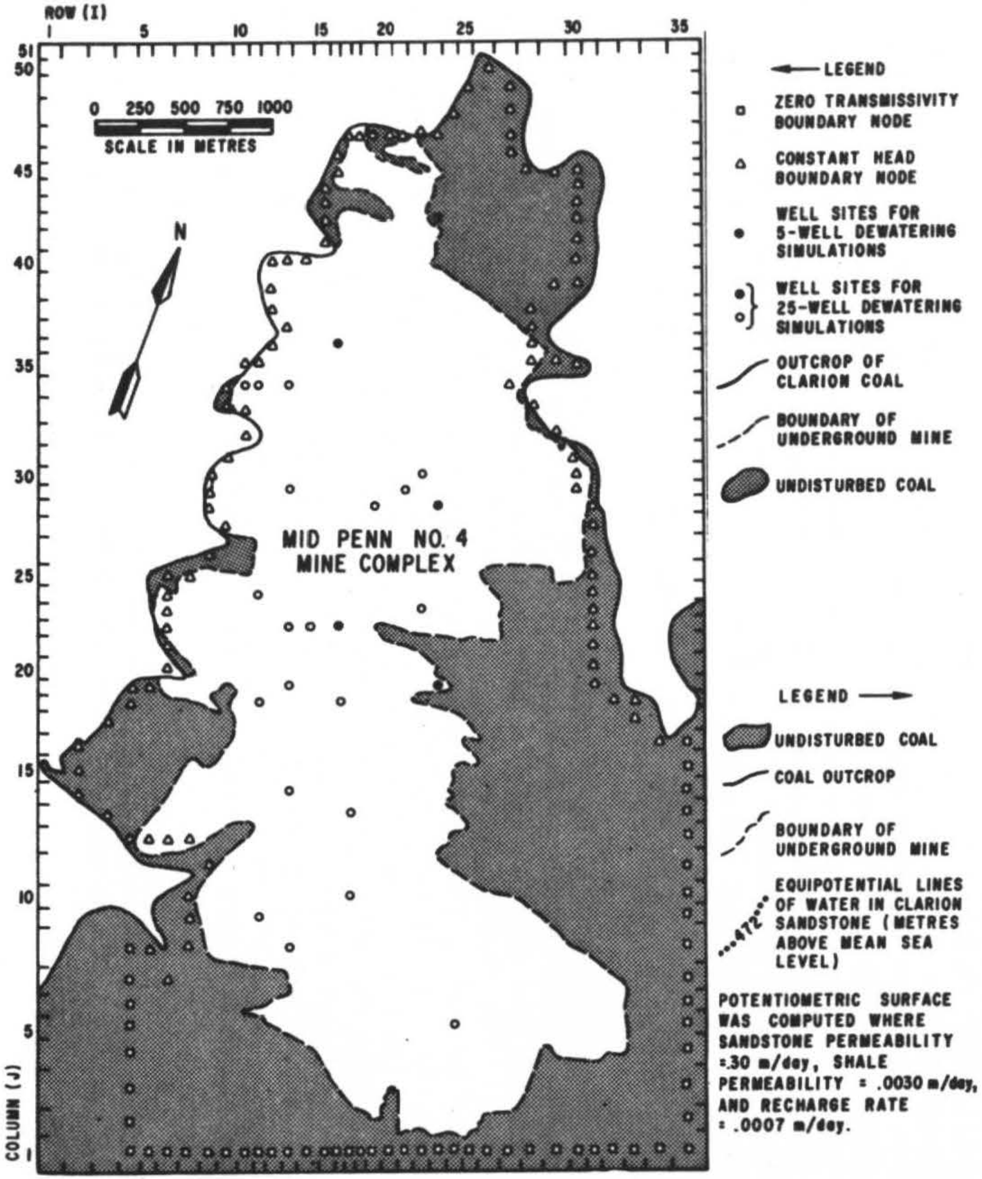

Figure 5. FINITE-DIFFERENCE GRID AND WELL LOCATIONS

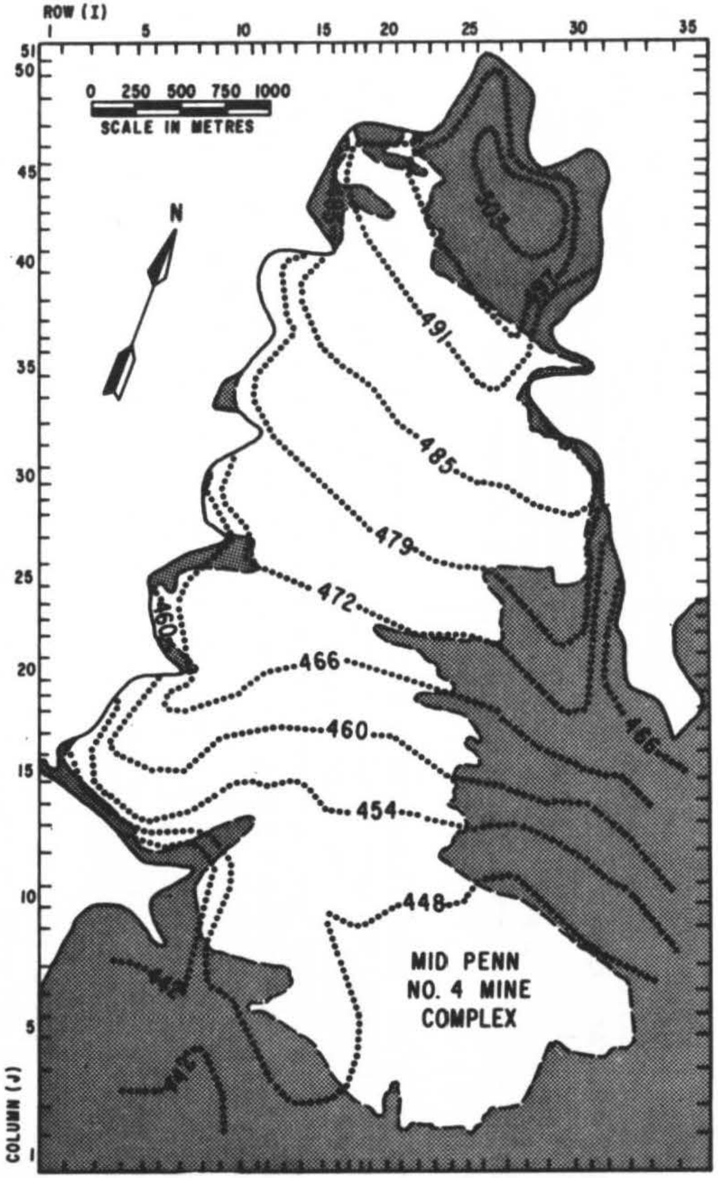

Figure 6. COMPUTED POTENTIOMETRIC SURFACE OF WATER IN CLARION SANDSTONE

sandstone aquifer, potentiometric surface at the base of the confining layer, initial potentiometric surface of the aquifer, and aquifer boundary flow conditions (constant head and zero flux boundaries). Parameters that were modified between simulation runs included: horizontal permeability of the Clarion sandstone, vertical permeability of the Clarion shale unit, constant recharge rate to the Clarion sandstone, and the number, location, and drainage rate of connector wells.

To estimate the potentiometric surface at the base of the shale unit, the following procedures were used: 1) where a mine pool exists, hydraulic potential was set equal to the mine pool elevation, 2) in unflooded portions of mine, hydraulic potential was set equal to the mine roof elevation, 3) where the Clarion coal cropped out along the western, northern, and northeastern edges, potential has been assigned a value of 0.9 m above the elevation of the top of the coal. Between the mined areas and the outcrop areas, hydraulic potential has been assigned an elevation higher than the top of the Clarion coal. The hydraulic potential distribution for the base of the shale unit is fixed and does not fluctuate during simulation.

Accurately estimating the initial potential distribution for the Clarion sandstone is not critical because the computer program will calculate a steady-state potentiometric surface of the aquifer based on other input data. The hydraulic potential values assigned to boundary blocks were, however, very important because they were fixed as constant head boundaries and influenced the horizontal movement of water into or out of the aquifer around its boundaries. Where the aquifer crops out along the western, northern, and eastern boundaries, potential was set to the bottom elevation of the aquifer plus 0.9 m, thus providing a seepage face for horizontal flow from the sandstone. Along the southern and southeastern blocks of the grid, the sandstone does not crop out and thins considerably (Fig. 4). For these blocks, aquifer thickness has been set to zero and therefore has zero transmissivity. These nodes form a no-flow boundary for the aquifer.

The horizontal permeability of the Clarion sandstone was varied between simulation runs; values used were 0.03, 0.15, 0.3, and 3.0 m/day. The values of 0.03 to 0.3 m/day are in the range of permeability values calculated from recovery test data. The Clarion sandstone above the Mid Penn No. 4 Mine is coarser-grained (contains a thin basal conglomerate at some locations) than the sandstone where recovery tests were conducted. Therefore, 3.0 m/day may be a reasonable value of permeability and has been included in some simulation runs. For each run, a single value of sandstone permeability was assigned to all nodes and permeability was assumed to be isotropic. The vertical permeability of the Clarion shale is another parameter that was varied for each modeling run; values used ranged from 10^{-5} to 10^{-3} m/day. These values lie in the range found from recovery test analyses and values given by Parizek (1971) and Brown and Parizek (1971).

Recharge rate to the entire hillside has been approximated as ranging from 0.21 to 0.42 m/year. Since some of this groundwater recharge leaves the hillside as springs and seeps at elevations above the Clarion sandstone, 0.012, 0.178, and 0.254 m/year included a range of recharge rates to the Clarion sandstone that seems most reasonable.

The computer solution of the flow equation for all aquifer blocks, using the Strongly Implicit Procedure (SIP) of numerical analysis, yields the distribution of hydraulic head (potentiometric surface) in the aquifer and an accounting (water budget) of flow rates entering and exiting the aquifer. The water-budgeting feature enables a rapid evaluation of the flow system response to any change in aquifer parameters or the addition of dewatering wells.

Simulation of Natural Flow System (Model Calibration)

Three values of recharge rate, three values of horizontal permeability of the sandstone aquifer, and eight values of vertical permeability for the shale aquitard that appear realistic in terms of the data presented in previous sections were used to generate 54 possible steady-state potentiometric configurations, and are summarized by Schubert (1978). In the 54 simulations, the sandstone went mostly or completely dry in 24 runs when shale permeability was high or recharge rate was low. However, this condition is discounted by the fact that several springs emerge at many locations along the sandstone outcrop area. In 15 other simulations, completely unrealistic increases in potentiometric surfaces occurred when shale permeability was low or recharge rate was high. The possible combinations of variables that result in reasonable potentiometric surfaces are indicated in Table 1. The model was particularly sensitive to changes in shale permeability and recharge rate, and was only slightly affected by altering sandstone permeability.

In each case, the hydraulic head distributions show combined water table-artesian conditions in the aquifer with highest elevations occurring in the interior of the north end of the hill. The potentiometric surfaces decrease gradually toward the south and dip steeply toward the perimeter in outcrop areas, as shown in Figure 6.

Table 1. Calibration Tests of Natural Steady-State Flow Simulations

Shale Permeability (k´) (m/day)	Recharge Rate (m/day)		
	0.00027	0.00049	0.00070
0.00305			
0.00152			
0.00091	aquifer goes dry		
0.00061			X
0.00046			X
0.00030		X	X
0.00015	X		
0.00003	excessive increase in potentiometric surface		

X = calculated potentiometric surface is similar to natural conditions when sandstone permeability equals 0.0305, 0.1524, or 0.3048 m/day.

Recharge rates, boundary flow rates, and leakage rates were calculated by the computer program for each simulation run. For the simulation runs having reasonable potentiometric surfaces (see Table 1), ratios of leakage rate to total discharge rate appeared to be quite high ($\geq$ 98.0%), indicating that nearly all of the water being recharged to the aquifer is leaking downward, and that very little water was flowing toward the constant head boundaries around the outcrop. Ratios with slightly lower values occur when the k/k' ratio is higher, which is to be expected. To account for the flow rate of springs from the aquifer around its boundary, the mean horizontal permeability of sandstone must be in the range of 0.152 to 3.05 m/day or higher. Estimates of discharge rate from the Mid Penn No. 4 Mine range from 4893 to 29359 m^3/day. Leakage rates calculated from computer simulations range from 15489 to 53972 m^3/day. This is a favorable comparison showing that the model is simulating downward leakage that corresponds very well with measured values. The calculated leakage rates are higher than the actual mine discharge rates, but this discrepancy can be accounted for because: 1) the mine does not extend under the full area of the aquifer being modeled; therefore, some water will leak into the undisturbed coal rather than the mine and probably continue downward into the underlying Mercer Formation, 2) leakage water is pooled within the mine for a period of time, thus allowing some vertical leakage into the underlying Mercer Formation.

Simulation of Connector Well Dewatering

Once the groundwater model was satisfactorily simulating the flow system, stress involving various hypothetical connector well systems (variable well numbers and spacing) was applied. The responses of the flow system and the leakage into the underground mine were determined for each hypothetical dewatering scheme, enabling the relative effectiveness of each scheme to be evaluated.

A dewatering well would hypothetically be screened the entire thickness of the Clarion sandstone. No well can completely dewater the aquifer immediately adjacent to the well bore, for there will always be a small seepage face existing. According to model design, wells must be assigned constant discharge rates. Thus, to simulate a connector well, the discharge rate for each well was gradually increased until the water level approached the base of the aquifer. Although wells were not placed on known positions of fracture traces or fracture-trace intersections, the potential hydraulic effects of wells placed on fracture traces were simulated by assigning the effective radii of wells to be 0.61 or 1.22 m. The large radii account for the increased storage and higher permeability of the fracture zones; the actual effective radii of such wells are not known, but are greater than the mechanical well radii.

The first dewatering simulations utilized 5 wells (locations are shown on Figure 5), and the following generalizations can be made: 1) very little water (<5.66 m^3 per day) can be drained by the wells on a continuous basis when the sandstone permeability is less than 0.16 m/day, 2) flow rates into wells were small (8.50 to 42.5 m^3/day) when sandstone permeability equalled 0.30 to 3.0 m/day, 3) flow rates into wells were much higher when sandstone permeability exceeded 3 m/day, and 4) the reduction in vertical leakage into the underlying mine ranged from 0.0 to 0.5 percent as a result of five dewatering wells.

Based on the preliminary simulations using 5 wells, more extensive dewatering systems of 25 wells were tested. Because only small sustained yields of water flowed to the wells where sandstone permeability was less than 0.305 m/day, the first 25-well test was run under the following conditions: well radii = 0.61 m, sandstone permeability = 0.305 m/day, shale permeability = 0.0003 m/day, and recharge rate = 0.00007 m/day. An aerial view of the potentiometric surface generated under these conditions (without connector wells) is shown in Figure 6. The maximum decline in water level for an aquifer block containing a connector well was only 4.02 m. The overall effects of the 25-well dewatering system is summarized in Table 2. The range of yields for the connector wells was 4.25 to 27.75 m^3/day and average 12.91 m^3/day. The decrease in leakage rate was only 0.49 percent.

Since connector wells in an aquifer where sandstone permeability = 0.30 m/day do not appear to produce a significant reduction in leakage, a second test was conducted where permeability was assigned the value of 3.0 m/day. The potentiometric surface generated under these conditions has a geometry very similar to the one presented in Figure 6, but is generally 0 to 4.6 m lower in elevation. The maximum decline in hydraulic head of a block containing a well was 6.6 m. The effects of this dewatering system is summarized in Table 2. The well yields ranged from 21.0 to 128.3 m^3/day and averaged 71.4 m^3/day. Vertical leakage from the aquifer was reduced by 2.44 percent (5 times more effective than the previous test where sandstone permeability = 0.30 m/day).

Both tests involving 25 wells were run again after one of the wells (location i=21, j=29) was removed. By comparing the potentiometric surfaces of the 25-well and 24-well systems, the extent of interference effects between dewatering cones of adjacent wells could be evaluated. When sandstone permeability = 0.30 m/day, removal of the well located at block (21,29) caused a recovery of 1.58 m in aquifer block (21,29), about 0.61 m in adjacent blocks (183 m distance), and about 0.15 m at 396 m distance. Water levels in wells (23,28; 22,30; and 19,28) located in the proximity of block (21,29) recovered from 0.61 to 1.22 m. When sandstone permeability = 3.0 m/day, water level in block (21,29) recovered about 1.83 m, water levels in adjacent blocks recovered 0.91 and 0.52 m at distances of 183 and 396 m respectively, and water levels in neighboring wells recovered 1.68 to 2.29 m when the well at block (21,29) was eliminated. From these tests it becomes evident that if additional wells were brought into the dewatering system and spaced less than 300 m apart, detectable interference effects of spreading cones of depression would likely occur. By adding additional wells, more water would certainly be drained from the aquifer, but placement of additional wells would slightly decrease the sustained yield and dewatering effectiveness of each individual well.

From the information obtained in the 25-well dewatering simulations, the following generalizations can be made.

1) Higher sandstone permeabilities ($\geq$3.0 m/day) are more conducive to dewatering; 25 connector wells could potentially decrease vertical leakage into the Mid Penn No. 4 Mine by 2.44%, if sandstone permeability = 3.0 m/day. Sustained

Table 2. Dewatering Simulations Utilizing 25 Wells

Before Dewatering	Sandstone Perm. = 0.30 m/day Shale Perm. = 0.0003 m/day Recharge Rate = 0.0007 m/day	Sandstone Perm. = 3.0 m/day Shale Perm. = 0.0003 m/day Recharge Rate = 0.0007 m/day
Recharge Rate	35469 m^3/day	35469 m^3/day
Boundary Flow	-573 m^3/day	-2423 m^3/day
Leakage Rate	-35939 m^3/day	-35285 m^3/day
During DeWatering		
Recharge Rate	35469 m^3/day	35469 m^3/day
Boundary Flow	-567 m^3/day	-2195 m^3/day
Leakage Rate	-35764 m^3/day	-34423 m^3/day
Range of Well Discharge Rates	-4.2 to -27.8 m^3/day avg. = -12.9 m^3/day	-21 to -128 m^3/day avg. = -71.4 m^3/day
Combined Well Discharge Rates	-322 m^3/day	-1784 m^3/day
Percent Decrease in Leakage Rate	0.49	2.44
Percent Decrease in Leakage Rate/Well	0.02	0.098
Percent Decrease in Boundary Flow	0.98	9.38

Negative numbers represent discharge from aquifer.

yields for wells where permeability equals 3.0 m/day are about 5 times greater than sustained yields of wells where sandstone permeability is equal to 0.30 m/day.

2) Dewatering of the sandstone aquifer decreased boundary flow (springs and seeps in outcrop area) by 9.38% when sandstone permeability equalled 3.0 m/day and by 0.98% when sandstone permeability equalled 0.30 m/day. Residential wells in outcrop areas would not be perceptibly affected by well dewatering.

3) A large number of wells will be required to affect significant reductions in leakage rate into the mine. The effectiveness of dewatering wells could be higher (thus requiring less wells) if the permeability of the Clarion sandstone is higher than estimated or if location and placement of wells in fracture zones can significantly increase sustained yields of the wells above that estimated.

Conclusions

Significant reduction of leakage rate of water into the Mid Penn No. 4 Mine by connector wells does not seem to be feasible under the geologic, hydrologic, and mining conditions identified in this study. However, additional drilling would provide detailed data so that connector well dewatering could be more accurately simulated and evaluated. Based on the simulations where sandstone permeability was greater than 3.0 m/day, aquifer dewatering and reduction of leakage into a mine to reduce mine discharges could be very successful. The model used for this study was a two-dimensional, finite-difference model (Trescott, 1975), with slight modifications. Some additional modifications and experimentation, such as developing techniques to better represent aquifer boundary conditions, would be useful. Three-dimensional and finite-element models could also be utilized for mine drainage dewatering feasibility studies.

With great concern and money being spent on water quality control and mine drainage abatement projects at present, the technique of connector well dewatering merits consideration for additional studies and actual demonstration projects. Because of increasing legal responsibilities and costs for mine drainage treatment, this abatement technique also has great potential benefits for active underground mines. The costs of diverting good quality groundwater away from a mine will be much less than treating acid water discharges.

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