IC 9024

Bureau of Mines Information Circular/1985

Feasibility of Water Diversion and Overburden Dewatering

By Noel N. Moebs and Michael L. Clar

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES 75TH ANNIVERSARY 1910 1985

Information Circular 9024

Feasibility of Water Diversion and Overburden Dewatering

By Noel N. Moebs and Michael L. Clar

UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
Robert C. Horton, Director

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. administration.

Library of Congress Cataloging in Publication Data:

Moebs, Noel N

Feasibility of water diversion and overburden dewatering.

(Information circular / United States Department of the Interior, Bureau of Mines ; 9024)

Bibliography: p. 47-49.

Supt. of Docs. no.: I 28.27:9024.

1. Mine drainage. 2. Mine water. 3. Coal mines and mining—Appalachian Region. I. Clar, Michael L. II. Title. III. Series: Information circular (United States. Bureau of Mines) ; 9024.

TN295.U4 [TN321] 622s [622'.334] 84-600364

CONTENTS

CONTENTS--Continued

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	km	kilometer
cm^2/s	square centimeter per second	km^2	square kilometer
ft	foot	L	liter
ft^2	square foot	lb/in^2	pound per square inch
ft^3	cubic foot	lb/ton	pound per ton
ft^3/s	cubic foot per second	L/d	liter per day
gal	gallon	L/s	liter per second
gpd	gallon per day	m	meter
gpd/ft	gallon per day per foot	m^3	cubic meter
gpd/ft^2	gallon per day per square foot	mg/L	milligram per liter
gpd/mi^2	gallon per day per square mile	mi^2	square mile
gpm	gallon per minute	pct	percent
h	hour	ppm	part per million
hp	horsepower	t	metric ton
in	inch	ton/yr	ton per year
in/h	inch per hour	tpy	metric ton per year
kg/m^2	kilogram per square meter	yd^3	cubic yard
kg/t	kilogram per metric ton	yr	year

FEASIBILITY OF WATER DIVERSION AND OVERBURDEN DEWATERING

By Noel N. Moebs[1] and Michael L. Clar[2]

ABSTRACT

The Bureau of Mines studied the feasibility of water diversion and overburden dewatering for underground coal mines in the Appalachian region. All relevant published literature pertaining to the occurrence and control of surface and ground water in underground coal mines was reviewed, and the impacts of mine water with respect to health and safety, production, environment, and costs were assessed and are described in this report. The report also identifies the sources of water inflow into underground coal mines, and gives a summary description and evaluation of techniques that can be used to reduce the amount of water entering these mines. Engineering practices currently used by operating coal mines in the Appalachian region to prevent the movement of ground and surface water into active coal workings were reviewed and are summarized. Major emphasis has been placed on the identification of geologic and hydrologic conditions of the site, the water control methods used, and an evaluation of their technical and cost effectiveness.

[1]Geologist, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.
[2]Vice president, Hydro-Terra, Inc., Columbia, MD.

INTRODUCTION

This report presents the results of a study undertaken by the Bureau of Mines to determine the feasibility of water diversion and overburden dewatering techniques in advance of underground coal mining operations in the Appalachian coal districts.

The presence and, in particular, the ponding of water in the active workings of underground coal mines can be very detrimental to health and safety, production, costs, and the environment. The negative impacts that a wet mine has in these areas are generally well recognized. However, there exists no comprehensive and quantitative reporting of these impacts in the published literature.

In the Appalachian coal districts, where major underground mine expansions are anticipated, drainage in the coal mines is extremely variable. The volume of water to be handled, which is typically expressed in terms of tons of water pumped out of the mine for every ton of coal mined, can range from an average of 5 tons in the Pennsylvania bituminous mines to 36 tons in the anthracite region.

Several approaches have been proposed either to dewater the mine area in advance of mining or to substantially reduce the amount of water reaching the mine area by diverting or reducing the infiltration of surface waters. Many of these methods, however, address hypothetical conditions rather than actual situations. Some of the literature treats special situations such as preventing water from entering through boreholes, subsided or stripped areas, or surface streams entering through old mine openings. Some researchers have addressed water diversion and well dewatering techniques as control measures and proposed routing and rechanneling of surface flow as an effective method of excluding water from mines.

Although the methodology for implementing these approaches is not new, to date both the application and the success of these methods in underground coal mines have been limited. Consequently, these methods have not found widespread use in the coal industry in the United States. The most common approach to handling water in underground mines consists of collecting the water by gravity and pumping the water back out to the surface where treatment is provided if needed, prior to discharging to the receiving streams.

The still recent Surface Mining Control and Reclamation Act (SMCRA) and the ensuing permanent regulatory program of the Office of Surface Mining (OSM) represent an additional consideration. Several general requirements are stipulated that are related to the effects of underground coal mining activities on the hydrologic balance:

> Section 817.41 Hydrologic Balance: General Requirements[3]
>
> (a) Underground mining activities shall be planned and conducted to minimize changes to the prevailing hydrologic balance in both the mine plan and adjacent areas, in order to prevent long-term adverse changes in that balance that could result from those activities.
>
> (b) Changes in water quality and quantity, in the depth to ground water, and in the location of surface water drainage channels shall be minimized so that the approved postmining land use of the permit area is not adversely affected.
>
> (c) In no case shall Federal and State water quality statutes,

---

[3]U.S. Code of Federal Regulations. Title 30--Mineral Resources; Chapter VII--Office of Surface Mining Reclamation and Enforcement, Department of the Interior; Subchapter K--Permanent Program Performance Standards; Part 817--Underground Mining Activities; July 1, 1981.

regulations, standards or effluent limitations be violated.

(d) Operations shall be conducted to minimize water pollution and, where necessary, treatment methods shall be used to control water pollution.

(1) Each person who conducts underground mining activities shall emphasize mining and reclamation practices that prevent or minimize water pollution. Changes in flow shall be used in preference to the use of water treatment facilities.

(2) Acceptable practices to control and minimize water pollution include, but are not limited to--

(i) Stabilizing disturbed areas through land shaping;

(ii) Diverting runoff;

(iii) Achieving quickly germinating and growing stands of temporary vegetation;

(iv) Regulating channel velocity of water;

(v) Lining drainage channels with rock or vegetation;

(vi) Mulching;

(vii) Selectively placing and sealing acid-forming and toxic-forming materials;

(viii) Designing mines to prevent gravity drainage of acid waters;

(ix) Sealing;

(x) Controlling subsidence; and

(xi) Preventing acid mine drainage.

(3) If the practices listed at paragraph (d)(2) of this section are not adequate to meet the requirements of this part, the person who conducts underground mining activities shall operate and maintain the necessary water treatment facilities for as long as treatment is required under this part.

As the above clearly indicates, any method proposed for use must include a thorough assessment of the impact it may produce on the hydrologic balance of the mine site and will require the approval of this new regulatory agency (OSM) or the appropriate State agency.

The combined concerns for environmental protection and for a safe and productive workplace demand additional studies and research on the feasibility of water diversion and overburden dewatering to advance the state of the art. The performance characteristics of these methods need to be evaluated and documented. It is unlikely that widespread use of such methods will occur until sound quantitative data that justify their use are presented.

This Bureau research project was undertaken to study the feasibility of water diversion and overburden dewatering in advance of mining in underground coal mines in the Appalachian coal districts. This basic objective was accomplished through--

1. A review of the literature relative to preventing surface or shallow ground water from entering underground coal mines. The literature evaluation focused on three major areas: (1) the impacts of mine water, (2) sources of water inflow to underground mines, and (3) available water control practices.

2. An on-site review and analysis of current engineering practices. Three individual case studies are presented in appendixes A, B, and C.

The combined results of the literature evaluation and on-site review are summarized in this report.

ACKNOWLEDGMENTS

The authors are grateful for the cooperation of numerous coal mining companies who contributed information for this study. In particular, the authors wish to thank the Barnes and Tucker Co., Jones and Laughlin Steel Corp., and Mettiki Coal Corp., for information used in compiling the case studies. John J. Ferrandino and Connie Bosma of Hittman Associates, Inc., contributed substantially to the text and data collection.

Figures A-3, A-4, A-5, A-6, A-7, A-8, and A-9 were adapted from illustrations by W. A. Wahler in "Dewatering Active Underground Coal Mines: Technical Aspects and Cost Effeciveness" (38).[4] Figures 3, 4, and 5 were adapted from illustrations by H. L. Lovell and J. W. Gunnett in "Hydrological Influences in Preventative Control of Mine Drainage From Deep Coal Mining" (19).

IMPACTS OF MINE WATER

An understanding and a quantification of the extent to which water can benefit or impede underground coal mining operations is a prerequisite to conducting an assessment of the effectiveness of available water control practices. For the purposes of this study, the effects of mine water have been organized into four categories: (1) health and safety, (2) production, (3) environment, and (4) costs.

Most recent publications underemphasize the health, safety, and productivity problems associated with water in underground mines, and instead focus on the environmental effects of mine water. In underground mines in the Pennsylvania anthracite region, 36 tons of water are pumped out of the mine for every ton of coal mined. In the bituminous coal mines, this average is between 5 and 6 tons of water for every ton of coal.

Regardless of the water source, the determinants of the water problems in a mine are (1) the rate of inflow, (2) the mode and location of inflow, and (3) provisions to handle the inflow. A uniform rate of inflow will not normally present severe problems in designing a pumping plant. However, unforeseen high inflow rates have the potential to cause major disruptions in normal activities.

Water seeping into the mine at locations far removed from the active workings can be directed to suitable sumps and pumped out of the mine. When the inflow is in the active workings and is a slow seepage, the water can be allowed to accumulate and can then be pumped out to a section sump using portable pumps. Water problems tend to become critical when high inflow rates are generated in active workings by the advance of the work itself.

HEALTH AND SAFETY

In defining the significant effects of water on health and safety in the workplace, the following factors must be considered: (1) inrushes of water, (2) ventilation, (3) roof conditions, (4) maintenance problems, (5) corrosion, and (6) miscellaneous effects.

Inrushes of Water. - The Appalachian coal districts are the oldest coal mining districts in the country. New mines in these districts are often adjacent to and/or below older abandoned mines. Since these older abandoned mines are often flooded, they behave as underground water reservoirs, and the potential for inrushes of water must be considered in siting new mines. This concern is likely to increase in the future as the number of new mines grows, particularly since these new mines will often be sited in the deeper seams underlying the older waterlogged workings. The Bureau has developed guidelines to prevent and control the inrush of mine waters. These guidelines include the work by Wardell (40) and Skelly and Loy (32).

---

[4]Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

Ventilation. - Water can affect a mine's ventilation in three ways: It can aggravate the heat and humidity problem, increase the methane emission, and block the ventilating airways.

Roof Conditions. - Several studies have been performed on the influence of humidity on roofs in underground mines. These studies indicate that roofs composed of soft shales or some form of clay, with mud partings, are most vulnerable to failure. Sometimes an effort is made to recover an upper seam that was not mined before a lower seam was extracted. In this case, the subsidence in the overlying strata, as a result of the lower seam mining, can cause roof control problems. Cracks and fissures in the broken strata may be filled with mud and clay. When the upper seam is developed for mining, water tends to wash into these fillings and create weakened roof conditions. Water seeping through strata is indicative of poor strata conditions.

Roof collapses are often associated with the presence of water in conjunction with geologic unconformities. Water will act as a lubricant to decrease frictional resistance to movement of rock strata. Lubrication of a slip surface, such as a slickenside, requires only small volumes of water or moisture, although the precise amount has yet to be quantified. It is known, however, that the moisture supplied by the mine ventilation system is sufficient to cause failure in weak shale roofs.

Maintenance Problems. - Water in mines creates special problems in the operation of electrical equipment. Whereas permanently located electrical equipment can be adequately protected from water, mobile equipment cannot be so easily protected. Trailing cables and trolley wires are of greatest concern from a safety point of view. Defective splices and breaks in the insulation of cables have been responsible for severe shocks and burns [Mason (21)]. Trailing cables of all types are used at or near the coal face, where they are most likely to be damaged. Trailing cables are continually being handled, in many cases under wet conditions; therefore, there is always the danger of electrical shocks should a fault arise.

Water tends to carry dirt and clay into exposed bearings, sockets, conveyor chains, and other machinery parts, increasing the frictional resistance to movement. In addition to the increased wear and tear, this can result in excessive heat generation. If unattended for long periods of time, the frictional heat can cause a fire.

Corrosion. - Although most corrosion of mining equipment is minor, serious corrosion can occur under certain circumstances. This problem is discussed in detail in papers by White (41) and Kenny (16). According to White, mine water can be classified as follows:

Type	pH
1--Highly acid................	1.5- 4.5
2--Soft, slightly acid.........	5.0- 7.0
3--Hard, neutral to alkaline...	7.0- 8.5
4--Soft, alkaline.............	7.5-11.0
5--Highly saline..............	6 - 9
6--Soft, acid.................	3.5- 5.5

In laboratory tests, it was found that water fitting the description of types 1 and 5 causes corrosion. Type 1 water is most corrosive because of the free sulfuric acid and ferric ions. Usually pyrite in the coal seams is the source for this water. Type 5 water contains a high concentration of dissolved salts, particularly sodium chloride. The salt may come from the strata and is highly corrosive as a result of the high electrical conductivity and of the interference to the rust-forming process.

Miscellaneous Effects. - The accumulation of water in the mine makes it unpleasant to work, and cuts down on work time and efficiency. More importantly, it may lead to an increase in accidents.

Although dangers from water account for a relatively small portion of accidents resulting in injuries and deaths, there is always the possibility of serious disasters when mining activity is in the vicinity of large bodies of water. Even if the existence of a water body is known, its exact location and the volume and head of water are usually not well defined.

Owing to the variety of problems that can occur, it is impossible to form one set of rules that can be uniformly applied in all cases. However, there are several general preventive measures that must be taken:

- The potential water danger must be studied and surveyed on a mine site, area, and regional basis to assess the full extent of the danger.

- Adequate sumps and gravity flow paths into them should be established as early as possible.

- A plan must be formulated to ensure that workers are withdrawn safely in the event of an inrush.

PRODUCTION

The productivity of a mining system has been expressed as a function of a number of major independent variables [Stefanko (34), Manula, Bouillot, Rivell, and Sandford (20), Suboleski (35)]. Excluding the mechanical equipment and the human element, these independent variables include (1) roof quality, (2) methane liberation, (3) bottom quality, (4) water, (5) grades, (6) hardness and strength of seam, (7) seam height, and (8) depth of seam.

To some extent these all are interrelated with the presence of water; however, each can also be a factor independent of others--for example, the roof may simply be weak and the floor may have little bearing strength even when dry.

ENVIRONMENT

Underground coal mines can have an impact on both the quantity and quality of surface and ground waters. The impact on water quality has long been recognized and regulated by both State and Federal agencies. These regulations generally require that mine waters be treated to neutralize and remove pollutants prior to discharge to receiving streams. Consequently, some information is available related to the technology of controlling this impact.

All of the water pumped from the mine will generally require treatment. A number of dewatering schemes have been proposed based on the assumption that by intercepting the ground water before it contacts the mining operation, the requirement for treatment and the related cost could be avoided.

The impacts of underground coal mines on water quantity can be short term or long term and can occur both during active mining and after abandonment. The two most noticeable and immediate impacts are changes in water levels and ground water flow. Lowering of the water table level or a decrease in ground water flow can result in the dewatering of shallow wells and the loss of ground water supplies.

The mechanisms that cause these hydrologic impacts include (1) the removal of the coal seam, resulting in underground cavities that serve as broad sinks or underdrains, which receive ground water percolating downward from overlying strata, (2) the fracturing and separation of overlying strata resulting from the removal of the coal seam, and (3) the removal of the water from the mine by gravity drainage in the case of updip drift mining or by pumping in downdip drift, slope, or shaft mining.

It must be pointed out that use of a dewatering technique will also result in changes (lowering) of water levels and will reduce ground water flows. Thus, the same type of hydrologic impacts will be experienced during mining. The dewatering techniques will not prevent the development of the mechanisms discussed above. Consequently, the hydrologic impacts will continue to be experienced after the mining operation is completed.

A recent investigation suggests that the hydrologic impacts of underground mines may be less severe in the future. An inventory of water levels in domestic wells in Marion County, WV, showed that

TABLE 1. - Relationship between mine depth and well dewatering

Mine depth, ft	Effect on wells completed above mining zone
<200.........	All wells permanently dewatered.
200 to 250....	Most wells permanently dewatered.
250 to 300....	Some wells occasionally dewatered.
>300.........	No wells dewatered.

Source: Sgambat, Labella, and Roebuck (30).

variations in long-term dewatering are related to mine depth [Rauch (27)]. A similar investigation (table 1) found that when the mine depth exceeded 300 ft (91 m), no wells completed above the mining zone were dewatered. A recent survey of 325 operating sections in Appalachia revealed that 92 pct of the surveyed sections were 300 ft (91 m) deep or more. The average depth was 600 ft (183 m), and the most frequently reported depth was 500 ft (152 m). These data suggest that dewatering of wells by underground mines may not be a frequent occurrence in the future.

COSTS

Mine water can affect mining costs in both direct and indirect ways. The direct costs associated with mine water include costs for--

- Water handling (collection, treatment, and disposal).
- Coal preparation (additional costs).
- Miscellaneous wet and waterproof pay items (such as blasting agents).

The indirect costs include--

- Additional costs of time lost owing to health and safety aspects: ventilation, floods and inrushes, and roof support.
- Productivity losses.
- Cost associated with additional maintenance requirements.

The literature review revealed that there is very little information available on the direct costs associated with mine water and even less on the indirect costs. Mining companies do not normally separate water-related costs from other costs in much detail. To date, water treatment costs are the only direct cost that has been thoroughly investigated. (The available data on water treatment costs are too extensive to summarize in this report, but selected references were reviewed and are given in the reference list at the end of this report.)

Figure 1 presents a comprehensive summary of water-handling costs experienced by an underground mine in central

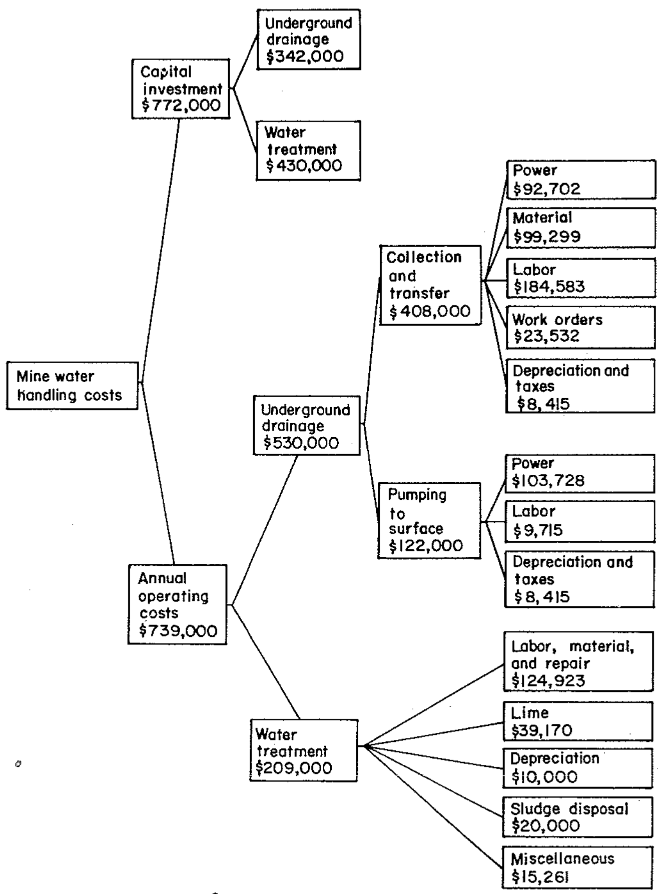


FIGURE 1. - Summary of cost analysis of water handling at one mine (38).

Pennsylvania and serves to illustrate the major cost components (38). The water-handling costs for this mine were generated as part of a study to evaluate the effectiveness of dewatering an active mine from the surface, which represents a rare situation where cost data have been reported. The practicality of establishing standard figures for the industry is questionable because of the great variation in physical factors such as depth, water quality, size of mine, geology, and engineering methods. However, examination of costs incurred by mines within local mining districts operating in the same coal seam might yield useful planning guidelines.

Information on the indirect costs of mine water was very scarce. The indirect costs associated with the effects of mine water on health and safety and with additional maintenance requirements have yet to be quantified. A partial assessment of the indirect cost resulting from the impact of mine water on production can be generated based on the work of Suboleski (35).

According to Suboleski, a reduction in the range of 32 to 50 tons (29 to 45 t) of coal per shift might be experienced between a mining section with a dry, hard floor and a section with a wet, rutted, and slippery floor. Assuming that the section operates three shifts per day, and 220 days per year, a decrease in production ranging from 21,120 to 33,000 ton/yr (18,000 to 29,700 tpy) per section would result. Assuming a selling price of $20 per ton, a potential production loss ranging from $422,400 to $660,000 annually per section would be suffered.

SOURCES OF INFLOW TO UNDERGROUND MINES

BACKGROUND

Problems associated with water inflow into underground coal mines have an important effect on the cost and progress of the mining operations. Greater knowledge and increased efficiency in reducing the risk of sudden water inflows, in improving stability, and in reducing dewatering and mining costs are goals at many underground operations. To identify the best approaches to mine water control, it is necessary, as a first step, to identify the sources of water infiltration into the mine. Once the sources are identified for any given mine, the potential solutions to reduce or control the water problem can then be developed.

Water may enter mine workings via a number of different avenues. Water-bearing strata that are in contact with the coal seams can be sources of inflow. These strata include sandstones and limestones, which are associated with the coal seams, and any unconsolidated deposits, such as sand and gravel, which may lie above the coal seams. In addition, the coal seams themselves may contribute water to the mining environment and, therefore, deserve consideration as a source.

The development of an underground mine alters the natural ground water flow patterns. The extent of the alteration is dependent on the geohydrology of the site and the type of mining system used. These aspects are briefly reviewed.

Water may also enter shallow coal mines via seepage from surface water bodies or through general surface infiltration. The amount of water entering the mine will depend upon the nature of the strata above the mine and the depth to the mine.

Earth fractures, such as faults, fracture zones, joint systems, and subsidence fractures, also allow water to enter underground mines. These fractures tend to localize inflow and destroy the confining effect of any relatively impermeable beds above the coal. They are the prevalent avenue by which water enters underground coal mines in the Appalachian coal region.

Water may also enter underground mines through manmade pathways. Abandoned deep mines and active and abandoned strip mines can serve as sources of water accumulation and infiltration. Water from these sources can enter the mine workings directly through barrier pillars and interconnections, or these pathways may facilitate the entry of surface runoff into the ground water system, which eventually works its way into an underground mine. In addition, boreholes, abandoned wells, shafts, and mine openings also serve as water collection points and direct conduits to underground mines by tapping overlying aquifers and collecting surface waters.

WATER ENTRANCE INTO MINES

The quantity of water varies with local conditions during the construction or later development of many mines. Some mines are dry, while in others the weight of water to be removed is many times that of the coal raised to the surface. For example, at the Colver Mine in West Virginia, the pumping load averages approximately 31 tons of water per ton of coal produced, while the Sonman Mine in West Virginia pumps 33 tons of water per ton of coal produced [Coal Age (8)].

Water may enter mine workings in several ways:

1. From water-bearing strata that are in contact with coal seams;

2. Through shallow mines from surface seepage;

3. Through faults and fractures in coal seams and adjacent strata;

4. Through active sections from abandoned workings.

There is considerable overlap in the ways that water enters the mine workings. For example, water may enter simultaneously through water-bearing strata in contact with the coal seams and through faults and fractures from the same overlying strata. Water may also enter from the surface via percolation or through faults and fractures that run through to the surface. Also, percolated water from the surface may be the source of water for faults and fissures, which may later feed the mine. Here, these pathways will be dealt with separately, but under natural conditions water may enter the mine workings through any means possible, no matter where it originates.

In considering the problem of water passing into the mine workings, it is essential to take into account:

1. The prevailing geologic and hydrologic conditions, including the composition and permeability of the associated coal strata and the presence of any discontinuities such as faults, joints, or igneous intrusions.

2. The depth of the mine workings and thickness of the coal seam being mined.

3. The mining system employed and its effect on the prevailing geologic conditions.

Underground coal mines can create a measurable change in water levels and ground water flow as a result of removal of water, coal, and rock from the mine. The removal of the water occurs by gravity drainage in the case of updip drift mining or by pumping in downdip drift, slope, or shaft mining.

Ground water movement through aquifers from areas of higher piezometric pressure to regions of lower piezometric pressure has been described as follows [Wilson, Mathews, and Stump (43)]: When a mine shaft sinks into water-bearing strata, it creates a region of lowered piezometric pressure, causing water to flow from the strata to the mine shaft, which in turn drains water from the pores and crevices in the strata. If pumping is started to remove the water, the flow into the shaft continues as the piezometric pressure in the shaft is lowered. As pumping continues, the water level is artificially depressed and assumes the shape that a stretched membrane would have if punched downward with a stick. The water table has the shape of a flat, inverted cone with its apex at the shaft, known as the cone of depression. However, it is not a true cone, since its sides, when viewed in cross section, are not straight lines, but curves that steepen toward the shaft.

The flow of water into a mine shaft is heaviest when sinking begins. If sinking of the shaft is halted and pumping continues at a steady rate, the flow into the shaft gradually decreases and after some time becomes virtually constant, equaling the rate of recharge. Accordingly, the cone of depression assumes a shape that is practically stable, as the flow of water into the shaft reaches a state of equilibrium with the supply of water entering the aquifer and percolating through it. If shaft sinking is resumed, the process is repeated; the new cone is deeper and requires a higher rate of pumping to keep it drained.

If a drift is extended from the bottom of the shaft, the cone of depression is no longer a symmetrical cone; what was formerly the point of the cone is elongated into a horizontal line, with the water table sloping upward from it at both sides and at the ends. If closely spaced crosscuts are driven from the drifts, the cone assumes the form of a bathtub with flat-sloping sides. If upper levels are now driven from the shaft, they will encounter little water until they are out far enough to reach the sides of the cone. They will then begin to tap the water reservoir, diminishing the flow that enters the deepest workings.

The creation of the cone of depression by shaft sinking provides piezometric highs and lows and allows for the flow of water into the mine when the shaft is lowered through water-bearing strata.

Detecting water-bearing strata and measuring water levels and water movement are being increasingly recognized as a necessity for determining the economics of mining. Drilling is a means of accomplishing this. Water levels and water movement can be delineated and studied by plotting the data on water level contour maps, water level change maps, and well hydrographs.

Gallaher of the U.S. Geological Survey performed a study in West Virginia that included the drilling of 28 boreholes (43). In addition, 137 other private and public wells were investigated. The study determined the effect of deep mining on ground water movement. The data were correlated with information gathered from seasonal and areal distribution of precipitation, and the conclusions were--

1. No two mines are expected to be alike in environment, hydrology, source of pollution, or treatment.

2. Mining can affect speed, course, and quality of water moving through the mining area.

3. Mining accelerates the natural flow and hydrogeological conditions already existing in the area basins.

4. Water under pressure as a result of flow through strata located at elevations above the mine workings can enter the mine from all directions, including the floor.

5. The chemistry of the ground water depends primarily on the composition of the minerals with which it comes in contact.

6. Water samples collected at different depths varied widely in quality. Samples taken at shallow depths were less mineralized than those taken at great depths.

COAL AND WATER-BEARING STRATA

The strata most frequently found immediately above or below coalbeds are shales, clays, and sandstones. These may form either the roof or bottom and the hanging and foot walls in pitching seams. Conglomerates are rarely found in contact with the coal but are frequently part of the rock group associated with coalbeds. This is also true of limestone beds. The water-bearing capacity of these rocks will depend on their depth, since the capacity of a rock to store and transmit water will decrease with depth, owing to the increasing pressure of the overlying strata.

Shales are generally the desired roof materials when coal is mined. This is because they are aquitards, having only minor ground water leakage through them. An exception to this condition is when clay veins or similar structures are present. Clay veins are slickensided wedges of indurated clays and silts that penetrate the coalbed from either above or below. They can be vertical or form an angle of about 45° with the vertical. Clay veins encountered in mines are usually crooked and angular and interfinger with the coal. They have thicknesses ranging from 1 in (2.54 cm) to several feet (a few meters) and may be hard enough to damage mining equipment. Clay veins generally extend into the strata immediately overlying the coalbed, breaking up the lateral continuity of the layered roof strata, causing roof instability. Water can then flow into the mine through these zones.

Coal itself acts as a minor aquifer since it possesses a fracture permeability, although transmissivities appear to vary from well to well by a factor of a hundred or more. Transmissivities range from less than 100 gpd/ft (0.14 cm^2/s) to over 10,000 gpd/ft (14 cm^2/s). An important aquifer characteristic of this unit is its widespread continuity.

Sandstone is formed chiefly by accumulation of sands in shallow water adjacent to land from which stream action carries the material. Many of the massive sandstones are extensively jointed. Even a rock that has little or no water-bearing capacity may yield water from joint openings.

In Pennsylvania, the Allegheny Sandstone yields from 50 to 300 gpm (3.2 to 19 L/s), while the Pottsville Sandstone yields from 100 to 400 gpm (6.3 to 25 L/s). The Pocono Formation of Pennsylvania has also yielded from 300 to 600 gpm (19 to 38 L/s) in some places. The Triassic sandstones of Pennsylvania, particularly those incorporating conglomerates and fanglomerates, yield as much as 200 to 300 gpm (13 to 19 L/s). The Pottsville in West Virginia has also yielded over 250 gpm (16 L/s). On the average, sandstone aquifers yield 50 gpm (3.2 L/s) and are an excellent source of water for communities throughout the Appalachian region [Lohman (18); Doll, Meyer, and Archer (11)].

Limestone is a hard sedimentary rock composed chiefly of calcium carbonate, a calcareous sediment that may at first contain a large proportion of interstitial space; however, subsequent solution and recrystallization accompanying compaction may ultimately produce a limestone with very little original porosity. A seemingly impermeable rock may be rendered permeable by joints or fractures, or by the development of solution passages. Solution passages in limestone result from the solvent action of circulating ground water charged with carbon dioxide and usually follow preexisting joints or bedding planes.

When the rock is deeply buried and the ground water circulation is sluggish, or when the rock has not been long subjected to solvent action, the solution passages may be few and small. If, however, the topography and geologic structure have favored rapid circulation, and conditions have been stable over long periods, the rock may be rendered cavernous. Some solution passages are large enough to carry the entire flow of a stream. The term "lost river" has been applied to a stream that disappears completely underground in limestone terrain. Large springs are frequently found in limestone areas.

This solution of limestone proceeds most rapidly above the water table, where downward movement of the water is relatively vigorous and the supply of carbon dioxide is adequate. Below the water table, the content of dissolved carbon dioxide, and consequently the solvent power of the water, becomes depleted. The largest yields are obtained from limestone that has been depressed with relation to the water table, so that its upper, cavernous areas become submerged and saturated. Ultimate development of a limestone terrain forms a karst region where subterranean drainage through the limestone creates large ground water reservoirs.

In Pennsylvania, both the Cambrian and Ordovician limestones and dolomites yield abundant supplies of ground water. These rocks are more or less fractured, and solution channels have been created. Most of the wells yield adequate supplies ranging from 100 to 1,000 gpm (6.3 to 63 L/s). Boiling Springs, in Cumberland County, is the largest spring in Pennsylvania and yields 13,500 to 20,600 gpm (850 to 1,300 L/s). Bellefonte Spring, in Centre County, yields roughly 14,000 gpm (880 L/s). The Devonian age Helderberg Limestone also yields moderate to large supplies of water in Pennsylvania, while the springs of the Mississippian age Greenbrier Limestone of West Virginia yield more than 140 gpm (9 L/s) (18).

As previously stated, while they remain intact, the shales and clays immediately above and below the coal will not allow water to infiltrate the mine workings. Occasionally though, the shale above the coal or the underclay is absent. Then sandstone, and less frequently limestone, is adjacent to the coal. This may result in the transmission of many thousands of gallons of water into the mine, depending on the depth of the mine. In the Cahaba Coalfield of Alabama [Johnston, Foster, and Howard (15)], conglomerates and porous strata directly above the coal seams transmit water into the mines, resulting in the need to establish a pumping system to keep the mine dry. In central Pennsylvania [Parizek, Sgambat, and Clar (24)], when the shale above the coal pinches out and sandstone lies on the coal, it is usually fractured into blocky shapes and is very difficult to support.

Unconsolidated deposits of glacial, marine, and alluvial origin can store and transmit huge quantities of water and can cause problems when in proximity to any coal workings. Ninety percent of all developed aquifers consist of these types of deposits [Todd (36); UOP, Inc. (37)]. They are widely distributed and have caused considerable trouble to miners in the past. The anthracite region of Pennsylvania has been especially plagued with this type of problem and deserves mention here, even though it is not part of the Appalachian bituminous coal region. It is estimated that the northern anthracite field of Pennsylvania contains 10 billion tons (9.1 billion t) of these deposits, or a sufficient quantity to cover the 176 mi^2 (450 km^2) of coal area to a depth of about 26 ft (8 m) [Bunting (7)]. These deposits overlying coal measures attain a maximum depth of more than 300 ft (91 m). The materials vary widely in particle size and degree of sorting, with a corresponding variation in their water-yielding capacities. However, many are often saturated to the point of being semifluid. It is this condition of fluidity that limits the mining of coal seams cropping in these deposits or in close proximity to them.

A considerable number of inrushes have occurred because mine workings were too close to these deposits (7, 40).

- In 1882, the workings at the Maltby Mine in Swoyersville, PA, broke into sand and water, which filled the mine and shaft to within 65 ft (20 m) of the top in a few hours.

- In 1884, an inrush of sand and water filled the slope of the Fuller Mine at Swoyersville, PA, to the shaft level, a vertical distance of almost 100 ft (30 m).

- In 1885, the inrush of a culm bank with sand and water completely filled the gangways in the vicinity in less than 1 h at the No. 1 Slope Mine in Nanticoke, PA. The accident took the lives of 26 men.

- In 1912, an inrush of sand and water broke into the workings at the Superba-Lemont Mines in Stanton, PA, killing four miners.

- In 1914, an inrush of approximately 19,600 yd^3 (15,000 m^3) of semifluid sand and clay filled several thousand feet (a couple of thousand meters) of gangways and tunnels, and required months to clean up. The accident occurred at the Sugar Notch No. 9 Mine in Sugar Notch, PA.

- In 1917, an inrush of sand and water broke into the Wilkeson Mine workings in Wilkeson, PA, killing six miners.

- In 1927, an inrush due to a breakthrough into 200-ft (60-m) thick gravel beds killed seven miners in Carbonado, WA.

- In 1959, an inrush of water killed 12 miners at the Lehigh Valley Coal Co.-Dillston Coal Co. in Pennsylvania when the workings broke into the alluvial deposits of the Susquehanna River.

The coal seams that are being mined currently are deep enough so that they do not come into contact with these types of deposits. However, the huge quantities of water contained in these deposits may be tapped by means other than direct contact with coal workings. These means will be examined in other sections of the report.

WATER IN SHALLOW MINES

Strata will tend to store and transmit less water with increasing depth, as the porosity of the strata is affected by the increased confining pressure resulting from the weight of the overburden [Ash, Dierks, and Miller (3); Miller and Thompson (22); Wrathers, Swanson, and Langill, (44)]. This pressure also tends to close up any fissures and cracks that exist. At depths of less than 300 ft (92 m), it is comparatively easy for water to percolate to a certain varying depth as a consequence of the porosity of the surface rocks, according to Miller and Thompson. The coal measures are generally very wet to work at these shallow depths. There is a marked difference between the quantity of water pumped in summer and in winter in the areas where water can percolate rapidly into the mine workings.

Surface Seepage

The volume of water seeping into mine workings during and after any period of rainfall varies greatly in adjoining basins and even in adjoining mines in the same field because of differences in the condition of the strata as affected by the progress of coal extraction [Ash (1), Ash, Dierks, and Miller (3); Ash and Link (4); Ash, Link, and Romischer (5); Ash and Whaite (6)]. The ratio between runoff and seepage varies for each period of rainfall in any given area because of variables in (1) the rate of rainfall, (2) duration of storms, (3) rate of evaporation (depending on temperature and humidity), (4) transpiration (depending on the season and amount of vegetation), (5) status of the water table, (6) frost that seals crevices in the ground, (7) presence of anchor ice sealing stream bottoms, (8) distribution of rainfall, (9) topography, and (10) surface soil condition and type.

Surface water entering underground coal mines may originate either at a surface body or through general surface infiltration. Any bodies of surface water may contain a sufficiently large volume of water so that significant seepage into underground workings could occur. However, the most important avenue of surface water seepage is that of streambed seepage into underground waterways.

Most streams that cross coal measures usually lose some of their water, which eventually enters underground mine workings. It is usually impossible, except in small streams, to accurately measure the amount of seepage that will require the use of corrective measures. This is because the loss at any particular point is usually very small, and the distance between the point where the water left the stream and the point where it entered into the mine workings may be great.

Many different factors affect the volume of water infiltrating mine workings. The following factors play a significant role in the inflow to mines from streams (3-6): (1) quantity of water flowing in streams, (2) velocity of the water flowing in streams, (3) nature of material composing the stream channel, (4) wetted perimeter of stream channels, (5) weather conditions, (6) gradient or slope of streams, and (7) fractures in the coal measures underlying the streams.

Stream seepage will not increase significantly unless the volume of water added to the stream is enough to appreciably increase the cross section of the stream channel in contact with the water.

A noticeable increase in the depth of water flowing in the channel of a river or stream after a heavy rain indicates an increase in seepage due to the increase in the wetted perimeter of the stream channel (3). When streams are in flood stage, water spreading out beyond normal streambanks further increases seepage.

The anthracite region of Pennsylvania serves as a classic example of stream seepage into underground mines. Many of the smaller streams in the region lose all of their water soon after crossing the outcrop of the lowest anthracite bed, where they enter the area that overlies the coal measures. These streams carry water throughout their original length only during periods of heavy runoff. For the greater part of the year, their entire flow seeps into the mine workings. This flow can range from a few gallons to several thousand gallons per minute (3).

A study of larger streams indicated a marked decrease in flow between the point where they intersect the coal outcrops and the point where they flow into the main stream. This was true at almost all periods when relatively low water levels permitted comparable observations. However, at the same levels of water, such decrease did not occur when the bed of the stream was sealed by anchor ice. Consequently, a project is being undertaken in western Maryland to reline a streambed for a distance of approximately 4-1/2 miles (7-1/4 km) in order to reduce infiltration. Water currently infiltrates through the streambed at a rate of roughly 15,000 gpm (990 L/s). This water is entering abandoned underground mines, causing the stream to dry up during the summer months. The project involves putting down a clay bottom, topped by a layer of sand and a layer of riprap. The estimated cost of the project is $3.5 million.

Natural surface seepage is also a problem in permeable areas where the infiltration rate is so great that some operating companies have dug ditches and built flumes to divert the runoff into natural stream channels. In addition, mining operations have changed the configuration of the terrain, thereby affecting the original drainage patterns of the region. The continued increase in the number and size of culm banks, cinder dumps, and unreclaimed spoil banks has blocked the normal flow of water to the surface streams so much that water now collects in many low places and eventually seeps into the ground. In addition, denuding woodlands destroys a control of runoff, and solids from breakers and banks pollute and choke stream channels. The dry beds of thousands of small former watercourses are evidence of the general disturbance of the surface (3-6).

Surface Water Inrush

In considering the problems of water passing from a surface source into mine workings, the proximity of mining to a given body of water is a vital factor in the risk of inundation. Another important factor is that the height of a roof fall can be in part related to the height of workings and in part to the nature of the solid strata between the workings and the streambed.

Studies in the anthracite region of Pennsylvania are presented here to provide a clearer picture of the quantity of water capable of entering underground coal mines via stream and surface seepage. One study involved the Lackawanna Basin and the Wyoming Basin of the Northern Field, the Western Middle Field, and the Southern Field (3-6).

The Lackawanna River and its tributaries drain a troughlike area of 347 mi^2 (900 km^2). The synclinal axis of this trough lies within the coal measures. For 1948, the U.S. Weather Bureau recorded 44.9 in (114 cm) of rainfall, indicating that there were 135 billion gal (510 billion L) of runoff from the Lackawanna River drainage area. This is approximately three times the volume of water pumped for this area in 1948. Because of the pervious condition of the strata overlying the mine workings, approximately one-third of the total runoff in the Lackawanna River area becomes mine water. Approximately 22 pct of this water arrives underground as a result of direct surface seepage. In addition, an equal volume seeps into the mine workings through the pervious beds of 52 streams. The remaining 56 pct of the pumped water seeps underground through the bed of the Lackawanna River.

Similarly, the Susquehanna River and its tributaries drain an area of 169 mi^2 (437 km^2) overlying the Wyoming Basin. Even though this is slightly less than half the size of the Lackawanna River drainage area, the total volume of water pumped to the surface is 21 pct more than in the Lackawanna Basin. The average volume of water pumped per year is 112 billion gal (425 billion L), which corresponds to more than 214,300 gpm (13,500 L/s) pumped against an average hydrostatic head of 394 ft (120 m). It is difficult to achieve good runoff because of the relatively flat terrain created by the wide floodplain in the Wyoming Valley. Consequently, much of the surface water seeps directly into the ground, eventually ending up in the mine workings.

Approximately 30 pct of the seepage water is direct surface seepage, while another 21 pct seeps through the pervious beds of 59 streams. The remaining 49 pct seeps through the bed of the Susquehanna River.

In contrast to these two basins, the Western Middle Field and the Southern Field do not have major rivers overlying them. Therefore, there is a higher percentage of mine water from surface seepage. In 1951, 36 billion gal (136 billion L) were pumped to the surface from the Western Middle Field, while 17 billion gal (64 billion L) were pumped from the Southern Field. This corresponds to roughly 67 pct and 34 pct of the total runoff into the respective drainage areas. The general surface seepage in the coal areas is 90 and 92 pct, respectively. The remaining 10 and 8 pct are seepage from the streambeds.

In the bituminous region, surface restoration and stream reconstruction have also been underway to check water inflow due to seepage. A project involving the construction of a new channel on Little Sandy Run in north central Pennsylvania was undertaken in 1974 [Klingensmith, Miorin, and Saliunas (17)]. The channel was to be constructed approximately 1,000 ft (305 m) over underlying mine workings. A significant loss of streamflow had been noted here during earlier watershed investigations. The area was cleared and grubbed; the new channel was excavated; the existing channel was filled; a layer of sand and bentonite was placed as an impermeable membrane in the new channel; riprap protection was provided for the impermeable membrane; two underdrains were laid to convey acid water from new mine pool overflows (possibly caused by Hurricane Agnes in June 1972) into the new channel; and the affected area was graded, limed, fertilized, and seeded. This work was completed in September 1974, at a total construction cost of $96,545.97. This channel also successfully carried the runoff from Hurricane Eloise in September 1975. No maintenance has been necessary since construction was completed. An estimated average infiltration of 400,000 gpd (1.52 million L/d) of water was prevented from entering the underlying mine workings.

Another project involved the reconstruction of the streambed of a headwater's branch of Morris Run (17). The reconstructed streambed was first lined with a layer of locally available clay, which was then covered by a protective filler blanket and quarry stones. The entire area was then limed, fertilized, and seeded. The total construction cost of this project, which was completed in October 1975, was $453,925.20. This project, together with the reclamation of two adjacent strip mines, has prevented an estimated average daily infiltration of 1.25 million gpd (4.73 million L/d) of water into underlying mine workings.

These data indicate that huge quantities of water can enter mine workings as a result of seepage, and because of the seriousness of this problem, preventative measures must be taken.

WATER ENTRANCE THROUGH FRACTURES

Earth fractures, such as faults, fracture zones, joint systems in rocks, and fractures caused by surface subsidence, allow water to enter underground mines in various quantities. They are a major avenue of water entrance into underground mines, because coal measures are usually overlain by impervious strata consisting of shales. No water will enter the mine from the surface or from any aquifer above the coal seam if these strata remain intact.

Fracture flow, which tends to localize inflows, is prevalent within the eastern margins of the bituminous coal region. These zones of fracture concentrations show up on the surface as fracture traces. These fracture traces have been used to locate highly productive water wells with aerial photography, and more recently, with remote sensing. Here, subtle lines are present on the Earth's surface; indicators include more lavish vegetation due to ground water in decomposed rocks, surface sags and depressions, and stream valley alignments. There is often an abundant supply of water where two or more of these fracture traces intersect. Wells drilled at these intersections have yielded up to 3,000 times more water than wells drilled at random.

Joints

A joint is a fracture in a rock in which there is no observable relative movement between the sides. A series of parallel joints is called a joint set, while two or more sets intersecting produce a joint system.

Joints are important because they locally control drainage patterns and because they provide a passage through which water may penetrate deeply into a rock mass, thus allowing weathering to take place. This is especially evident in limestone, where the end result of this weathering is karst scenery. In addition, joints increase the porosity and permeability of a rock mass, thereby creating aquifers in previously impervious strata. If they are developed enough, the joints can also tap overlying aquifers and water sources, and provide flow paths to the mine workings.

The intergranular permeability of shale is relatively low because the rock is fine grained and lithified. Shales have a high porosity relative to most sandstones, but the interstitial spaces are so minute that the water movement is restricted. For this reason, shales usually provide an excellent means for keeping water out of underground mines. However, where shales are jointed, they have provided significant water supplies to users. In many rocks, shales and joints are the principal means by which the water is stored and transmitted.

Wells penetrating strata whose water capacity is determined by joints yield up to 200 gpm (13 L/s), with most wells yielding 50 gpm (3 L/s). Pre-Cambrian rocks of southeast Pennsylvania, consisting of schists, slates, and crystalline rocks, yield up to 100 gpm (6 L/s), while the rocks in the lower Cambrian sandstones, quartzites, and conglomerates yield up to 200 gpm (13 L/s) (18).

Joints tend to close and heal with depth, resulting in a decreasing yield of ground water. Closed joints are sometimes called latent, blind, or incipient. The majority of open joints are close to the ground surface, and significant flows are encountered, usually in the first 100 ft (30 m) of excavation (44). With increasing depth, the increased confining pressure caused by the overburden weight tends to limit the space created by jointing. At depths greater than 300 ft (90 m), the water storage capacity of joints becomes less significant. However, the presence of higher differential heads in deep mines tends to negate the advantage of lower permeabilities created by this healing, resulting in the inflow of stored water into the mines.

Faults and Fracture Zones

Faults can cause water problems in underground coal mines by (1) acting as a water reservoir, releasing water when tapped by the mine workings, and (2) acting as a conduit, hydraulically connecting a water source, such as an aquifer or surface water body, to the mine workings. Faults and fracture zones can also cause very bad roof conditions, especially if a significant amount of water is present. As a rule, jointing and faulting tend to coincide in folded regions. No real distinction is made between faults and joints since both act as conduits, transmitting water from other sources to the mine workings.

The most noteworthy example of how faults can be a cause of inundations is the flooding of the Higashisome Colliery in Japan in 1915. (Although collieries in Japan are outside the scope of this report, they serve as excellent examples of how costly, in both production and safety, a fault zone can be.) On April 12, 1915, an estimated 10.5 million ft^3 (0.3 million m^3) of water flooded the entire mine in 2 h, killing 237 workers. The source of the flooding was a fault that acted as a hydraulic connection between a seabed above the workings and the workings themselves. The fault extended 155 ft (47 m) through a sandstone bed, and another 83 ft (25 m) through an alluvial deposit of clay and sand (40).

Japanese collieries have been known to be susceptible to flooding through faults. In 1934, 54 lives were lost when the Matsushima Mine was flooded. Here the fault penetrated over 200 ft (61 m) of cover to a surface seabed. In 1942, 183 miners were killed when the Chosei Mine was flooded by seawater penetrating 119 ft (36 m) through a fault (40).

In the United States, fracture-dominated flows have not been as severe. In some cases, especially where the fault zone is serving as a storage reservoir and the recharge to the fault zone is limited, water inflow is virtually negligible. Republic Steel's North River No. 1 Mine in Berry, AL, exemplifies this. Here, the major source of water is from water-bearing fractures. The workings are dry, except when occasional water-bearing fracture zones are penetrated by mine openings. The initial penetration of water-bearing openings usually releases a large inflow averaging 200 to 300 gpm (12.6 to 18.9 L/s). This would be a problem should this inflow remain constant. However, after a period of time, the flows decrease to a trickle, indicating that the water storage system is very restricted both vertically and laterally [Shotts, Sterett, and Simpson (31)].

The Lancashire No. 20 Mine near Carrollton, PA, illustrates another feature of fracture-dominated flows (38). Here, baseline monitoring of water quantities established that the flows responded rapidly to wet and dry conditions in spite of a depth of over 500 ft (152 m). This rapid response indicated that the fracture zones had a hydraulic connection to the surface. It was even possible to recognize recharge from individual rainstorms. Geologic investigations indicated that the fracture zones consisted of steeply dipping fractures that intersected the surface, permitting rapid recharge from precipitation and from streams or ponds on the surface. It was noted that secondary aquifers also fed the fracture zones.

Mine Subsidence Fractures

Mine roof fracturing and the resulting surface subsidence following the removal of mine roof supports such as pillars and blocks is one primary cause of water entrance into deep mines. Here, water descends on fractures resulting from the subsidence of mined-out ground. Such fissures form direct conduits that carry water. It has been found that as pillars are removed, the cost of pumping increases greatly. In some of the Pratt Mines (Alabama), where pillars were robbed as the entries were driven to the boundary, from 10 to 15 tons of water were pumped for each ton of coal produced (15).

Whittaker, Singh, and Neate (42) have attempted to quantify the effects of subsidence on the increased permeability of these zones in England. Although this work was done in England and not in the Appalachian coal region of the United States, it is the only current investigation that quantifies the effects of subsidence. One of the studies was performed in the East Midlands Coalfields, involving the deep soft seam. The retreating longwall mining method was employed in the study. The mine was 1,970 ft (600 m) deep and had a longwall face width of 690 ft (210 m), and the seam was 31 in (80 cm) thick. The results showed that the closer the stratum was to the coal seam, the more the permeability was increased by caving.

A second site investigated by Whittaker, Singh, and Neate (42) was the Yorkshire Coalfield. Here, the shallow Wood Seam at Wentworth was being mined by the retreating longwall method. The depth of the seam was rather shallow at 175 ft (53 m). Results showed that a discernible change in the waterflow was taking place at 164 to 197 ft (50 to 60 m) ahead of the face line. This flow increased in marked steps, indicating the opening and closing of near-surface cracks and fissures. The flow curve settled to a constant value of about 98 to 131 ft (30 to 40 m) behind the face line. The onset of permeability change occurred significantly ahead of the face line with the upper test strata in comparison with the lower test strata.

A third site investigated (42) was the Lynemouth Mine. Here, the seam under consideration was the Brass Hill Seam. A retreating longwall method was being used on a 3.3-ft (1-m) seam. The face length was 600 ft (183 m). Static head measurements were taken at six different depths in two boreholes. The lowest test section showed the largest change in static head, with the higher sections displaying progressively less change. However, permeability changes occurred first in the higher test section.

All test results show a marked increase in the permeability of the strata as a result of subsidence. Marked increases in flow rates were also observed. It is important to compare the quantity of water flowing when a possible aquifer is tapped by the fracturing, with that flowing when only the immediate roof, consisting of relatively impervious strata, is tapped.

Another example of water inflow in underground deep mines that was due to subsidence occurred at the Jones and Laughlin Steel Corp.'s Shannopin's Section No. 1 Mine in Greene County, PA [Doyle, Chen, Malone, and Rapp (12)]. The Pittsburgh Coal Seam was being mined. It has a minable thickness of about 6.6 ft (2 m). Section 1 underlies Dooley Run drainage basin, which during the investigation had no flow. The method of mining was retreat room-and-pillar, which resulted in surface subsidence and fracturing of the overlying rock strata. The overburden thickness of 350 ft (107 m) was not sufficient to prevent the total loss of streamflow. The river flow was estimated at 1 ft^3/s (28 L/s), which corresponds to a loss of 650,000 gpd. The researchers concluded that essentially all precipitation within the drainage basin (less the loss through evapotranspiration) is percolating into the mine through subsidence fractures and fissures. This is an example of mine subsidence capturing most of the precipitation falling in the drainage basin.

ABANDONED DEEP MINES

Flooding of abandoned mines is a major factor affecting the future of the coal industry. The proximity of these flooded mines to active workings results in the infiltration of water either through barrier pillars, which separate the abandoned workings from the active workings, or through interconnections [Ash, Cassap, Eaton, Hughs, Romischer, and Westfield (2); Peters, (26)]. Therefore, the abandonment of a mine and suspension of pumping in that mine tends to increase pumping costs for adjacent mines. Adjoining mines must prepare to handle more water seeping through barrier pillars or maintain the water in the abandoned mine at such an altitude that the barrier pillar will not fail or allow excessive seepage. Thus, the operating mines gradually assume the pumping loads of all abandoned mines in their basin. This is impossible in some mines so mine pumps have been installed in abandoned mines to prevent the flooding of active mines.

Barrier Pillars

Coal mines are usually separated by barrier pillars, which are formed by leaving part of a coal seam unmined along the lines of adjoining mining properties, or between mines or parts of mines. The principal function of barrier pillars is to act as a dam to confine accumulating mine water and prevent it from seeping, flowing, or breaking into an adjacent mine and causing loss of life and property [Ash, Cassap, Eaton, Hughs, Romischer, and Westfield (2); Dierks, Eaton, Whaite, and Moyer (10)].

A barrier pillar should be designed to hold water in abandoned mines under high head, since the pressure may be sufficient to force water through the strata either above or below the otherwise adequate barrier pillar. The size of these barrier pillars is based on (1) the extent of waterlogged workings and accumulation of water, (2) physical-mechanical properties of coal, (3) presence of geological disturbances, and (4) head of water against the proposed drivages [Gulati and Singh (14)].

The path of seepage in the vicinity of a coal barrier will depend on the flow gradient and position with relation to major circulation. In downward circulating zones, seepage tends to occur along and under the coal, with a smaller amount over the coal. In upward circulating zones, seepage tends to occur along and over the coal, with perhaps a smaller amount under the coal. The underclay significantly prevents seepage below the coal (22).

Investigations have revealed that the extent of damage to many barrier pillars during subsidence cannot be anticipated since many are too small, or are partly removed, punctured, or encroached upon (32). The extent of bridging of roof rock above a mined coal will affect the ability of a barrier to restrict seepage. Undisturbed permeability in roof rock will be limited to a wedge of unfractured rock above the barrier. A highly permeable bed close to the level of the coal will also decrease the effectiveness of seepage restriction by a barrier, especially in the presence of subsidence fractures. In addition, barrier pillars often are punctured by passageways in which masonry or concrete dams are constructed to resist hydrostatic pressure. However, a masonry dam can fail even before the barrier pillar itself collapses if the barrier pillar is unstable.

The abandoned flooded portion of the Republic Steel Corp.'s Clyde Mine, in Washington County, PA, is the largest source of water infiltration to Bethlehem Steel Corp.'s Marianna No. 58 Mine to the west. The Clyde Mine is higher up, and the impounded water behind the barrier pillar that separates the two mines seeps through fractures. Percolation reduction would require at least 9,600 ft (3,000 m) of grout curtain to seal the fractures (12).

At Jones and Laughlin Steel Corp.'s Shannopin Mine Complex in Greene City, PA, sections 1 and 2 experience water infiltration of about 750,000 gpd (30 L/s) from the worked-out sections of the Maiden Mine. The water infiltrates through barrier pillars (12).

Present-day problems would be much simpler if the need for and value of barrier pillars had been understood 75 yr ago, when mining at depth was getting underway. Unfortunately, particularly in the anthracite coal region of Pennsylvania, lands were not generally controlled in large blocks by one company or individual; because of the irregular shape of holdings, the quantity of coal that would have had to be left for adequate barrier pillars was too great to be considered. In the past, barrier pillars were not established soon enough. Excavations were made too close to property lines before there was any attempt to establish a barrier pillar.

Interconnections

Abandoned deep coal mines are usually not completely separated from the active workings by barrier pillars. Great mining activity with the resultant abandoned and waterlogged workings results in the connection of both active and abandoned workings by shafts, boreholes, cross-measure drifts, and in-seam roads. These interconnections permit water from inactive mines to enter the active workings. Unreliable old mine maps compound the problem, because the extent of the waterlogged workings is not always known.

Large quantities of surface water are often collected by nonregraded surface mines. These mines usually consist of open pits with no surface exit point for this water. Water collecting in these pits can then infiltrate into any nearby underground mines. Many active and abandoned underground mines also outcrop into areas that have been contour-stripped. This provides a direct hydraulic connection into an underground mine. In addition, water collected by a surface mine on the updip side of an underground working can enter the working through a permeable coal seam, either directly or by entering the ground water system.

Recontouring and revegetation of the strip mines located above an underground mine should control and reduce ground water infiltration. Improved contouring for surface drainage would favor surface runoff. Vegetation will hold water and increase evapotranspiration. The addition of limestone to the cover, in conjunction with revegetation, would improve the quality of water seeping into the water table. Draining the strip pits would accompany recontouring and would lessen vertical leakage. The pits could be drained with ditches without recontouring or by installing pumps and piping.

At the Beech Creek Mine in northern Pennsylvania, the restoration of an abandoned strip mine reduced the amount of water flowing into the underground workings to approximately 36,000 gpd (2 L/s). The work included backfilling and regrading, providing ditches and flumes to convey surface water across the restored strip mine, liming, fertilizing, and seeding the area (17).

Another site where waters were entering underground mines through the surface mines was near Williamsport, PA, at the Tioga River (17). Here, an inactive 16-acre (6.5-hectare) strip mine partially full of water was restored, a streambed running across the mine was reconstructed, and the entire area was limed and fertilized. Also, an 80-acre (32-hectare) portion of an inactive strip mine was restored and graded to blend into an adjacent, previously restored strip-mined area. This has prevented an estimated daily infiltration of 1.23 million gpd (50 L/s) of water into underlying deep mine workings.

Active strip mines have also been known to create water problems for underground coal mines. In Great Britain, the Abergergum Colliery had its main returns blocked when water from the Maesgwyn Cap Opencast Site entered them in 1963 [Davies and Baird (9)]. On December 30, 1974, the pumps at Tower No. 4 Shaft of Tower-Ferhilt Mine were overwhelmed by water after the pillar that had separated old workings in the 9-ft (3-m) seam at Tower from the disused workings of Rhigos Mine had been penetrated by the Dunraven Opencast Coal Site. The result was overflowing sumps and flooded roadways, and the obstruction of one roadway serving as a return from a longwall face. When opencast operations are allowed to encroach on old workings connected with working mines, there is a risk of inundation. The likelihood of flooding increases during periods of high rainfall.

Boreholes, Wells, and Shafts

Boreholes and abandoned wells act as water collection points and conduits to underground mines. They are usually vertical, or near vertical, and tap overlying aquifers and surface waters. They are usually drained when the holes are penetrated during mining.

Shafts and mine openings are very similar to boreholes and abandoned wells since they act as water collection points and conduits to underground mines by tapping overlying aquifers and collecting surface waters. The difference is that they are usually an integral part of the mining operation, and therefore cannot be sealed. An example of this is the Shidler Air Shaft located in an abandoned section of Marianna No. 58 Mine in Washington City, PA. The air shaft provides some ventilation of active operations, and sealing the shaft would affect mine ventilation (32).

It is evident that there are a considerable number of avenues by which water may enter underground coal mines. Most of these avenues are interrelated in that any one source could feed any number of other sources; for example, seepage could feed faults, aquifers, abandoned mines, or the mine itself. The danger of a sudden influx of water from an overlying flooded mine, as strata are disturbed by pillar extraction in the lower bed, cannot be overemphasized.

Knowledge of the various sources of water inflow will assist the mining engineer in identifying sources of inflow to a specific mine, in the planning and design stages. Early identification of the sources of water inflow together with the information on water control practices provided in the following section will enable the mining engineer to evaluate and select the most effective method(s) of water control.

WATER CONTROL PRACTICES

This section discusses practices that have been used, or proposed for use, to control the inflow of surface and ground water into active underground coal mines. This compilation was obtained by reviewing the available literature and selecting those practices that are designed to be preventative in nature, rather than prescriptive. Thus, the common objective of all of the practices described is to prevent or reduce the inflow of water into active mines for the implicit purpose of reducing the costs of coal production by improving one or all of the three categories previously discussed: (1) health and safety, (2) production, and (3) the environment.

Ten water control practices are described. Although each practice is described separately, they can be grouped according to whether they are designed to control surface or ground water inflow. Figure 2 is a matrix listing the 10 control practices and indicating which of the sources of water inflow, previously discussed, can be controlled by the use of these practices. The first five practices described in this section are suitable primarily for controlling surface water inflow, while the last five practices described are suitable primarily for the control of ground water inflows.

The water control practices presented are not universally applicable, and the choice of a particular technique to use for a given situation will ultimately depend on the cost effectiveness of the technique. The cost effectiveness of the technique will depend on the hydrogeological conditions in the area and the benefits derived from the use of the practice with respect to health and safety, production, and the environment. Unfortunately, the literature evaluation revealed that the technical feasibility and cost effectiveness of many of these practices have yet to be determined. Many of these practices were selected because they represented the best, and in some instances the only, available control technology. However, provisions were seldom incorporated to monitor the short- or long-term performance of these controls.

For example, an interim report prepared by Schmidt and Ahnell (28) for the Bureau describes the tasks necessary for the application of a mine dewatering strategy and the implementation of a dewatering scheme at a mine in Preston County, WV. Results of the mine dewatering efforts were inconclusive, partly because of problems encountered in attempting flow measurements inside the mine. The depth

Water sources		Surface water controls					Ground water controls				
							Reduce permeability of overlying strata				
	Water controls	Siting of surface facilities and openings	Surface runoff diversion	Surface regrading and restoring	Soil sealing	Streambed modification	Grouting and grouting curtains	Borehole sealing	Subsurface soil sealing	Abandoned mine sealing	Well dewatering
Coal and contacting water-bearing strata	Strata associated with coalbeds						•				•
	Other strata serving as a water source						•		•		•
Surface water entrance	Surface water body seepage	•	•	•	•	•					
	General surface seepage	•	•	•	•				•		
	Surface water inrush		•	•	•	•					
Water entrance through fractures	Joint system in rocks						•				•
	Faults and fracture zones					•	•				•
	Mine subsidence fractures			•	•	•	•		•		•
Constructed pathways	Abandoned underground mines (barrier pillars, interconnections)						•			•	
	Abandoned and active surface mines	•	•	•	•	•			•		
	Borings, boreholes, gas and oil wells	•	•	•				•			
	Shafts and mine openings	•	•	•			•			•	

•Indicates that water control techniques can be used to control the water source

FIGURE 2. - Matrix of mine water controls versus mine water sources.

of cover at this time ranged from 100 to 300 ft (31 to 92 m), considerably shallower than the average depth of mining in the Appalachian region, which is approximately 600 ft (183 m). A cost analysis of this dewatering was not available.

SITING SURFACE FACILITIES AND OPENINGS

A considerable amount of water can be prevented from entering underground mine workings simply by proper siting of surface facilities and mine openings. Important considerations in siting surface facilities and openings are access, surface rights, power and water availability, government and municipal restrictions, material availability, surface space, topography, wind direction, floods, slides, and costs. All of these considerations may have an effect on how much water may enter the mine. Boreholes, shafts, and other mine openings should not be located in floodplains, naturally depressed areas, or other low-lying areas that retain surface runoff, since water accumulating in these areas will enter the mine through these openings. In addition, surface facilities located in these areas will tend to puddle water, enabling it to infiltrate into the mine via surface water-body seepage and general surface seepage.

SURFACE RUNOFF DIVERSION

The amount of water with potential to enter an underground mine can be controlled by reducing the amount of surface runoff that enters the area overlying a mine. Surface runoff can infiltrate the soil and eventually enter the mine through surface water-body seepage and general surface seepage. Ponding of surface runoff may also cause water to enter an underground mine via surface water inrush. In addition, surface runoff can collect and enter abandoned and active surface mines, borings, boreholes, gas and oil wells, and shafts and mine openings, thereby finding direct access into underground mines in many instances. Surface runoff diversion is the process of intercepting and channeling the surface runoff to natural watercourses before it reaches these potential infiltration sources.

Methods for diverting surface runoff include ditches, trench drains, flumes, pipes, and dikes. Diversion ditches are frequently used to divert surface water around the mine area. Flumes and pipes are used to convey water across surface cracks and subsidence areas. Dikes can be used for the same purpose as ditches; however, they are often used together, with the excavated material from the ditch used to form the downslope dike.

Advantages of surface runoff diversion methods include low maintenance requirements, relatively low cost, a potential for a high degree of effectiveness, and a long service life.

The disadvantages include the need for surface restoration once mining is complete and the need for obtaining access to the surface land required for construction of the diversion facilities. Underground mining companies may not own all of the surface land needed for diversion facilities and, consequently, may not have ready access to modify the surface drainage patterns. An additional disadvantage may be that the diversion of surface runoff into streams, especially during maximum flow conditions, can aggravate flooding and erosion problems downstream.

In most cases, the cost of surface water diversion will be less than the costs involved in treating an equal volume of mine water to meet acceptable standards. Surface water diversion costs will vary depending on the following factors: topography, availability of equipment, type and condition of soil, size of area, and quantity of water expected.

SURFACE REGRADING

The amount of water available to infiltrate the soil and, eventually, the underground mine can be decreased by increasing surface runoff over the overlying surface area. Surface runoff can be increased by regrading selected areas to provide a better drainage configuration, thereby limiting the amount of surface water-body seepage, general surface seepage, and surface water inrush that can occur. Areas suitable for regrading are those that retard the flow of surface runoff, thereby providing the opportunity for water to enter the soil strata. These areas include natural depressions, depressions caused by subsidence, or nonregraded surface mines. Nonregraded surface mines are a common source of underground mine water in the Eastern United States where coal outcrops are contour-stripped. Depressions occurring around borings, boreholes, gas and oil wells, and shafts and mine openings are particularly important in that a considerable amount of water can freely enter an underground mine through these avenues.

The effectiveness of a particular application of surface regrading will depend on the site hydrology. On-site evaluations are necessary to determine the amount of infiltration caused by correctable situations. This amount can be estimated by using flow measurements and by comparing the infiltration capacity at similar adjacent undisturbed areas.

The amount of water that can be prevented from infiltrating the soil as a result of regrading depends on the following factors: the size of the drainage area that is tributary to the depressed area, annual precipitation rates, and the change in runoff coefficients caused by the filling and grading activities.

Strip mines can intercept underground mine workings along the highwall. If interception takes place on the updip side of an underground mine, a significant amount of surface runoff can be conveyed to the underground mine workings. The regrading method should be designed to divert surface runoff from the highwall. In addition to regrading, ditches and flumes can be constructed to aid in increasing surface runoff. Impervious materials or spoil material can be compacted against highwalls before backfilling to prevent water from flowing into adjacent mines.

The advantages of surface regrading are similar to those for surface runoff diversion: low maintenance requirements, relatively low cost, a potential for a high degree of effectiveness, and a long service life. An additional advantage is the restoration of abandoned areas.

The disadvantages include the need for obtaining access to the use of the surface land and the possibility that the increase in surface runoff into streams, especially during periods of maximum flow, could aggravate flooding and erosion problems downstream. An additional disadvantage for regrading and restoring surface mines involves assessing the responsibility for performing the work. The mining company involved with surface mining may not be the same company involved with underground mining.

The costs of surface regrading and restoring depend on factors such as the length and height of the highwall, the number of cuts made, the size of the affected area, the degree of regrading necessary, the method of revegetation, and whether surface mining reclamation activities are included in the mining operation or take place sometime after mining activities have stopped. The costs for surface regrading and restoration may include clearing and grubbing, backfilling, grading, revegetation, establishing mine access, diversion ditches, flumes, and seals.

A project to control water infiltration by regrading a surface mine was undertaken in the Roaring Creek-Grassy Run watersheds near Elkins, WV [Scott and Hays (<u>29</u>)]. The contour method of regrading was used when the highwall was fractured and unstable, and the pasture and swallowtail regrading methods were used when the highwall was stable. Also included in this project was sealing of an opening in the highwall to prevent water from infiltrating through the opening and into an adjacent underground mine. Representative costs for this reclamation are shown in table 2.

The actual effectiveness of this regrading project was difficult to determine because of cost overruns, and incomplete reclamation and sealing of a large underground mine. A preliminary evaluation, however, revealed that flow in streams adjacent to the regraded area was increasing, which indicates an increase in surface runoff and a decrease in the amount of water entering the soil strata.

SOIL SEALING

Another method of increasing surface runoff and, subsequently, reducing the amount of water infiltration is to reduce the permeability of the surface soil. The permeability can be reduced by sealing the soil with an impermeable material, which will limit the amount of surface water-body seepage and general surface seepage. Soil sealing may also be effective in cases of potential inrush occurring from surface runoff. Mine subsidence fractures extending to the surface may also be partially sealed at the surface. Soil sealing can also be used on soils in active and abandoned surface mines to limit the seepage of water ponding in these mines into underground mines. Materials that have been investigated for soil-sealing purposes include clay, asphalt, concrete, rubber, and plastic.

Soil sealing is often used in conjunction with other water infiltration control methods. For example, areas that have subsided because of mining activities are often filled and graded to provide better surface drainage patterns. In addition to filling and grading, impermeable materials can be placed in the area, compacted, and graded to increase the rate of surface runoff. Another example is the placement and compaction of impermeable materials against the highwall of a surface mine during regrading and restoration activities. These materials will prevent ground water from penetrating the highwall and entering an adjacent underground mine.

The advantage of soil sealing is its potential effectiveness in reducing water infiltration. A disadvantage of soil sealing is that, depending on the type of sealant, the future use of the land may be severely limited for activities such as agriculture, industry, and recreation. Other disadvantages include the need for obtaining access to the land and the potential for aggravating downstream flooding and erosion problems by increasing surface runoff.

Reported costs range widely, as follows:

Concrete	\$42.30-\$84.60	per cubic yard
Clay....	2.80- 8.50	per cubic yard
Rubber..	.70- 1.40	per square foot
Asphalt.	.30- .80	per square foot

STREAM CHANNEL MODIFICATIONS

A stream that flows over highly permeable areas may be a significant source of underground mine water. Such streams can lose water to underground mines through their streambeds by surface water-body seepage or surface water inrush. Vertical fractures and subsidence of strata

TABLE 2. - Representative costs for surface regrading and restoring

Item	1975 dollars		1980 dollars	
	Per acre	Per hectare	Per acre	Per hectare
Clearing and grubbing...	$500	$1,235	$700	$1,740
Backfilling and grading:				
Contour...............	2,000	4,938	2,820	6,950
Terrace...............	1,800	4,445	2,540	6,260
Revegetation[1]...........	$500- 550	$1,235-1,358	$700- 775	$1,740- 1,910
Regrading:				
Contour...............	1,800-3,800	4,445-9,383	2,540-5,350	6,260-13,220
Terrace...............	1,500-3,400	3,704-8,395	2,115-4,790	5,220-11,830

[1]Includes lime, fertilizer, seeding, and mulch.

Source: Scott and Hays (29).

overlying underground mines can also provide openings through which surface streams can penetrate. A stream flowing over such areas may allow water to infiltrate into mines at rates 1,000 times higher than those of an adjacent area. Streams flowing through abandoned and active surface mines can also, owing to the more permeable soils at the mine, allow water to infiltrate the underground mine.

Advantages of channel modification are the potential for a high degree of effectiveness in reducing mine water inflow, a long service life, low maintenance requirements, and relatively low costs compared with pumping and treating mine water.

The disadvantages include the need for obtaining surface access to construct the facilities, determining the party responsible for restoring abandoned surface mines and subsidence areas, and the potential for aggravating downstream erosion and flooding problems.

The costs of channel modification will normally be much less than pumping and treatment costs of an equal volume of mine water. The costs of channel excavation are estimated to range from \$1.40 to \$4.20 per cubic yard (\$1.85 to \$5.50 per cubic meter). Lining the channel bottom with clay costs from \$1.40 to \$2.80 per square yard (\$1.70 to \$5.10 per square meter). The cost of stabilizing the channel with riprap or with a vegetative cover should also be included in estimating channel modification costs. The total cost of reconstructing a channel is estimated to range from \$14.00 to \$35.25 per linear foot (\$46.25 to \$115.60 per linear meter). These cost estimates are in 1980 dollars and are based on data developed by Scott and Hays (29).

GROUTING

The process of grouting consists of injecting fluid materials into permeable rock and/or soil formations to fill pore spaces and allowing the material to set, forming a stiff gel or hardened cement-type material. The purpose of grouting is to reduce the permeability of the grouting medium by sealing fissures, fractures, and other permeable formations.

An impermeable barrier formed by grouting is called a grout curtain. Grout curtains are used to control leakage around underground hydraulic seals, to stabilize outcrop areas, and to reduce water infiltration through subsidence areas and through fracture zones. Grout curtains are also used to reduce water infiltration through barrier pillars, around mine openings, and during shaft sinking by reducing the permeability in these areas.

In addition, grout retainers consisting of large bags made from materials such as cloth or plastic can be placed in large openings (e.g., mine shafts) and filled with grouting materials.

The advantages of grouting are its convenience and effectiveness for sealing fissures, cracks, and permeable formations. Grouting can also increase the strength and load-bearing properties of ground formations.

The greatest disadvantage of grouting is its requirement for skilled labor knowledgeable in grouting materials, equipment used, and geological formations. Additionally, some grouting materials are toxic and present a potential safety hazard to personnel.

BOREHOLE SEALING

Boreholes are vertical or near-vertical holes, usually drilled during mineral exploration activities, which are often used later for supplying power to underground equipment or for discharging water pumped from the underground mine workings. The boreholes that intercept mines act as conduits and are capable of transmitting large volumes of water to the mine from surface water sources and from overlying aquifers.

Boreholes can be effectively plugged to prevent the passage of water. The boreholes can be sealed by placing packers and injecting a cement grout, or by filling the hole with rock over which a concrete or clay plug is installed.

When the boreholes are sealed with cement grout, the packers should be placed below the aquifers overlying the mine to prevent subsurface water infiltration. These packers should, however, be located well above the mine roof to guard against roof collapse from additional water pressure. Boreholes can also be sealed by filling the hole with rock until the mine void directly below the hole is filled to the roof, then placing successive layers of increasingly smaller stone above the rock, and installing a clay or concrete plug. The remainder of the hole can then be either filled with rock or capped.

Boreholes can be sealed from the surface or from below in an active underground mine. It is usually more difficult to seal a hole from the surface. In many instances, the holes must be cleared of debris prior to sealing.

An advantage of borehole sealing is that the seals will prevent not only the passage of water into the underground mine but also the discharge of mine water pollutants from a flooded abandoned mine having a water level above the borehole elevation. An additional advantage is that little operation and maintenance is required after the sealing is complete.

A disadvantage of borehole sealing from underground is that the roof strata lose their support as coal is removed during mining, which increases the danger of roof collapse. If roof collapse occurs, the sealing operation may be rendered ineffective. An additional potential disadvantage may be the determination of responsibility for sealing a borehole for an abandoned mine. Borehole sealing should be conducted as part of a mine closure and sealing program.

During 1973, the Pennsylvania Drilling Co. installed a borehole seal to eliminate the flow of water from the Lower Freeport Coal Seam to the Lower Kittanning Coal Seam at the Tanoma Complex, Upper Crooked Creek, Indiana County, PA (29).

The 10.25-in (26-cm) diameter borehole was sealed in the following steps: A packer was hydraulically set at 323 ft (98.5 m) by pumping water through a 7-in (17.8-cm) steel casing at pressures up to 1,000 lb/in^2 (703,000 kg/m^2); cement grout was then pumped through ports to the outside of the casing until the cement rose to the Lower Freeport opening; a top cementing plug was then pumped into place; a threaded cap was placed on top of the casing; and a plate was tack-welded between the existing borehole casing and the steel casing.

The completed seal cost a total of $8,611 and successsfully stopped the leakage between the coal seams.

SUBSURFACE SOIL SEALING

Subsurface soil seals can be applied to control surface seepage above underground coal mines and in abandoned and active surface mines. They may also have limited use in controlling mine subsidence fractures occurring near the surface. Subsurface seals are formed by injecting an impermeable material into the soil strata to control subsurface water movement. Materials that may be used for this purpose include asphalt, cement, and gel. Various latexes, water-soluble polymers, and water-soluble inorganics have been demonstrated to be effective in laboratory and field tests. Grouting materials injected below the surface can be an effective method of soil sealing; however, in severely fractured areas, the grout does not fill the void space and, consequently, the sealing efficiency is reduced.

Placing a seal below the surface has several advantages over using a surface seal: (1) A subsurface seal is less affected by mechanical and chemical actions, (2) the future land use of the area would not be as severly restricted, and (3) the seal could be located in an area of lower natural permeability.

The disadvantages of subsurface soil sealing include a significant reduction in sealing efficiency if the material is injected in a severely fractured area, the lack of large-scale applications demonstrating the success of this technique, and the need to obtain access and disturb the surface area overlying the mine.

Although many laboratory and small-scale field tests have been conducted on subsurface sealants, there has been no full-scale application of this technique to demonstrate its feasibility.

MINE SEALING

Abandoned underground mines are a potential water source to nearby active underground mines. As such, the abandoned mine not only contributes to the water-handling problems in the active mine but also poses a safety hazard to mine workers owing to the possibility of a sudden inrush of large quantities of water.

To reduce these potential problems, the following preventive measures can be implemented as part of the mine closure operation: (1) leaving safety pillars or barriers, (2) providing a standby submerged pump facility, (3) constructing water dams, (4) erecting bulkhead doors, and (5) maintaining records concerning the mine.

Implementation of these measures may not be entirely successful in preventing water from exfiltrating from the abandoned mine perimeter. Pumping the mine water to the surface would also not be entirely successful if additional water infiltrates the abandoned mine and would, furthermore, incur considerable operating expenses. In order to effectively prevent water from escaping an abandoned mine, all of the potential sources of water exfiltration must be sealed. Mine sealing involves the closure of mine entries, drifts, slopes, shafts, subsidence holes, fractures, and any other openings.

There are two kinds of seals that can be used for water seepage control:

1. Dry seals: The purpose of dry seals is to prevent air and water from entering underground mines. These seals are used only when mining is in the down-dip direction and when there is little or no flow and little danger of a hydrostatic head developing. Dry seals are installed in openings on the high side of a mine. Suitable materials for dry seals include masonry block, clay, concrete, and soil.

2. Hydraulic seals: The purpose of hydraulic seals is to cause and maintain flooding of the mine. In hydraulic sealing, the mine creates an impoundment and the entire mine acts as an underground reservoir. The effectiveness of a hydraulic seal depends largely on the location of the sealing area relative to ground water levels and the extent of fracturing in the surrounding strata. Seals placed above ground water levels create a hydraulic head that the surrounding strata must be able to contain. If these surrounding strata contain a number of fractures or a good aquifer, the ground water flow will increase as the mine floods.

The entire dam area must be able to withstand the water pressure, which can be in excess of 1,000 ft (300 m). Mineral barriers left along mineral outcrops and between adjacent mines are often the weakest link in the underground impoundment. These barriers are usually of nonuniform thickness and frequently cannot withstand water pressure.

The first step in hydraulic sealing is to conduct an examination of the geologic, hydrogeologic, and mine extent and condition perimeters to identify the hydraulically unsound areas. These areas may include surface-mined outcrops, subsidence holes, boreholes, and fractured mineral barriers. If feasible, these areas should be improved by sealing or grouting. If this is not feasible, the mine pool elevation should be lowered or the sealing project abandoned. The effectiveness of mine sealing is often determined primarily by the physical and mining framework and less by the actual effectiveness of the sealing technology.

The hydraulic seals most often used for mine sealing are the single and double bulkhead seals. These seals can be made from concrete, quick-setting cement material, or grouted aggregate and are formed by either injecting the material through vertical boreholes or by placing the material directly within the mine opening. The single bulkhead seal could also be made from masonry block or brick. In addition to the bulkhead seals, gunite, clay, and grout bags can be used to hydraulically seal mine openings.

The seals should be anchored into the mine openings. Additionally, to ensure effectiveness of the seal, a grout curtain may need to be placed directly adjacent to the seal. Vertical shafts and surface breaks can be filled with impervious materials such as compacted clay, earth cover, or cement.

Mine sealing can be an effective technique for controlling a potential water source for a nearby active mine. It also reduces potential safety hazards by reducing the possibility of a large inrush of water into the active mine. Another advantage of mine sealing is that after the initial capital expenditure, assuming that the sealing is effective, no additional operating and maintenance costs would be incurred.

The disadvantages of mine sealing are (1) if the roof strata lose their support (as a result of mining) and collapse, the sealing operation would be ineffective, (2) it is difficult to locate and, subsequently, seal all of the water leaks, because of inadequate records kept by mining companies and because of backfilling operations that cover evidence of fracture, and (3) seals lose their effectiveness with time, depending on the method of construction and any change in the strata surrounding the seal. Another problem is the inability to successfully anchor the seal into the surrounding mine strata, resulting in leakage around the seal. Other disadvantages involve secondary effects of mine sealing. A hydraulic seal placed in a mine in Pennsylvania created sufficient head to cause ground water levels to rise and flood cellars and damage foundations. The sealed mine was subsequently opened to relieve the ground water pressure.

A double bulkhead seal was constructed in the drift entry of an abandoned mine in the Kittanning Coal Seam in West Virginia (29). The front and rear bulkheads were constructed with quick-setting cement. Grout pipes and limestone were placed in front of the rear bulkhead, which was located in front of an existing air seal. The limestone was stabilized and rendered impermeable by grouting with light cement. Prior to sealing, the average rate of discharge from the mine was 74 gpm (4.7 L/s).

One week after the sealing was complete, the head behind the seal was 3.20 ft (0.98 m) and an opening near the seal was observed to be leaking. After placing a permeable aggregate seal in this opening, the head behind the seal stabilized at 3.8 ft (1.2 m).

Approximately 2 yr after the sealing was complete, the seal was inspected. Although there was some flaking off of the front bulkhead, no seepage was observed. The total cost of constructing this seal was $9,463.

A grouted, aggregate, double bulkhead seal was developed for sealing inaccessible mine entries in the Middle Kittanning Coal Seam in Butler County, PA. Between February 1969 and August 1971, this seal was constructed in the openings of 19 mines.

Double bulkhead seals were constructed by placing coarse, dry aggregate through vertical drill holes and then grouting the boreholes to form solid seals. Water was pumped from the space between the bulkheads and replaced with a center plug formed by poured concrete. Curtain grouting was performed for a minimum of 50 ft (15 m) from both sides of the seal at each mine entry.

This sealing program had the following effects on mine water discharges: (1) Eight mines had no flow, (2) one mine had an average flow less than 1 gpm (0.06 L/s), (3) eight mines had reduced flow rates, (4) one mine had the same flow rate, and (5) one mine had a 1.5-gpm (0.095-L/s) increase in flow rate.

The water level in the mines ranged from 1 to 5 ft (0.3 to 1.5 m), which fluctuated with precipitation and infiltration. The head behind the seals ranged from less than 1 ft (0.3 m) up to 38 ft (11.6 m).

The costs of the seals ranged from $8,308 to $58,437, with an average cost of $19,480 per seal. Approximately 61 pct of this cost was attributable to curtain grouting. Representative costs for constructing various types of mine seals are shown in table 3.

WELL DEWATERING

Aquifers situated both above and directly below an underground mine are potential sources of water infiltration

TABLE 3. - Representative costs for constructing various types of mine seals

Seals	Est. 1980 dollars	Per
DRY SEALS		
Masonry block	$3,520 -$4,230	Seal.
Placement of clay seals	2.80- 5.60	Cubic yard.
	3.70- 7.40	Cubic meter.
Construction of clay bulkheads	3,520 - 6,340	Seal.
HYDRAULIC SEALS		
Double bulkhead seals:		
Grouted aggregate (with grout curtain)	14,100 -42,270	Do.
Quick-setting (no grouting)	21,150 -25,360	Do.
Grouting around seal and curtain grouting of adjacent strata.	28,180	Do.
Single bulkhead seals (with grouting)	7,050 -14,100	Do.
Gunite seals	18,300	Do.
Clay seals	2,800 - 5,600	Do.
Grout bagseals	14,100 -21,150	Do.
Shaft seals:		
Backfilling shafts [from 100 to 300 ft (30 to 100 m)].	9,860 -49,300	Do.
Concrete seals	28,200 -35,200	Do.
Gel materials (AM-9 chemical grout)	12,700	Do.
Curtain grouting:		
Vertical curtains	49 - 113	Linear foot.
	160 - 370	Linear meter.
Horizontal curtains	16,900 -28,200	Acre.
	41,750 -69,600	Hectare.

Source: Scott and Hays (29).

into the mine. In addition, joint systems, faults, fracture zones, and subsidence fractures can be potential sources of water in an underground mine. To reduce these potential water infiltration sources, well dewatering sysems have been suggested to intercept the aquifers and to control the movement and ultimate discharge of the ground water.

Three basic well dewatering systems have been suggested in documented literature. These systems are (1) ground water pumping directly to the surface, (2) gravity drainage to the mine, with subsequent discharge at the surface, and (3) gravity drainage into underlying aquifers. These systems, which are all in a developmental stage, are discussed in greater detail below.

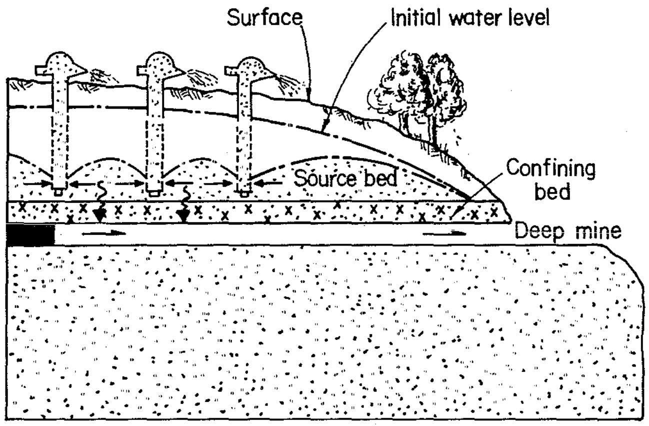
Ground Water Pumping Directly to the Surface

This type of well dewatering system, which is illustrated in figure 3, involves installation of closely spaced wells that are drilled from the land surface and tap aquifers lying above and below the mine. The wells are cased above the source bed. The ground water is then pumped to the surface and can be either discharged to a nearby stream or used for water supply purposes. Since the ground water does not enter the mine environment, the quality of the water is maintained and treatment should not be required.

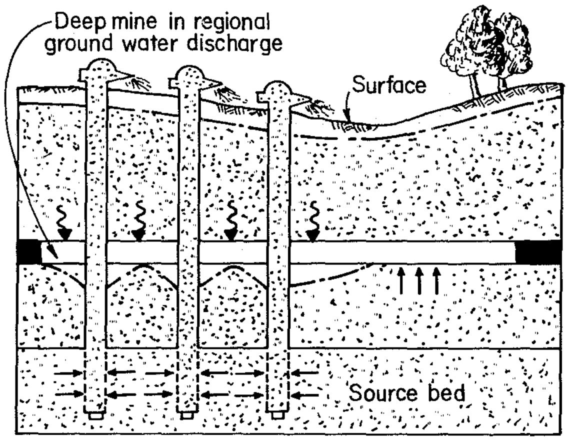
In figure 3, ground water pumping systems are illustrated for dewatering aquifers located above and below the mine. In the cases shown, it would not be feasible to try to force the water into lower rock units.

Gravity Drainage to the Mine

This system, which is illustrated in figure 4, is similar to the ground water pumping system except that the ground water drains by gravity to the underground



Source beds located above deep mines



Source beds below mines located in ground water discharge areas

FIGURE 3. - Ground water pumping systems.

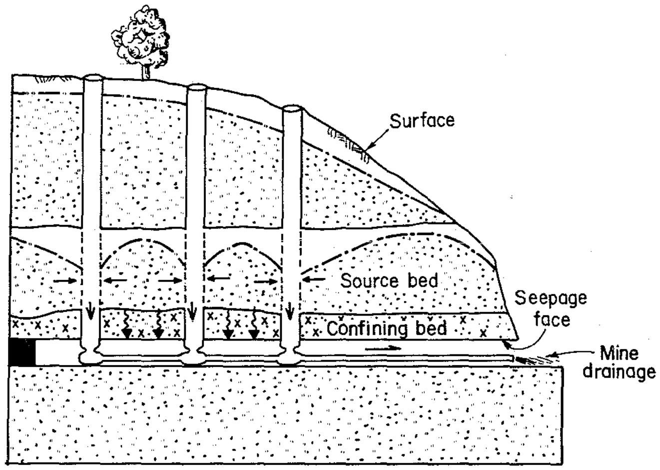


FIGURE 4. - Gravity drainage into mine.

mine and is then pumped to the surface for disposal. This system eliminates the need for a pump in each dewatering well. Instead, it requires a central collection and pumping system within the mine, which is already common practice in many underground mines. The collection and conveyance system, however, would consist of a piping arrangement whereby the water would not come into contact with the pyrite-bearing rock and would, consequently, not require treatment prior to discharge.

In updip mining from drift or slope entries, a gravity drainage system could be installed whereby the overlying aquifer is drained into the mine and the water is drained by gravity to the slope of the drift opening.

Gravity Drainage Into Lower Aquifers

This system, shown in figure 5, is similar to the ground water pumping system except that the ground water drains by gravity through wells drilled through the underground mine and, eventually, into a deeper aquifer. The mine roof rock and the mine opening should be cased and grouted to prevent water from entering the mine and to prevent contaminated mine water from entering the underlying aquifer. Double casings and grout may be needed to prevent corrosion of the steel casing within the mine.

This system requires the availability of favorable geologic conditions reasonably close to the mine area. Both a regional recharge area and a deep aquifer system have to be present for the system to work. A hydrogeologic setting where two to three distinct water tables and rock beds occur is ideal. The ground water flow must be downward. This system is not feasible for high fluid volumes in excess of 3 million gpd (130 L/s). In the Appalachian region, this factor alone may create limitations, as the aquifer must be capable of accepting the anticipated flow.

A possible alternative to installing separate dewatering systems for each mine would be to construct a regional drainage system designed to reduce the flow of water into several mines within a given drainage basin. One such system, the

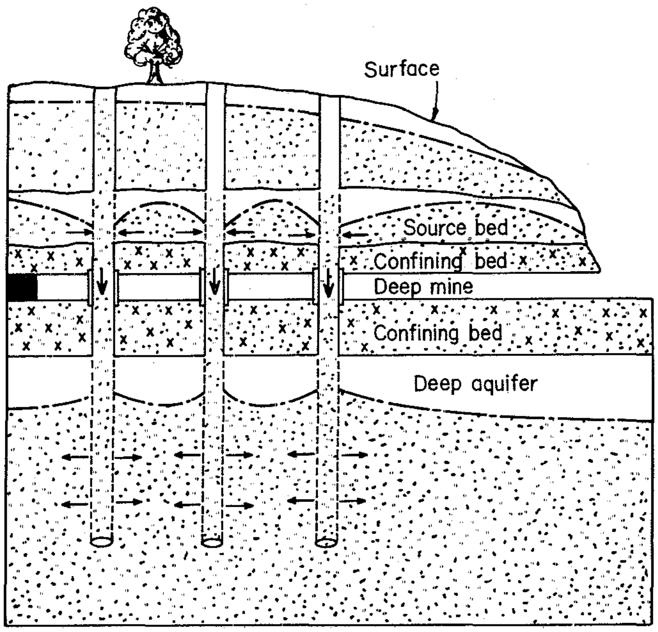


FIGURE 5. - Gravity drainage into underlying aquifers.

Hoffman Tunnel, was constructed in the Georges Creek Basin water province in Allegany County, MD [Slaughter and Darling (33)].

The Hoffman Tunnel, which was constructed in the early 1900's to drain the Pittsburgh Coal Seam, has a total length of 10,646 ft (3,245 m) with approximately 2,600 ft (800 m) of auxiliary tunnels and 26,700 ft (8,100 m) of ditches draining to it. The drainage area covers roughly 14 mi^2 (36 km^2), which extends north from Midland to Zihlman. The mean flow of the tunnel in the late 1950's averaged about 940,000 gpd/mi^2 (16 L/s for each square kilometer of surface area). During low-flow periods, the tunnel can divert nearly all of the flow of the upper third of Georges Creek, which is a tributary of the Potomac River.

The potential benefit of well dewatering systems is that they are preventative, rather than prescriptive, techniques that rely on natural geochemical and hydrogeological systems. Other advantages are a reduction in the amount of mine water that must be treated and a possible reduction in pumping and maintenance costs. Additionally, if the local need for water becomes sufficient in the future, the dewatering wells can be converted to water supply wells.

Well dewatering systems are still in the developmental stage, and large-scale applications of these systems have not been shown to be cost effective in the United States. Since it is usually not possible to completely eliminate water infiltration into the mine, the dewatering system just reduces, does not eliminate, the water-handling requirements in the mine. Depending on the character of the rock, a dewatering system may not produce noticeable results for more than a few hundred feet from the wells and it may take several months before results are noticed.

Prior to implementing a dewatering system, the impact on neighboring land uses must be considered. If the system will threaten local water supplies, the yield of the well system must either be reduced or used to supplement the water supply. The possibility of well plugging is another potential problem. If the aquifer contains ferrous iron, precipitation of iron oxyhydroxide and growth of iron-oxidizing bacteria around the wells could reduce the permeability of the aquifer and decrease well efficiency.

Costs

The cost effectiveness of a well dewatering system will depend on a comparison of the cost of pumping and treating mine water with the cost of the dewatering system. The cost of a dewatering system will depend on the the number and spacing of wells, the well depth and diameter, casing requirements, and depth to static and pumping levels. The cost will include hydrogeologic evaluations, drilling, casing, piping, and possibly grouting to control leakage through the mine roof.

The total annual costs per well in dollars per million gallons of water a day delivered to the surface are estimated as follows:

Well yield, gpm	Annual cost, per million gpd
75................	$36,970
230................	19,460
760................	13,430

These estimates assume a 25-yr service life for the well and equipment.

Mine water treatment costs are estimated to range from $0.10 to $2.45 per 1,000 gal ($0.02 to $0.64 per 1,000 L) depending on the water quality and on the effluent discharge limitations. The lower estimate is for water containing 2 to 3 ppm iron and up to 20 ppm acidity. The higher estimate is for water with 500 to 700 ppm iron and 2,000 to 5,000 ppm acidity.

The cost estimates in this section were taken from a Pennsylvania State University research report prepared by Parizek (23), and adjusted to 1980 dollars.

Case Study

A pilot dewatering program was conducted at the site of the Lancashire No. 20 Mine, near Carrolltown, PA (38). The objectives of this program were to assess the impact of a well dewatering program on the quantity and quality of mine water inflows, to evaluate the potential effectiveness of the well dewatering technique, and to conduct an economic evaluation of the program.

A total of seven wells were drilled and used for dewatering. A pumped-well system was selected for dewatering because pumped wells provide more information and create fewer mining disruptions and safety hazards than the other dewatering systems considered.

Some of the conclusions of this program were--

1. Fracture-dominated flow systems usually prevail where large mine water inflows are experienced. Ground water flows into the subject mine were concentrated along two fracture zones that appeared to intersect at the area of greatest inflow.

2. Flows responded rapidly to wet and dry periods in spite of the 500-ft (152-m) mine depth, indicating that the fracture zones had hydraulic connections to the surface.

3. Dewatering with three wells was performed continuously for 14 days with an average well effectiveness, initially, of 45 pct (i.e., 45 pct of the pumped water was diverted from mine inflow). The average well effectiveness increased to 55 pct at the end of the test, and it was projected that it would increase to 80 pct after 120 days of pumping with no recharge. The well effectiveness for full-scale mine dewatering was estimated to range from 50 to 80 pct.

4. The wells in this study were not cost effective unless the average well yield was increased from 3 to 4 times. The cost of well dewatering was estimated to be at least twice as great as water removal and treatment costs. If, however, the acidity of the mine water were higher, i.e., 500 to 1,500 ppm (500 to 1,500 mg/L) and if the coal seam were less than 150 ft (45 m) deep, the dewatering system would have been cost effective. Three significant variables in the cost comparison were depth of the well system, the acidity level of the water, and ground water flow patterns. Additionally, if the wells had been located along the fracture zones, a higher well yield could have been obtained, which would have increased the cost effectiveness of the dewatering system. The cost-effectiveness analysis did not consider the indirect benefits of dewatering (e.g., increase in productivity, more stable roofs, and reduced safety hazards).

SUMMARY OF WATER CONTROL PRACTICES

Table 4 is a summary of the water control practices previously discussed. (The siting of surface facilities and openings is not included because there is not enough information on this practice as a method of controlling water inflow.)

Table 5 shows equivalent water control costs. These tables list information on each practice's applicability, limits of control, field experience, and costs. The limits of control and the field experience taken together give an indication of each practice's effectiveness. Thus, a preliminary attempt can be made to assess the cost effectiveness of most of the control practices listed. This is important since it is the cost effectiveness of a control method for a given situation that should determine the choice of that measure.

As indicated in table 4, all of the surface control measures listed and all but two of the ground water control measures have some information available regarding their cost effectiveness in controlling inflow into underground mines. Only subsurface soil sealing and well dewatering lack sufficient data on effectiveness.

Of the control practices that have available performance information, only soil sealing is considered to be unsatisfactory. The performance data on soil sealing indicate that its use would be very costly, on the order of $30,500 to $61,000 to seal an acre of land with rubber. This should be compared with surface regrading and restoring, which costs roughly $1,800 to $3,800 for the equivalent conditions of applicability. Although the literature evaluation has provided information on the effectiveness of these practices in controlling water inflow in underground coal mines, a quantitative analysis is needed to accurately determine the cost effectiveness of these measures. The quantitative analysis should include the benefits and drawbacks associated with the use of each practice, taking into account factors such as health and safety, the environment, and production.

ANALYSIS OF THREE WATER CONTROL PROJECTS

The water control practices considered for evaluation were identified through a combination of literature review and personal conversations with a large number of knowledgeable individuals, State and Federal agencies, and private and public organizations associated with the coal mining industry. These water control practices have been described in the preceding sections. It must be emphasized, however, that most of these practices have been used principally to control water problems associated with abandoned coal mines.

Discussions with personnel of both State agencies and mining companies in Appalachia made it very clear that the only widely accepted method of dewatering underground coal mines is to collect the water in sumps and pump it up to the surface, where treatment is provided, as needed, prior to discharge to receiving streams. Personnel of both the State regulatory agencies and mining companies indicated very limited, if any, knowledge of the application of dewatering techniques in advance of mining in the Appalachian coalfields. In fact, the investigations identified only three cases where dewatering in advance of mining was either being considered or applied.

Of these three cases, only one represented an actual documented demonstration of the feasibility of dewatering in advance of mining. This particular demonstration evaluated an attempt to dewater a section of a mine using a series of dewatering wells drilled from the surface.

The second of the three cases was a preliminary feasibility study to determine whether dewatering in advance of mining using dewatering wells would be technically and economically feasible for a new mining operation.

The third case represents an ongoing attempt to control water problems in the last working section of an old mine. Subsidence is being induced in the area of heaviest inflow in order to concentrate the mine drainage in a system of sumps, which will then allow the safe extraction of the remaining coal.

The three case studies differed markedly. Case study 1 was a federally funded demonstration project, which spanned a period of approximately 33 months. This study provides the most comprehensive and detailed data available to date on the

TABLE 4. - Summary of water control practices

Water control practice	Applicability	Limits of control	Field experience
Surface water controls:			
Runoff diversion.....	Prevents infiltration into soil, mine openings, outcrops, rock fissures, strippings, cave-ins, surface cracks, subsidence areas, and nonregraded surface mines.	Can be effective if mine inflow is due to infiltration from the surface. If mine operator does not have access to the surfaces, method may not be feasible. May increase streamflow.	Has been used in many cases with varying levels of success.
Surface regrading and restoring.	Eliminates ponding and improves drainage. Highly applicable near surface mines or other large land disturbances.	Depends on size of drainage area, annual precipitation, rate of infiltration into soil. Access to land may limit success. May increase streamflow.	Has been used especially at strip mine sites. Can be very effective if mine water is due to ponding of water over mine.
Soil sealing.........	Prevents infiltration into soil by reducing permeability.	Prevents infiltration into soil only. Not effective in sealing fractures or other flow conduits. Not usually a long-term solution. May limit future land use.	Success has been limited.
Stream channel modification.	Prevents inflow to mines from streams, especially in areas of vertical fractures, subsidence, or high permeability.	Can prevent large quantities of water from entering a mine.	Has been proven to be very effective.
Ground water controls:			
Grouting and grouting curtains.	Reduces permeability of overlying strata by sealing fissures, fractures, and other permeable formations.	Most effective in limiting inflow via direct conduits, such as fractures.	Very effective in curtailing water inflow during shaft sinking. Has also been used to cement localized areas of water inflow such as faults and joints.

Borehole sealing.....	Prevents inflow to mines through boreholes from surface water sources and/or overlying aquifers.	The sealing operation may be rendered ineffective should the roof collapse. Also, it may be difficult to determine who is responsible for sealing a borehole of an abandoned mine.	Very effective in reducing direct inflow to mines through boreholes.
Subsurface soil sealing.	Prevents infiltration through the soil by reducing permeability.	Sealing efficiency is significantly reduced if the area is severely fractured. Must have access to surface area above the mine. Most sealants are judged to be uneconomical.	Lack of large-scale applications demonstrating the success of this technique.
Mine sealing.........	Prevents water from escaping an abandoned mine and infiltrating active workings.	Sealing operations may be rendered ineffective if the roof stratum loses its effectiveness with time, depending on construction method and strata changes. It is difficult to anchor seals into mine strata, resulting in leakage. Seals may cause ground water levels to rise, causing surface damage.	Very effective in reducing or eliminating flow from abandoned mines into active mines.
Well dewatering......	Intercepts aquifers and controls the movement and ultimate discharge of the ground water.	System requires the availability of favorable geologic conditions reasonably close to the mine area. May not produce noticeable results more than a few hundred feet from the wells. May take several months before results are noticed.	Success has been limited. Has been used effectively in the reduction of water-handling requirements in the mine. Still in development stage. Large-scale applications have not been shown to be cost effective.

TABLE 5. - Summary of water control costs

Water control practice	Cost item	Cost		Per
Surface water controls:				
Runoff diversion.....	Construction of diversion ditch.	$0.70-	$2.80	Linear foot.
		2.30-	9.25	Linear meter.
	Construction of dikes..	.55-	1.15	Cubic yard.
		.75-	1.50	Cubic meter.
	Dumped rock...........	3.50-	10.60	Cubic yard.
		4.60-	13.80	Cubic meter.
	Riprap................	17.70-	44.25	Cubic yard.
		23.00-	60.20	Cubic meter.
Surface regrading and restoring.	Clearing and grubbing..		700	Acre.
			1,740	Hectare.
	Backfilling:			
	Contour.............		2,820	Acre.
			6,950	Hectare.
	Terrace.............		2,540	Acre.
			6,260	Hectare.
	Revegetation..........	700 -	775	Acre.
		1,740 -	1,910	Hectare.
	Regrading:			
	Contour.............	2,540 -	5,350	Acre.
		6,260 -	13,220	Hectare.
	Terrace.............	2,115 -	4,790	Acre.
		5,220 -	11,830	Hectare.
Soil sealing.........	Concrete..............	42.30-	84.60	Cubic yard.
		55.00-	110.00	Cubic meter.
	Clay..................	2.80-	8.50	Cubic yard.
		3.70-	11.00	Cubic meter.
	Rubber................	.70-	1.40	Square foot.
		7.60-	15.15	Square meter.
	Asphalt...............	.30-	.80	Square foot.
		2.80-	8.50	Square meter.
Stream channel modification.	Channel excavating.....	1.40-	4.20	Cubic yard.
		1.85-	5.50	Cubic meter.
	Clay-lining bottom.....	1.40-	2.80	Square yard.
		1.70-	5.10	Square meter.
	Channel reconstruction.	14.00-	35.25	Linear foot.
		46.25-	115.60	Linear meter.

TABLE 5. - Summary of water control costs--Continued

Water control practice	Cost item	Cost	Per
Ground water controls:			
Grouting and grouting curtains.	Vertical curtains......	$50 - $113	Linear foot.
		160.30- 370	Linear meter.
	Horizontal curtains....	16,900 - 28,200	Acre.
		41,750 - 69,600	Hectare.
Borehole sealing.....	Cleaning..............	14 - 28	Linear foot.
		47 - 93	Linear meter.
	Sealing with cement grout.	21 - 28	Linear foot.
		69 - 93	Linear meter.
Subsurface soil sealing.	Drilling..............	2.80- 4.30	Linear foot.
		9.25- 13.90	Linear meter.
	Cement................	2.80- 6.35	Bag.
	Cement admixture.......	2.80- 5.60	Pound.
		6.20- 12.40	Kilogram.
	Fly ash................	11.30- 28.20	Ton.
		12.40- 31.00	Metric ton.
	Horizontal grout curtain.	16,900 - 56,360	Acre.
		41,750 -139,160	Hectare.
Mine sealing.........	Dry seals:		
	Masonry block seal...	3,520 - 4,230	Seal.
	Clay seal...........	2.80- 5.60	Cubic yard.
		3.70- 7.40	Cubic meter.
	Clay bulkhead........	3,520 - 6,340	Seal.
	Hydraulic seals, double bulkhead:		
	Grouted aggregate....	14,100 - 42,270	Do.
	Quick setting........	21,150 - 25,360	Do.
	Seal and curtain grouting.	28,180	Do.
	Hydraulic seals, single bulkhead.	7,050 - 14,100	Do.
	Curtain grouting:		
	Vertical curtains....	49 - 113	Linear foot.
		160 - 370	Linear meter.
	Horizontal curtains..	16,900 - 28,200	Acre.
		41,750 - 69,600	Hectare.
Well dewatering......	75-gpm well............	36,970	Year, per million gpd.
	230-gpm well...........	19,460	Do.
	760-gpm well...........	13,430	Do.

technical and economic performance of a dewatering system in Appalachia. Consequently, a very heavy emphasis has been placed on the results of case study 1.

Case study 2 was a preliminary feasibility study conducted by a private mining company to evaluate the advantages and disadvantages of dewatering a new mine in advance of mining. Both technical and legal factors were considered in this study; however, the major consideration was whether the additional costs incurred by the dewatering system would be recovered through a reduction in unit production costs. It was concluded that legal factors alone made the project unfeasible. In addition, the complexities of the technical problems resulted in both a technical approach and related high costs that made the project prohibitive to implement.

Case study 3 involved an ongoing attempt by a mining company to control water inflow in the last working section of an old mine. This situation occurs with some frequency in Appalachia and often results in substantial amounts of coal left unmined because of difficult mining conditions. The approach being attempted consists of inducing subsidence in the area of heaviest inflow to concentrate the mine drainage in a system of sumps, which will then allow the safe extraction of the remaining coal. This demonstration will not be completed in time to include a discussion of the actual effectiveness in this report. This method does, however, appear to represent a practical approach to the problem, and it provides an interesting comparison with the other two case studies.

The geologic conditions of the three study sites are compared and summarized in table 6. The parameters compared are (1) the coal seam mined, including depth and thickness, (2) the mining method used, (3) the surface geology, (4) the subsurface geology, and (5) the major structural features.

The hydrologic conditions of the three study sites are compared and summarized in table 7. The parameters compared are divided into three categories: surface water, ground water, and mine water. The surface water parameters include (1) drainage basin, (2) watercourses, and (3) springs. The ground water parameters include (1) aquifer(s) and (2) aquifer properties. The mine water parameters include (1) sources, (2) inflow rate, and (3) method of control.

TECHNICAL EFFECTIVENESS

Case Study 1

The technical effectiveness of case study 1 is described in detail in appendix A. As the data show, the dewatering operation had little impact on controlling the quantity of water flowing into the mine; only a 34-pct decrease in mine inflow was realized. The following description of the area's ground water conditions offers an explanation as to why the dewatering operation was ineffective.

The inflow rate at the test site was estimated to range from 100 to 150 gpm (6.3 to 9.5 L/s), yet the geologic and ground water conditions of the area indicate that aside from the Saltsburg Sandstone, no discernable aquifer units exist. In addition, a rapid response to heavy rainfall was observed in the well water levels and in the mine inflow. This indicates that the ground water system is fracture controlled. Since most of the water is located in the fracture zones, wells that do not intersect any of these water conduits will do little to relieve the water problem in the mine. The study demonstrated this very well. The wells could only intercept some of the ground water storage space, while the major avenue of water infiltration into the mine was never dealt with. As a result, only a small decrease in the mine inflow was achieved. It must still be demonstrated technically that dewatering in advance of mining can be achieved when the ground water conditions are fracture controlled. The fractures must be well delineated and their hydraulic characteristics well defined, so that wells can be properly located. This is not beyond the technology available today. Parizek and Tarr (25) have demonstrated that water supply wells sometimes can be located via

TABLE 6. - Comparison of geologic conditions at three case study sites

Parameter	Case study 1	Case study 2	Case study 3
Coal seam:			
Type	Lower Kittanning (B)	Upper Freeport	Pittsburgh.
Depth.........ft..	500 to 550	500[1]	400.
Thickness.....ft..	5	8 to 10	8.
Mining method	Longwall	Continuous	Continuous.
Surface geology	Unconsolidated materials: mostly quarternary alluvium, colluvium, and sedentary soil. Outcrops of sandstone and shale are relatively few, generally covered by by soil. Conemaugh Group: Glenshaw Formation: thinly to thickly bedded sandstone and shale.	6 soil groups Conemaugh Group: gray and brown claystone, shale, siltstone, sandstone, some redbeds, some calcareous claystone, some fossiliferous shales, some fire clay.	Alluvium: river channels--unconsolidated silt, sand, and cobbles. Carmichaels Formation: ancient river channels--laminated clay, silts, sands, pebbles, and cobbles. Some boulders. Waynesburg and Uniontown Formations: mostly thinly to thickly bedded sandstones, shales, siltstones, and mudstones. Pittsburgh--Upper Member--mostly limestone.
Subsurface geology	Conemaugh Group: Glenshaw Formation: same as above. Allegheny Group: oldest group; Freeport and Kittanning Formations present here: Freeport Formation: mostly interbedded shales, siltstones, sandstones, with some limestone and coal. Kittanning Formation: 2 thick sandstone units sandwiching a coal and thick shale unit. Coal seams at top and bottom.	Conemaugh Group: same as above. Allegheny Group: Upper Freeport Coal: relatively soft; shale binder in middle; roof--Uffington Shale, mostly firm and hard; floor--Bolivar Fire Clay, basically soft.	Waynesburg and Uniontown Formations, Pittsburgh--Upper Member: same as above. Sewickley, Fishpot, Redstone and Lower Pittsburgh Members: predominantly interbedded mudstones, siltstones, and sandstones. The base of each member is marked by a layer of coal.
Major structural features.	Area is generally flat lying with gentle dip to the east-southeast. Strata are subparallel to one another. No fault features.	North Potomac syncline: trend: northeast to southwest; dips: 18° near outcrop of coal; relatively flat in basin. No true geologic faults. Major trends: N 7° E, N 26° E, N 74° E, N 11° W. Minor: N 43° E.	2 synclinal folds: Brownsville anticline, Lambert syncline. Both are symmetrical, open, and have undulatory flanks dipping 3° or less. Axes strike N 25°-45° E. Both folds have a general southward plunge of less than 1°.

[1]Average.

TABLE 7. - Comparison of hydrologic conditions at three case study sites

Parameter	Case study 1	Case study 2	Case study 3
Surface water:			
Drainage basin......	Susquehanna River............	Upper Potomac Basin..........	Monongahela River.
Watercourses........	Laurel Lick Run, Chest Creek.	Sand Run, Laurel Run, North Branch of Potomac River, and a number of smaller streams.	Monongahela River, Muddy Creek, a number of intermittent streams.
Springs.............	A number of springs with flows of 5 gpm. A number of seeps with flows of 1 to 2 gpm.	1 known spring on-site.......	Numerous small springs.
Ground water:			
Aquifer(s)..........	Saltsburg Sandstone (perched)	7 major aquifer units: most important--Lower Mahoning Sandstone.	Waynesburg Sandstone, Pittsburgh Sandstone.
Aquifer properties: transmissivities, permeabilities, or yields.	Transmissivity: 200 to 300 gpd/ft. Yield: 27 gpm.	Permeability: 0.047 gpd/ft^2. Yield: 2-3 gpm.	Yield: Waynesburg Sandstone: 65 gpm. Pittsburgh Sandstone: 34 gpm.
Mine water:			
Sources.............	Ground water in overlying and surrounding rocks--transmitted through fracture zones in roof. Abandoned mines.	Lower Mahoning Sandstone.....	Monongahela River--transmitted through bedding planes.
Inflow rate.........	Whole mine: 3.4 million gpd. Study area: 100 to 150 gpm.	After 1 yr development: Mine A: 10,500 gpd. Mine B: 21,000 gpd. Mine C: 10,500 gpd.	Whole mine: 2 million gpd. Working area: 200 to 300 gpm. Roof bolt holes: 50 gpm.
Method of control...	Dewatering in advance of mining was tested, but maximum reduction in mine inflow was only 34 pct. Currently using a series of sumps and pumps to dewater the mine.	Considered dewatering in advance of mining but rejected it. Will use series of pumps and sumps. When operations reach base of syncline, water will be pumped through wells from main sumps to the surface.	Series of sumps and pumps and directional mining have proved ineffective. Currently planning to create a sump by second-mining an area of the mine to intercept the water.

fracture analysis. However, the impact of this technology on mine water inflow has yet to be demonstrated.

Case Study 2

The technical effectiveness of case study 2 is described in detail in appendix B. In this case, dewatering in advance of mining was considered primarily because of the high cost of tramming within the mine under wet conditions. Each mine in this area receives inflows of approximately 10,000 to 20,000 gpd (37,850 to 75,700 L/d) in the first year alone. This amount increases as more mine area is exposed. Dewatering in advance of mining was also considered because the region is artesian. Unfortunately, test wells drilled to evaluate aquifer characteristics showed that the sandstone unit above the coal seam was not permeable enough to pump, yielding only 2 to 3 gpm (0.13 to 0.19 L/s). These results indicated that dewatering in advance of mining would be difficult and expensive, owing to the number of wells necessary for effective dewatering and the cost of drilling these wells. Also, the mining cycle would advance too rapidly for dewatering to be effective.

In addition, it was found that the natural water in the area has a pH of 4.0 to 4.5. State regulations require that water in this pH range be treated before being returned to the environment, which eliminates one of the major advantages of dewatering prior to mining.

After considering these and other facts, it was decided that dewatering in advance of mining would be technically and economically impractical for this area.

Case Study 3

Water has caused significant problems in the operation of the Nemacolin Mine (fig. 6). The inflow of water into the working section of the mine was so great that it disrupted face operations even with an adequate dewatering system of pumps and sumps. To remedy this problem, the mine engineers decided to vary the direction of mining by 90°, advancing the operations away from the Monongahela River, which borders the mine, instead of paralleling it. This brought some initial relief, but with time the problem returned.

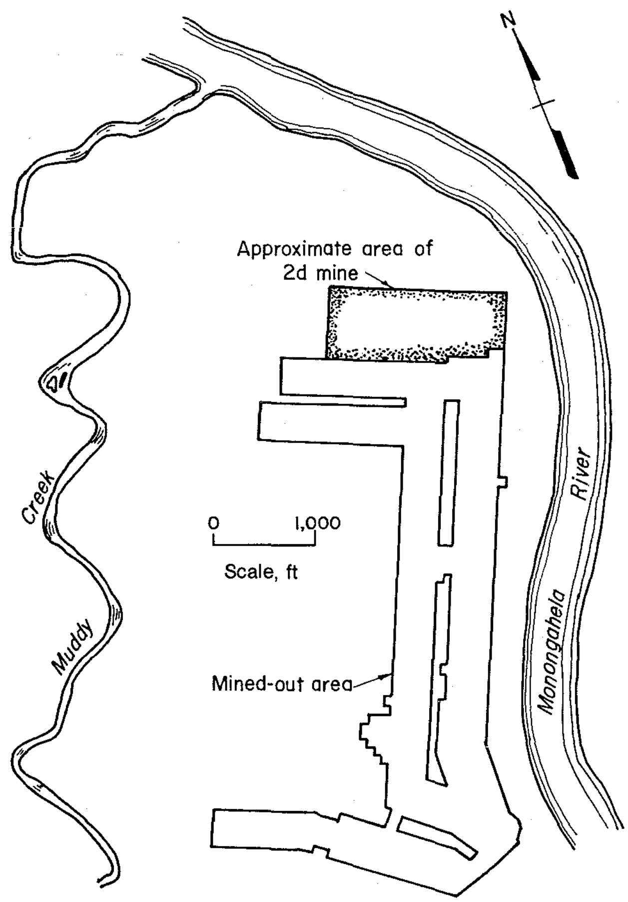


FIGURE 6. - Map of Nemacolin Mine.

The mine engineers decided that the best way to prevent the disruption of face operations was to dewater the overburden before the water reached the face operations. They are second-mining the area just north of the 90° turn and downdip of the Monongahela River, thereby creating a huge sump where water will collect. This water can then be pumped out of the mine.

This system is basically a modification of the gravity drainage and mine pumping system of dewatering the overburden above a mine (fig. 4). Instead of using drilled holes to collect water, the water is collected by fracturing the confining bed and part of the source bed so that the water will run along the fractures into the mine.

It would seem that this type of overburden dewatering system is very well suited for this kind of situation, since most of the water entering the workings is traveling along bedding planes from the Monongahela River. Although it has yet to be demonstrated that this type of system can adequately drain the overburden, the system is technically and economically feasible in this situation. As already stated, it would be necessary to second-mine an area of coal in order to implement this system. This would actually generate more income, since the coal could then be put on the market. In addition, no roof support would have to be instituted. The area would need less upkeep after retreat mining, resulting in a more economical, stable, and water-free environment.

COSTS

Case Study 1

The cost effectiveness of this demonstration project is detailed in appendix A. The overall conclusion of this specific project was that individually pumped wells constructed from the surface do not appear to be cost effective in controlling water quality at the specific demonstration site, unless the average well yield can be increased from the 30 gpm (1.9 L/s) used in the analyses. On the average, the cost of well dewatering at this study site appeared to be at least twice that of present water removal and treatment methods.

In addition to the requirements for higher flow rates as described above, two other factors were offered to improve the cost effectiveness of this approach: The acidity concentration of the mine water should be in the range of 500 to 1,500 ppm (500 to 1,500 mg/L), and the coal seam depth should be less than 150 ft (46 m).

Case Study 2

Mine engineers studied the possibility of using individually pumped wells constructed from the surface to control water flowing into the mine. After a period of information gathering, which included well drilling and aquifer testing, they decided that this approach would not be cost effective for the following reasons:

- The aquifer unit feeding water to the mine is not permeable enough to pump. Maximum well yield is only 2 to 3 gpm (0.13 to 0.19 L/s). In order to dewater the mine using wells, the wells would have to be placed on 100-ft (30-m) centers.

- If the water table or hydrologic balance is altered, a potable water supply must be made available by the mining company for the area's landowners.

- The natural water in the area has a pH of 4.0 to 4.5, which is not potable. By law, this water must be treated before being returned to the environment.

- The company would need to purchase surface rights for access, power lines, etc., needed for the wells.

- The cost of drilling in hard and fractured rock is extremely high.

Case Study 3

No cost data are available for this situation since the mining company did not investigate the use of individually pumped wells constructed from the surface to control inflowing mine water. Most of the company's mine property has been mined out, except for a small 1-1/4-mi^2 (3.24-km^2) area, which is currently experiencing water problems. It is not to the company's benefit to expend large amounts of money on well development and testing. However, it would be beneficial for the company to extract the existing coal, since it represents a considerable market value. Company officials have therefore decided to dewater the overburden by retreat mining the area between the water source and the workings, thereby creating a large sump where the water can be collected and pumped out of the mine. This type of system is extremely cost effective under conditions such as those at this mine.

OTHER CONSIDERATIONS

Well dewatering systems are not designed to control or influence sudden inrushes of water. Sudden inrushes are usually associated with one of the three following situations: (1) flood waters entering a mine opening located in the floodplain, (2) subsidence or caving below a large water body, or (3) breaching of an underground pool of water such as abandoned and flooded mine workings. Although a dewatering well can be used to drain abandoned flooded mine workings when they are identified, inrushes are usually associated with unidentified and unexpected underground pools. Consequently, well dewatering systems cannot be credited with providing any benefits in this area.

Roof collapses, which are a reflection of poor roof conditions, are often associated with the presence of water in conjunction with geologic unconformities. Water will either soften claystone roof or act as a lubricant to decrease the frictional resistance to movement of rock strata. It has been postulated that well dewatering systems may aid in the control of roof problems by reducing the volume of water entering the working section. However, since dewatering systems have been demonstrated to intercept less than 50 pct of the inflow to a given section, their benefit with respect to roof control is questionable. Reducing inflow to a working section from 100 to 50 gpm (6.3 to 3.2 L/s) is not likely to improve roof conditions significantly. Lubrication of a slip surface, such as a slickenslide, requires only small volumes of water or moisture, although the precise amount is variable. Thus, it would appear that in order to improve roof control problems, a dewatering system would have to intercept virtually all of the water coming in contact with slip or failure planes. Similarly, only small amounts of water are necessary to cause a softening of underclays, which leads to floor heave and pillar punching.

Ventilation problems associated with the presence and flow of water include increases in heat and humidity, and ventilation system blockages. The potential effect of well dewatering on heat and humidity has not been explored to date. However, with respect to ventilation system blockages, well dewatering systems do not appear to offer any advantages over conventional drainage systems.

In summary, the use of a well dewatering system in the Appalachian coalfields is not likely to provide any substantial advantage over conventional drainage systems with respect to health and safety.

An underground coal mine has the potential to substantially alter both the quantity and quality of surface and underground water. The impact of coal mines on water quality has been the focus of many research projects in the past. Regulation of the impact of coal mines on the quantity of both surface and ground water is a more recent development.

The use of dewatering wells to control the contamination of water by underground coal mines is particularly attractive from an environmental standpoint because it eliminates the need for treatment prior to discharge to surface waters. For those underground mines involved in the handling, pumping, and treatment of large volumes of contaminated water, it might prove cost effective to intercept the mine inflow prior to contamination and release the uncontaminated water directly to surface streams, thus avoiding the cost of treatment.

This practice is not directly applicable in Appalachia for a number of reasons. There are wide variations in the characteristics of natural waters throughout the Appalachian coalfields. Simply because ground water is "natural" does not imply that State regulatory agencies will allow its discharge to surface streams without treatment. For example, the ground water encountered in case study 2 was derived from an acidic sandstone and displayed a natural pH in the range of 4.0 to 4.5. Consequently, this water would have to be treated to obtain a pH in the range of 6.0 to 9.0 prior to release. In addition, the natural ground water may be objectionable with respect to its iron, manganese, or dissolved salts concentrations.

A second major constraint to the successful application of this approach in Appalachia is the failure to demonstrate that it can result in well effectiveness (the ability to intercept a certain percentage of the mine drainage inflow) exceeding 50 pct [Fink (13)]. This method would require the use of two separate dewatering systems at the mine: the standard approach to mine dewatering, previously discussed, and the well dewatering system itself.

Well dewatering systems appear to be more advantageous at shallower depths. In order to obtain a well effectiveness of 80 pct, the depth of the mine would have to average less than 220 ft (67 m) for the system to be cost effective (13). The average depth of underground coal mines in Appalachia is approximately 600 ft (183 m), and this value is expected to increase in the future. Consequently, it is unlikely the high well-effectiveness values can be achieved at this time, and the likelihood decreases in the future as the depths of mines increase.

There is very little information available on the cost effectiveness of well dewatering systems in Appalachian underground coal mines. In fact, the only information available is that provided in case study 1, which represents the only known and reported demonstration of such a system.

The results of this demonstration program indicate that the cost of well dewatering appears to be, on the average, at least twice that of present water removal and treatment practices. The case study suggests that dewatering with individually pumped wells could be cost effective if the coal seam is less than about 150 ft (45 m) deep. As previously discussed, the average depth of underground mines in Appalachia is approximately 600 ft (183 m), and that figure is expected to increase. There are very few underground mines with depths of less than 150 ft (45 m) in Appalachia.

The case studies suggest that additional indirect benefits of dewatering, such as reduction of production losses due to high water inflows and unstable roofs, could enhance the effectiveness of well dewatering systems. However, the volume of water intercepted by the dewatering systems has not been demonstrated to increase productivity any more than conventional drainage methods.

CONCLUSIONS

IMPACTS OF MINE WATER

The effects of mine water fall into four major categories, as follows:

1. Health and Safety

- The concern for inrushes of mine water in Appalachia is likely to increase in the future as the number of new mines increases, particularly since these new mines will often be sited in the deeper seams, adjacent to and/or underlying the older water-logged workings.

- Mine water can affect a mine's ventilation in two ways: it can (1) aggravate the heat and humidity problem and (2) block the ventilating airways.

- Mine water seeping through the roof and moisture supplied by the ventilation system can cause failure in weak shale roofs.

- Mine water increases the maintenance requirements for both electrical and mechanical equipment.

- The presence of mine water, particularly when strongly acidic or alkaline, can accelerate the corrosion of mining equipment.

2. Production

- A survey of 325 working sections in the Appalachian region revealed that 56 pct of the sections had floor conditions in the wet to damp category. Thirty-nine percent of these sections displayed floor conditions with some degree of rutting and probable rolling resistance exceeding 100 lb/ton (51 kg/t).

• A correlation of these floor conditions with production suggested that a section would experience a decrease on the order of 16 to 25 tons (14.5 to 22.7 t) per shift per drop in bottom classification. Thus, a difference in the range of 32 to 50 tons (29 to 45 t) per shift might be experienced between a section with a dry, hard floor and a section with a wet, rutted, and slippery floor.

3. Environment

• The mechanisms that cause hydrologic impacts include (1) the removal of the coal seam, which results in underground cavities that serve as broad sinks or underdrains, which receive ground water percolating downward from overlying strata, (2) the fracturing and separation of overlying strata resulting from the removal of the coal seam, and (3) the removal of the water from the mine by gravity drainage and pumping.

• Recent investigations suggest that hydrologic impacts, such as dewatering of domestic wells, are not likely to be a frequent occurrence in the future for two reasons: (1) wells above the mining zone were not dewatered when the mine depth exceeded 300 ft (91 m), and (2) the average depth of existing mines in Appalachia is already 600 ft (183 m), and this figure will increase in the future.

4. Costs

• A difference in coal sales ranging from $422,400 to $660,000 per mining section per year can be experienced between a section with a dry, hard floor and a section with a wet, rutted, and slippery floor.

• Existing information on the effects of mine water on health and safety, production, environment, and costs is generally qualitative. Very little quantification of these impacts has been attempted to date, which precludes the determination of associated costs.

SOURCES OF INFLOW TO UNDERGROUND MINES

In order to assess conditions where water diversion and overburden dewatering might be feasible, it is necessary to briefly evaluate the characteristics of the aquifers associated with coal seams at mine sites in Appalachia. However, the literature survey revealed that there is a general lack of such data. This study also indicated that there is a general lack of information on sources of water inflows in underground mines.

The literature survey and consultations with mine personnel revealed that fracture-dominated flow systems are the major source of water inflow in underground mines, especially with large mine inflows of ground water. Fracture zones associated with faulting, jointing or subsidence are the avenues for the larger inflows.

WATER CONTROL METHODS

Several methods were identified for controlling surface and ground water inflow to underground mines, but the literature evaluation revealed that the technical feasibility and cost effectiveness of many of these methods have yet to be determined. A number of practices reported were developed or adapted for use in controlling water problems associated with abandoned underground mines. Many of the practices were selected because they represented the best, and in some instances the only, available control technology. Provisions were seldom made, however, to monitor the short- or long-term performance of these control measures.

CURRENT ENGINEERING PRACTICES

Consultation with mine personnel revealed only one widely recognized and accepted approach to managing the influx of water into underground coal mines in Appalachia. This approach consists of collecting the water that builds up within a section with one or more portable pumps and transferring it through a combination of conduits (either pipes or ditches), sumps, and pumps back to a surface holding facility for treatment and discharge to surface waters. As a consequence of this approach, the preferred method of planning an underground coal mine to minimize water problems consists of developing the mains along the strike of the coal. Panels are driven on the downdip during advance and on the updip during retreat. The investigations conducted during this project did not identify any new basic approaches that could replace the standard approach to mine dewatering described above.

The use of water diversions and overburden dewatering methods is not likely to control the flow of water into underground mines sufficiently to alleviate the need to develop a traditional system of gravity drainage and pumpage. These methods should not be viewed as alternatives, but rather supplements to traditional methods of handling water in underground mines.

To justify the application of water diversions and overburden dewatering, it is necessary to identify and quantify the benefits derived from the use of these control practices. These benefits must be greater than the benefits provided by the standard dewatering approach to justify the additional expense.

On the basis of reported data, the use of dewatering wells alone, drilled from the surface in advance of mining, does not appear to be a cost-effective method of dewatering underground coal mines in Appalachia, except under unusual conditions. These conditions include an average depth of overburden above the coal seam not exceeding 200 ft (67 m), interception of 80 pct of the normal mine water inflow, and an acidity concentration in contaminated mine waters in the range of 500 to 700 ppm (500 to 700 mg/L).

These are rather unusual circumstances in underground Appalachian coal mines, which average approximately 600 ft (183 m), a value which is projected to increase in the future. On this basis, it is concluded that the use of dewatering wells drilled from the surface in advance of mining is not practical at this time in Appalachia.

RECOMMENDATIONS

Methods of predicting water inflow to underground mines should be standardized and simplified. The regulatory requirements of the Office of Surface Mining require that a permit application for an underground coal mine include a determination of the probable hydrologic consequences of the proposed mine plan area and adjacent area, with respect to the hydrologic regime and quantity and quality of water in surface and ground water systems under all seasonal conditions [30 CFR 780.21(c)]. Particular emphasis should be placed on the feasibility of developing empirical values and constants on a regional or subregional basis, such as a drainage basin, to facilitate and simplify these computations.

The Bureau's Bulletin 570, "American Standard Recommended Practice for Drainage of Coal Mines (M6.1-1955, UDC 622.5)," needs to be updated. This publication, published in 1957, provides the latest in formal guidelines for drainage practices of coal mines. The guidance provided should be reviewed and reassessed in order to incorporate any developments that have occurred over the past 23 yr and, in particular, to assess the compatibility of the recommended drainage practices with new regulatory requirements such as those implemented by the Office of Surface Mining.

REFERENCES

1. Ash, S. H. Water Problem in the Pennsylvania Anthracite Mining Region. BuMines IC 7175, 1941, 11 pp.

2. Ash, S. H., W. E. Cassap, W. L. Eaton, K. Hughes, W. M. Romischer, and J. Westfield. Flood-Prevention Projects at Pennsylvania Anthracite Mines. Progress Report for Fiscal Year Ended June 30, 1947. BuMines RI 4288, 1948, 51 pp.

3. Ash, S. H., H. A. Dierks, and P. S. Miller. Mine Flood Prevention and Control: Anthracite Region of Pennsylvania. BuMines B 562, 1957, 100 pp.

4. Ash, S. H., and H. B. Link. Surface-Water Seepage Into Anthracite Mines in the Western Middle Field, Anthracite Region of Pennsylvania. BuMines B 532, 1953, 26 pp.

5. Ash, S. H., H. B. Link, and W. M. Romischer. Surface-Water Seepage Into Anhracite Mines in the Southern Field, Anthracite Region of Pennsylvania. BuMines B 539, 1954, 52 pp.

6. Ash, S. H., and R. H. Whaite. Surface-Water Seepage Into Anthracite Mines in the Wyoming Basin Northern Field, Anthracite Region of Pennsylvania. BuMines B 534, 1953, 30 pp.

7. Bunting, D. The Limits of Mining Under Heavy Wash. Trans. AIME, v. 51, Feb. 1915, pp. 177-199.

8. Coal Age. Coal Division Pumping and Drainage. V. 67, No. 10, Oct. 1962, pp. 125-127.

9. Davies, A. W., and W. K. Baird. Water Dangers. Min. Eng. (London), v. 136, No. 188, Dec. 1976, pp. 175-184.

10. Dierks, H. A., W. L. Eaton, R. H. Whaite, and F. T. Moyer. Mine Water Control Program, Anthracite Region of Pennsylvania: July 1955--December 1961. BuMines IC 8115, 1962, 63 pp.

11. Doll, W. L., G. Meyer, and R. J. Archer. Water Resources of West Virginia. WV Dep. Nat. Resour., Div. Water Resour. (in cooperation with U.S. Geol. Surv.), 1963, 134 pp.

12. Doyle, F. J., C. Y. Chen, R. D. Malone, and J. R. Rapp. Investigation of Mining Related Pollution Reduction Activities and Economic Incentives in the Monongahela River Basin (Appalachian Regional Comm. contract ARC-72-89/RPC-707, Michael Baker, Jr., Inc., Beaver Falls, PA). 1975, 416 pp.

13. Fink, G. B. Cost Effectiveness of Aquifer Dewatering. Paper in Coal Conference & Expo V (Symp. on Underground Mining, Louisville, KY, Oct. 23-25, 1979). McGraw-Hill, 1979, pp. 147-157.

14. Gulati, A. K., and A. K. Singh. Scheme of Developing Seams Below Water Logged Workings. J. Mines, Met., and Fuels, v. 25, Jan. 1977, pp. 3-8.

15. Johnston, W. D., Jr., M. D. Foster, and C. S. Howard. Ground Water in the Paleozoic Rocks of Northern Alabama. AL, Geol. Surv. (in cooperation with U.S. Geol. Surv.), Spec. Rep. 16, 1933, pt. 2, 58 pp.

16. Kenny, P. Corrosion Effects of Mine Waters. Paper in Proc. Symp. on Environmental Engineering in Coal Mining (London, Oct. 31-Nov. 2, 1972). Inst. Min. Eng., London, 1972, pp. 165-175.

17. Klingensmith, R. S., A. F. Miorin, and J. R. Saliunas. At Source Control Through the Application of Several Abatement Techniques. Paper in Sixth Symposium on Coal Mine Drainage Research (Louisville, KY, Oct. 1976). Bituminous Coal Res., Inc., Monroeville, PA, 1976, pp. 270-284.

18. Lohman, S. W. Ground Water Resources of Pennsylvania. PA, Topogr. and Geol. Surv. (in cooperation with U.S. Geol. Surv.), Bull. W 7, 1941, 32 pp.

19. Lovell, H. L., and J. W. Gunnett. Hydrogeological Influences in Preventive Control of Mine Drainage From Deep Coal Mining (PA Dep. Environ. Resour. contract EER-114). PA State Univ., Dep. Miner. Eng., University Park, PA, Spec. Res. Rep. SR-100, May 1974, 89 pp.

20. Manula, C. B., A. Bouillot, R. Rivell, and R. Sandford. Production Subsystem. U.S. Dep. Commerce, v. 6, 1974, 356 pp.; NTIS PB 255 424/AS.

21. Mason, W. A. Electrical Hazards in Underground Bituminous Coal Mines. MESA (now MSHA), U.S. Dep. Labor, Inf. Rep. 1018, 1975, 5 pp.

22. Miller, J. T., and D. R. Thompson. Seepage and Mine Barrier Width. Paper in Fifth Symposium on Coal Mine Drainage Research (Louisville, KY, Oct. 1974). Natl. Coal Association, Pittsburgh, PA, 1974, pp. 103-117.

23. Parizek, R. R. Prevention of Coal Mine Drainage Formation by Well Dewatering. PA State Univ., Dep. Geol. and Geophys., University Park, PA, Spec. Res. Rep. SR-82, April 1971, 73 pp.

24. Parizek, R. R., J. Sgambat, and M. Clar. Geology and Related Natural Resources of the Eastern Coal Fields. User's Manual for Premining Planning of Eastern Surface Coal Mining, v. 3, (U.S. EPA grant R803882, PA State Univ., College of Earth and Miner. Sci.). EPA-600/7-81-022, Mar. 1981, 344 pp.

25. Parizek, R. R., and E. G. Tarr. Mine Drainage Pollution Prevention and Abatement Using Hydrological and Geochemical Systems. Paper in Fourth Symposium on Coal Mine Drainage Research (Pittsburgh, PA, Apr. 1972). Bituminous Coal Res., Inc., Monroeville, PA, 1972, pp. 56-82.

26. Peters, T. W. Mine Drainage Problems in North Derbyshire. Paper in Proc. General Meeting of the Notts and North Derbyshire Branch of I Mine, Mines Rescue Station (Mansfield, England, Jan. 1977). Natl. Coal Board, London, 1977, pp. 462-472; Min. Eng. (London), v. 137, No. 200, Mar. 1978, pp. 463-473.

27. Rauch, H. Effect of Underground Mining on Water Wells in Monongalia County, West Virginia. Paper in Proceedings of the Fourth National Symposium on Aquifer Restoration and Ground Water Monitoring (Natl. Water Well Exposition, Columbus, OH, Sept. 20, 1978). Natl. Water Well Association, Worthington, OH, 1978, pp. 88-96; J. Ground Water, v. 16, No. 5, 1978, p. 358 (abstr.).

28. Schmidt, R. D., and G. Ahnell. A Fracture Dewatering Approach to Controlling Groundwater Infiltration in Underground Coal Mines (Interim Report). BuMines, Jan. 1983, 184 pp.; available upon request from R. D. Schmidt, Twin Cities Res. Cent., Minneapolis, MN.

29. Scott, L. R., and R. M. Hays. Inactive and Abandoned Underground Mines--Water Pollution Prevention and Control (U.S. EPA contract, Michael Baker, Jr., Inc., Beaver Falls, PA). EPA-440/9-75-007, June 1975, 338 pp.

30. Sgambat, J., E. A. Labella, and S. Roebuck. Effects of Underground Coal Mining on Ground Water in the Eastern United States (U.S. EPA contract 68-03-2467, Geraghty and Miller, Inc., Syosset, NY). EPA-600/7-80-120, June 1980, 183 pp.

31. Shotts, R. Q., E. Sterett, and T. A. Simpson. Site Selection and Design for Minimizing Pollution From Underground Coal Mining Operations (U.S. EPA contract 68-03-2015, Univ. AL, University, AL). EPA-600/7-78-006, Jan. 1978, 98 pp.

32. Skelly and Loy. Guidelines for Mining Near Water Bodies. Phase III. Recommended Guidelines for Mining Under Surface Waters (contract H0252083). BuMines OFR 29-77, 1976, 193 pp.; NTIS PB 264 728/AS.

33. Slaughter, T. H., and J. M. Darling. The Water Resources of Allegheny and Washington Counties. MD, Dep. Geol., Mines and Water Resour., Bull. 24, 1962, 408 pp.

34. Stefanko, R. Coal Mining Technology - Theory and Practice. Soc. Min. Eng. AIME, Littleton, CO, 1983, 402 pp.

35. Suboleski, S. C. Effects of Physical Conditions on Continuous Mine Production in Underground Coal Mines. Ph.D. Thesis, PA State Univ., University Park, PA, 1978, 362 pp.

36. Todd, D. K. Ground Water Hydrology. Wiley, 1959, 336 pp.

37. UOP, Inc., Johnson Division (St. Paul, MN). Ground Water and Wells. 4th ed., 1975, 440 pp.

38. Wahler, W. A., and Associates. Dewatering Active Underground Coal Mines: Technical Aspects and Cost Effectiveness (U.S. EPA contract). EPA-600/7-79-124, July 1979, 124 pp.

39. Walton, W. C. Leaky Artesian Aquifer Conditions in Illinois. IL State Water Surv., Rep. Invest. 39, 1960, 27 pp.

40. Wardell, K., and Partners. Guidelines for Mining Under Surface Waters. Phase III and Final Report (contract H0252021). BuMines OFR 30-77, 1976, 67 pp.; NTIS PB 264 729/AS.

41. White, P. E. Corrosion Research and Corrosion Resistance Fasteners. Min. Eng. (London), v. 127, No. 92, May 1968, pp. 463-473.

42. Whittaker, B. N., R. N. Singh, and C. J. Neate. Investigation and Evaluation Studies of Surface and Subsurface Drainage Pattern Changes Resulting From Longwall Mining Subsidence. Paper in Mine Drainage (Proc. 1st Int. Mine Drainage Symp., Denver, CO, May 1979). Miller Freeman Publ., Inc., 1979, pp. 161-183.

43. Wilson, L. W., N. J. Mathews, and J. L. Stump. Underground Coal Mining Methods To Abate Water Pollution: A State of the Art Literature Review (U.S. EPA, project 14010 FKK, Coal Res. Bureau, Morgantown, WV). Dec. 1970, 178 pp.

44. Wrathers, R. J., A. W. Swanson, and R. F. Langill. Investigation and Analysis of Subsurface Conditions for Coal Mine Development in Eastern Kentucky. Paper in 19th U.S. Symposium on Rock Mechanics (Stateline, NV, May 1978). Univ. NV-Reno, 1978, pp. 151-158.

APPENDIX A.--CASE STUDY 1

INTRODUCTION

The interception of ground water inflows to active coal mines was the subject of a study conducted by W. A. Wahler and Associates for the Environmental Protection Agency (38).[1] The study involved the construction and operation of a pilot well dewatering system, to collect and analyze both technical and cost data. The study site for this pilot dewatering program was the Lancashire No. 20 Mine, located near Carrolltown, PA, and owned by the Barnes and Tucker Co. (fig. A-1). The Lancashire No. 20 is a moderately deep slope mine, and the Lower Kittanning (B) coal of the Allegheny Group is the only seam mined. The coal seam averages 60 in (152 cm) in thickness and is located at depths ranging from 500 to 550 ft (152 to 168 m) in the vicinity of the study area. The "B" coal is metallurgical-grade, low-sulfur, low-volatile coal. The longwall method of mining is used.

[1] Underlined numbers in parentheses refer to items in the list of references preceding this appendix.

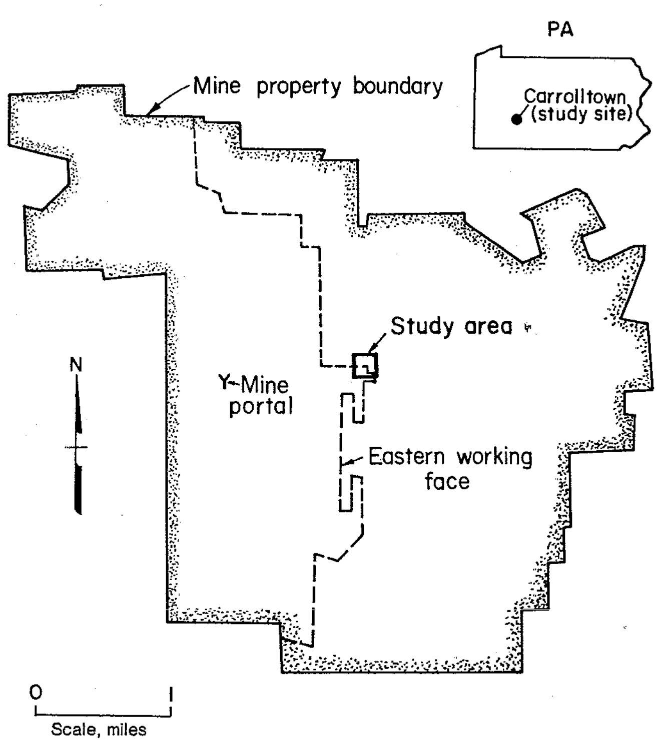


FIGURE A-1. - Location map of Lancashire No. 20 Mine and pilot well dewatering site.

The objectives of the pilot study were (1) to determine the impact of the dewatering operation on the quantity and quality of inflows in the limited area of the mine under study, (2) to evaluate, by extrapolating the results of this program, the potential effectiveness of the dewatering technique for the mine as a whole, and (3) to perform an economic evaluation of the technique.

GEOLOGIC ENVIRONMENT

Surface Geology

Unconsolidated materials cover most of the surface of the area and include quaternary alluvium, colluvium, and sedentary soil. Sedentary soil and colluvium make up the greater percentage of this cover and typically consist of silty sand to silty clay. They form a soil cover over bedrock units that varies widely in thickness. Quaternary alluvial material consists chiefly of sandy silt and sand. This alluvium is restricted to the floodplain and channel of Laurel Lick Run, which runs across the mine property.

All rocks exposed on the surface are of Pennsylvanian age and belong to the Glenshaw Formation of the Conemaugh Group. They generally consist of thinly to thickly bedded sandstone and shale. Sandstones are generally quartzose and/or argillaceous, fine to very fine grained, moderately hard to very hard, moderately weathered, and iron oxide stained. Shales are gray to gray brown, moderately hard, and moderately to severely weathered. The outcrops of sandstone and shale are relatively few in number and are generally covered by soil units.

Subsurface Geology

A generalized stratigraphic column of the units encountered is shown in figure A-2. All rocks in the subsurface are from Pennsylvanian period and are

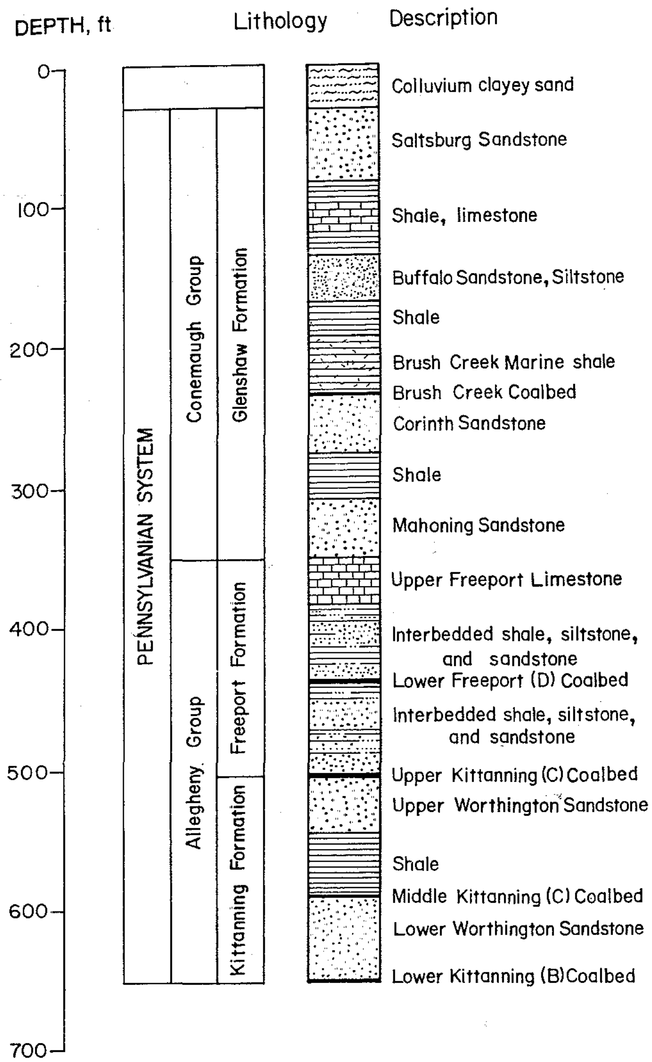


FIGURE A-2. - Generalized stratigraphic column, case study 1.

sedimentary in origin. Sandstone, shale, siltstone, limestone, coal, and clay were found.

The rocks in the subsurface can be divided into two stratigraphic groups: the Allegheny and the Conemaugh. The Allegheny Group, the older of the two, can be further divided into three formations (oldest to youngest): the Clarion, the Kittanning, and the Freeport. The maximum thickness encountered in the wells for the Allegheny Group was 250 ft (76 m).

The Conemaugh Group overlies the Allegheny and can be divided into two formations: the Glenshaw and the Casselman. The Casselman Formation is stratigraphiically higher than the Glenshaw and was not encountered on the surface or in the subsurface. The maximum thickness for the Glenshaw Formation was 328 ft (10° m). Names of members for both the Allegheny and the Conemaugh Groups, along with relative thicknesses, are indicated on the stratigraphic column.

Structurally, the area is generally flat with a gentle dip to the east-southest. Strata lie subparallel to one another except for the lowermost coal seam, the Lower Kittanning (a member of the Kittanning Formation of the Allegheny Group), which dips to the east at a slightly greater angle. No fault features were identified by correlation of geologic units.

HYDROLOGIC CONDITIONS

Surface Water

The mine area lies within the drainage basin of the Susquehanna River, whose flow ultimately reaches the Atlantic Ocean. Laurel Lick Run and Chest Creek both cross the mine property. Laurel Lick Run, with a drainage area of 9 mi^2 (23 km^2), flows into Chest Creek, which in turn flows into the West Branch of the Susquehanna River.

Laurel Lick Run and Chest Creek are relatively unpolluted and support trout and other aquatic life. In the past, Chest Creek has been used as a source of municipal water and could be used in this manner in the future. Because of the high quality of water in this watershed, treated mine drainage from the Lancashire No. 20 Mine is discharged into the West Branch of the Susquehanna, though Laurel Lick Run is closer.

Seeps, springs, and other hydrologic features are also present. Springs are few in number and not associated with any given horizon or topographic elevation. Only flows that are continuous year round were designated as springs, and flows for these are generally greater than 5 gpm (0.315 L/s). Seeps, on the other hand, were found to be quite common. Flow is usually less than 1 to 2 gpm (0.063 to

0.126 L/s), occurs intermittently, and is associated with wet periods. Seeps are commonly found in the topographic lows or swales or in areas with a break in slope.

Ground Water

Attempts were made to identify the principal water-bearing zones as they were encountered during air-rotary drilling. This was achieved by logging both the amount of water airlifted as the holes advanced and the rock types. Each water-bearing zone generally increased the amount of water airlifted as long as circulation was maintained. It was found, generally, that there was little correlation between rock types and the amount of ground water. There appeared to be some perching of ground water in the Saltsburg Sandstone, a member of the Glenshaw Formation of the Conemaugh Group, and possibly in the underlying unidentified limestone. Below this apparent perched zone, the bedded rock units could not be separated into distinct aquifers or zones with any degree of consistency. In particular, the various sandstone beds encountered did not indicate higher permeabilities than even the shales. There were some indications that the coal seams and the Upper Freeport Limestone are relatively permeable, but not with consistency. Also, there were indications that the thin shale bed above the Lower Kittanning (B) Coal, which forms the mine roof, is relatively permeable. This information, although not conclusive in itself, seems to indicate that fractures control the ground water flow.

Pump test data indicated a very asymmetric drawdown response with the cone of depression around the pumped well elongated along fractures, possibly in several directions. Also, it was observed that there was very rapid response to heavy rainfall both in well water levels and in inflows to the mine, indicating a hydraulic connection of fracture zones with the surface.

Using time-drawdown data from the pumped wells and distance-drawdown data, the transmissivities were calculated; they ranged between 200 and 300 gpd/ft (0.29 to 0.43 cm^2/s). This was later confirmed using data developed from the pilot dewatering operation.

In conclusion, the data strongly indicate that ground water drains into the study area along narrow, preferred flow paths. These flow paths are controlled by fractures and are directionally oriented. Permeabilities across these flow paths may be several orders of magnitude lower than permeabilities along the fracture planes. The bedded rock units probably act as secondary aquifers to various degrees and provide both hydraulic interconnection between fractures and ground water storage space. The fracture zones appear to consist mainly of steeply dipping fractures that intersect the surface. These permit rapid recharge from direct precipitation and from streams or ponds at the surface. The secondary aquifers also release ground water from storage to the fracture zones. The ground water flow regime is, therefore, quite complex and difficult to model with mathematical techniques because of the severe boundary effects and directional variations in permeability.

MINE WATER

The source of water inflow to the mine is ground water in overlying and surrounding rocks. Water flows into the mine primarily through the roof and is transmitted predominantly by fractures. There is probably some inflow through the mine floor, but it appears to be relatively minor. The mine floor is on an underclay (clay-shale) that restricts upward seepage of water.

Although minor drips and seeps are scatterd throughout the mine, the larger inflows are localized, probably along zones of more intense fracturing. Fractures and fracture zones are caused originally by geologic processes and later by the subsidence of rocks overlying the mine openings. Natural fractures were encountered while driving main haulageways and while establishing entries and crosscuts during the development of longwall panels for mining. Unstable roofs are often associated with areas of relatively high water inflow.

Inflows to the longwall panels and abandoned areas of the mine are influenced both by natural fractures and subsidence fractures. The longwall panels are 500 to 550 ft (152 to 168 m) wide and about 3,500 ft long. Normally, all of the coal is extracted in a continuous operation, and the roof support is moved forward with the coal cutting machine, allowing the roof behind the support to collapse. Entries previously driven along the panel partially dewater the panel area, but new fractures associated with roof collapse, along with preexisting fractures, promote more drainage into the mine. New fractures may extend to the surface, resulting in drainage of ground water that was not previously tapped. These fractures can result in inflows of water that are large enough to cause handling problems and that have hydrostatic heads sufficient to affect the caving characteristics of the roof. Both of these problems can affect production. Similarly, additional fracturing can be caused by the slow collapse of abandoned or inactive openings in which roof supports have not been maintained.

It appears that approximately 40 pct of the water enters through abandoned parts of the mine and 60 pct enters directly into the more recent workings. Inflows are affected by seasonal conditions, and it is even possible to recognize recharge from individual rainstorms. There is a tendency for high inflows to occur beneath stream channels, which probably tend to follow fracture zones along parts of their courses. Wells and springs overlying the mine may be affected or drained completely, especially where subsidence has occurred.

Water Removal

Water in the mine is collected and transferred through a series of sumps and conduits and eventually pumped to the surface. Initially, water is collected by small sludge pumps or allowed to drain by gravity into sumps. From there it is pumped from sump to sump through pipelines, as shown schematically in figure A-3. Water is pumped to the surface from F-1 and F-14 sumps, and the pipelines are combined to a single flow at the treatment plant, which has a design capacity of 5 million gpd (19 million L/d). Flow to the plant is controlled by pump operators underground, according to water levels in the sumps. Logs are kept for each pump and are used to determine flow rates, based on the pump curves for the two sumps.

Water Inflow Rate

General

Figure A-4 is a graph of average daily inflows to the treatment plant. The pattern of these flows tend to follow the dry and wet periods for this region. The yearly average flow for the period July 1976 through June 1977 is 3.4 million gpd (12.9 million L/d). The data after June 1977 are not reflective of normal flows, owing to the flooding on July 19 and 20 and cleanup operations extending well into August 1977.

Underground Study Area

The underground test site is referred to as the Main G study area and is located near the northeasternmost limit of workings along Main G heading or (as commonly referred to in the mine) the left side of Main G, near section G-14. The study area is bounded by the haulageway on the south, by the edge of underground working on the north and east, and by the G-11 entry on the west. Figure A-5 is a map of this portion of the mine.

This area was selected because it has relatively high ground water inflows [approximately 100 to 150 gpm (6.3 to 9.5 L/s)] and because it could easily be separated from other mine drainage and monitored. Mining in the immediate area had been temporarily halted because of unstable roof conditions and high ground water inflows, so advancement of the workings would not hamper the progress of the project.

Water enters the study area of the mine from the roof and from the coal seam. The roof is a gray to dark gray-brown shale-siltstone, which is fractured to intensely fractured. Slickensides and

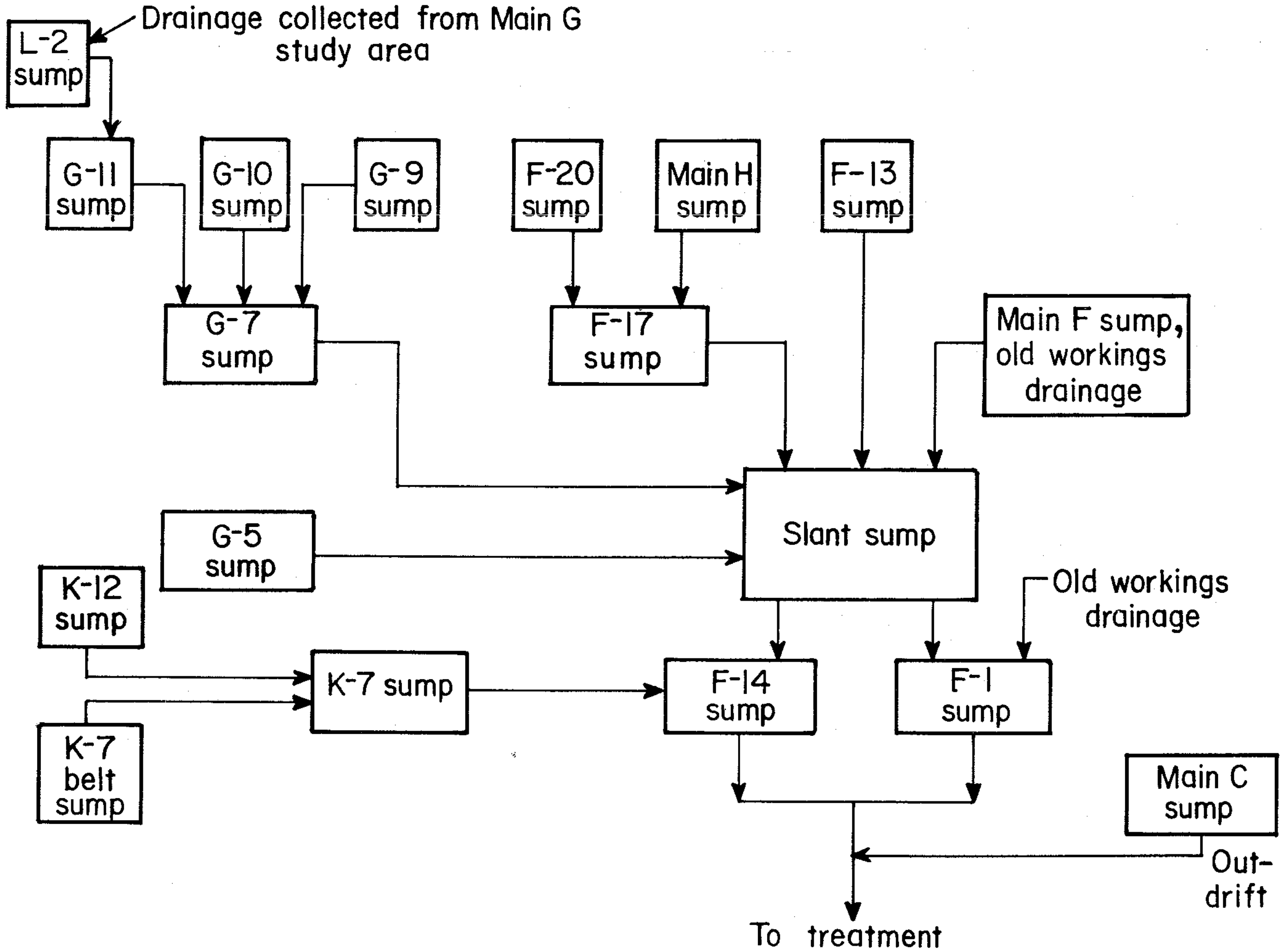


FIGURE A-3. - Water transport system.

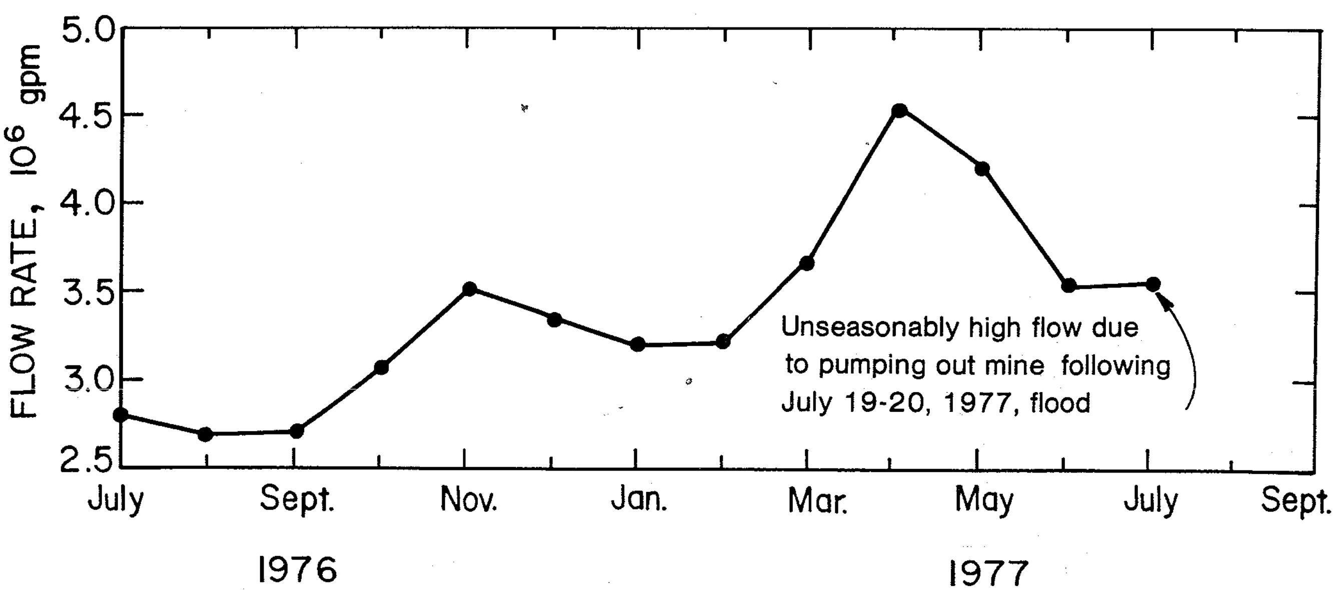


FIGURE A-4. - Average daily flows to treatment plant.

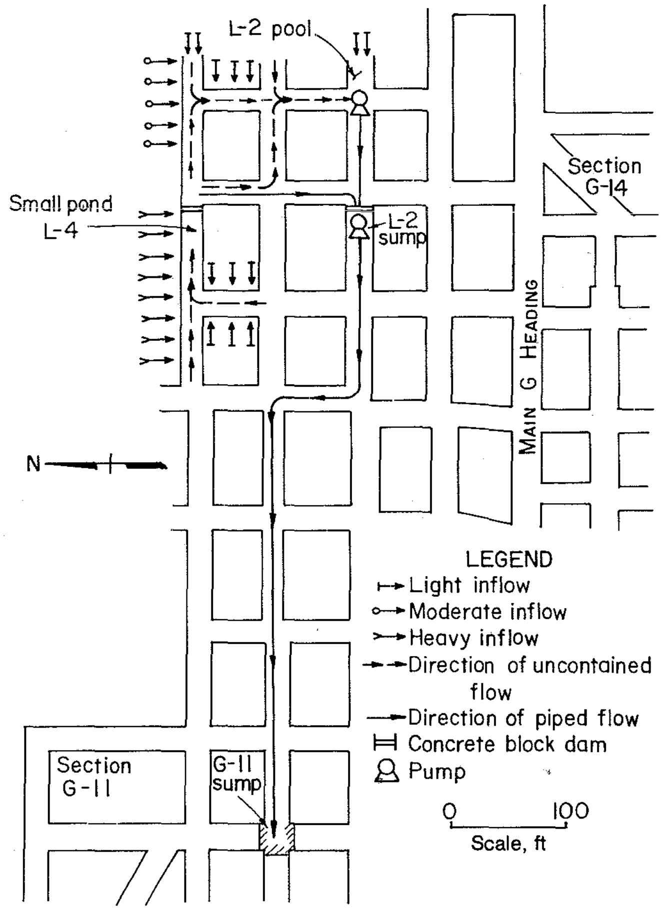


FIGURE A-5. - Main G study area.

polished surfaces are common on much of the rock, and water drains freely from these fractures. Fractures in the roof rock are common throughout this area of the mine. Water inflow, however, tends to be more localized in areal extent. The shale-siltstone roof is about 7 ft (2 m) thick and is overlain by a massive sandstone. Originally, it was thought that this sandstone was acting as an aquifer and was the source of ground water inflow to the study area. However, drilling and pump testing indicated that this unit is relatively tight, except along fractures.

The area of greatest mine inflow is along the L-4 heading near the northern face (see figure A-5) where most of it is collected behind a cement block dam. Overflow from the L-4 pond and any additional drainage from the left (north) side of the Main G heading is collected in a low area of the mine floor, forming a pool located at the east end of the L-2 heading. Prior to establishment of the underground monitoring system, the L-2 pool also collected drainage from the right (south) side of the Main G heading. Water from both the L-4 pond and L-2 pool is then transferred to the L-2 sump, which is formed by a cement block dam and is also located in the L-2 heading. Gravity flow is used to drain the L-4 pond, while pumping is required to remove water from the L-2 pool. Water collected in the L-2 sump includes all of the mine inflow to the Main G study area. From the L-2 sump, water is pumped to the G-11 sump where it is combined with water from adjacent areas and transferred through the mine and eventually to the surface.

Flow measurements at the underground monitoring station began in the late part of September 1976. Figure A-6 represents typical background flow data for the total water inflow occurring in the Main G study area of the mine. The data shown are average weekly values and the standard deviation for each 7-day period. These data are based on average daily flows derived from individual flowmeter readings and have been adjusted for changes in L-2 sump water levels where appropriate.

The average inflow rate for the entire period of September 26, 1976, through May 31, 1977, was 106 gpm (6.7 L/s), with a standard deviation of 9 gpm (0.57 L/s). As can be seen in figure A-6, the water inflow did vary somewhat over time, but such changes were generally gradual.

PILOT DEWATERING SYSTEM

Method of Approach

The objective of the dewatering program was to intercept a major portion of the ground water inflow to the Main G study area and to analyze the cost effectiveness of mine dewatering as a means of controlling acid mine drainage (AMD). Vertical wells were constructed adjacent to the mine openings to intercept ground water before it could be degraded in the mine. The wells were located along a line parallel to the mine face, in an

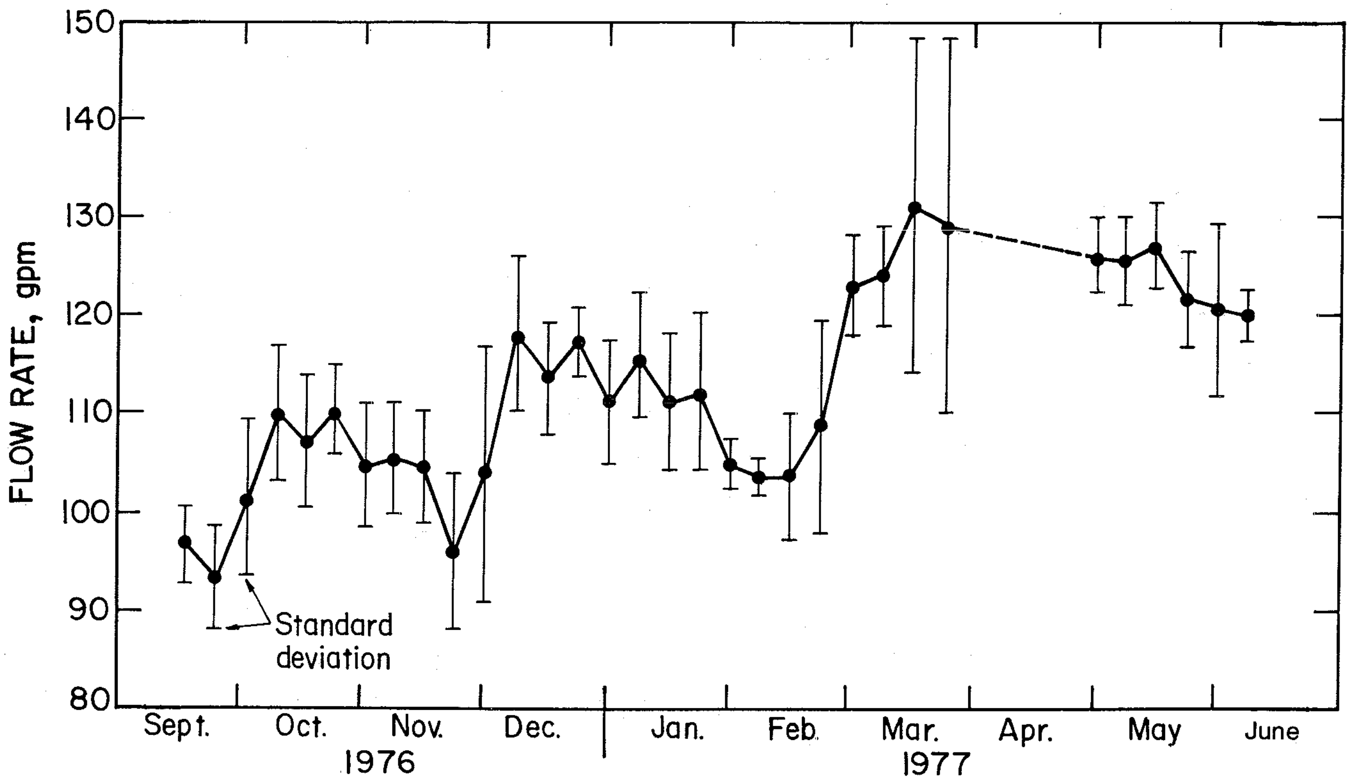


FIGURE A-6. - Average mine inflow in Main G study area.

attempt to create a hydraulic drawdown barrier against ground water movement toward the underground study area.

Results

The first pilot dewatering started on July 13, 1977, pumping from wells P-1, P-2, and P-3 (shown in figure A-7). The yield of the wells was increased gradually to a maximum total of 45.5 gpm (2.9 L/s). This yield was disappointing, because P-1 and P-3 were each expected to yield 40 to 50 gpm (2.5 to 3.2 L/s) on the basis of previous pump tests. Well P-2 did not produce much water and was later removed. Pumping continued for about 3 days and was stopped on July 16. During this period, flows in the Main G study area of the mine had decreased from 107 to 96 gpm (6.75 to 6 L/s), or 10 pct, as shown in figure A-8. About 24 pct of the water pumped from the wells was intercepted or diverted from the mine. These results were somewhat improved by an equipment change.

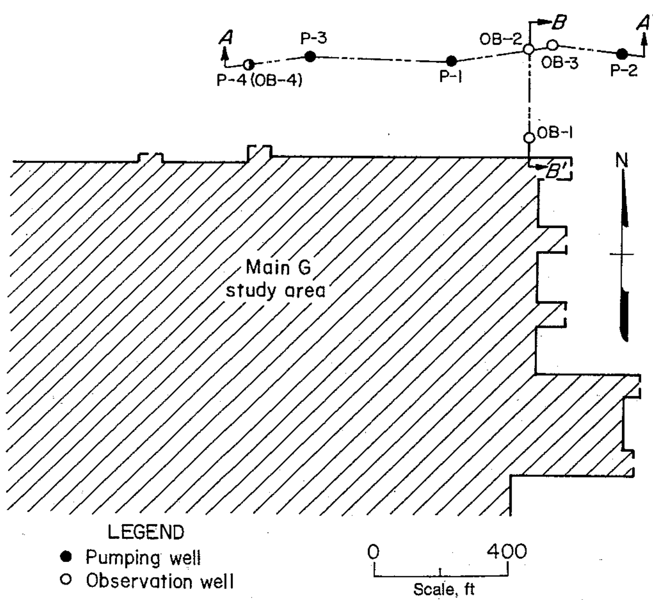


FIGURE A-7. - Location map of dewatering and observation wells.

The 5-hp pump was removed from P-2 and installed in observation well OB-4, thereafter designated P-4. Pumping resumed on July 18, and total pumpage was increased to 73.5 gpm (4.6 L/s). On July 19, flow in the Main G study area, which had increased to 111 gpm (7 L/s) just prior to restarting the pumps, rapidly decreased 23 pct to about 85 gpm (5 L/s). This indicated that 35 pct of the water pumped from the wells was diverted from mine inflows. The operation was interrupted by mine flooding, but these results were encouraging because the percentage of water intercepted should increase with time.

Dewatering was again resumed on September 16, 1977, after the wells were cleaned and the pumps were reset. The average total pumpage was approximately 82 gpm (5.2 L/s), ranging from about 95 gpm (6 L/s) near the start to about 75 gpm (4.7 L/s) at the end of the pumping period. Well OB-1 responded as expected, with generally consistent declines during pumping except near the end of the period. Well OB-2 declined rapidly at first and then more or less stablized. Water levels in P-2 declined slightly and then rose. Well OB-3 had essentially no response to pumping.

Inflows to the Main G study area (fig. A-9) decreased rapidly at first but showed only a slight decreasing trend after September 25. Inflows ranged from 70 to 76 gpm (4.4 to 4.8 L/s) after this date and quickly recovered to 112 gpm (7 L/s) after pumping stopped. The average inflow rate from September 25 through October 6 was 73.2 gpm (4.6 L/s), with a standard deviation of ±1.92 gpm (±0.12 L/s). The postpumping monitoring period, after inflows had recovered, from October 8 through October 22, showed an average flow of 110 gpm (6.9 L/s), with a standard deviation of ±4 gpm (±0.25 L/s). These values are comparable to all of the other background data, which showed an average inflow rate of 112±9.4 gpm (7±0.59 L/s).

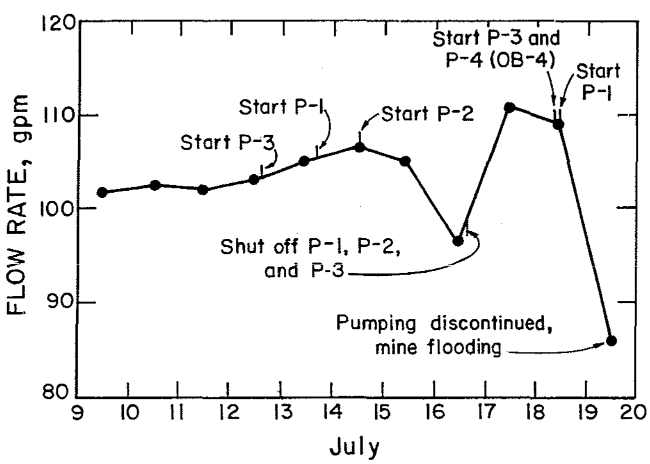


FIGURE A-8. - Average daily mine inflow, July 1977.

All of the pumping and observation wells, with the exception of OB-2, were affected by recharge from direct precipitation. The pumping and inflow data indicate that the mine study area inflow was decreased by about 34 pct, based on average flow rates. This decrease may have been as much as 38 pct, based on measurements at the end of the pumping period and the first inflow measurements after full recovery. These data indicate that 45 pct of the water pumped from wells comprised intercepted or diverted mine inflow, based on average rates for the pumping period. Theoretically, this percentage should increase with time, and at the end of the test, up to 56 pct of the water pumped was diverted from mine inflows. Projection of these data to 120 days of pumping indicated that up to 80 pct of the water pumped would be diverted from mine inflows. Recharge from storms or streams would reduce these percentages. Therefore, for purposes of estimating full-scale mine dewatering, it was assumed that 50 to 80 pct of the water yield from dewatering wells would be diverted from mine inflows.

During the dewatering operation, well yields were still disappointing. Only well P-3 was close to the maximum available drawdown, and that could not be sustained during the latter part of the pumping period. Well P-1 had more than 100 gpm (6.3 L/s) of available additional drawdown. The 7.5-hp pump in each of these two wells was not able to produce at its rated capacity, which was in excess of 40 gpm (2.5 L/s), with a pump lift of 510 ft (155 m). In contrast, the 5-hp pump performed relatively well throughout most of the dewatering program and during earlier pump tests. However, the yield of well P-4 gradually decreased, along with a small increase in drawdown. The impellers on the 7.5-hp

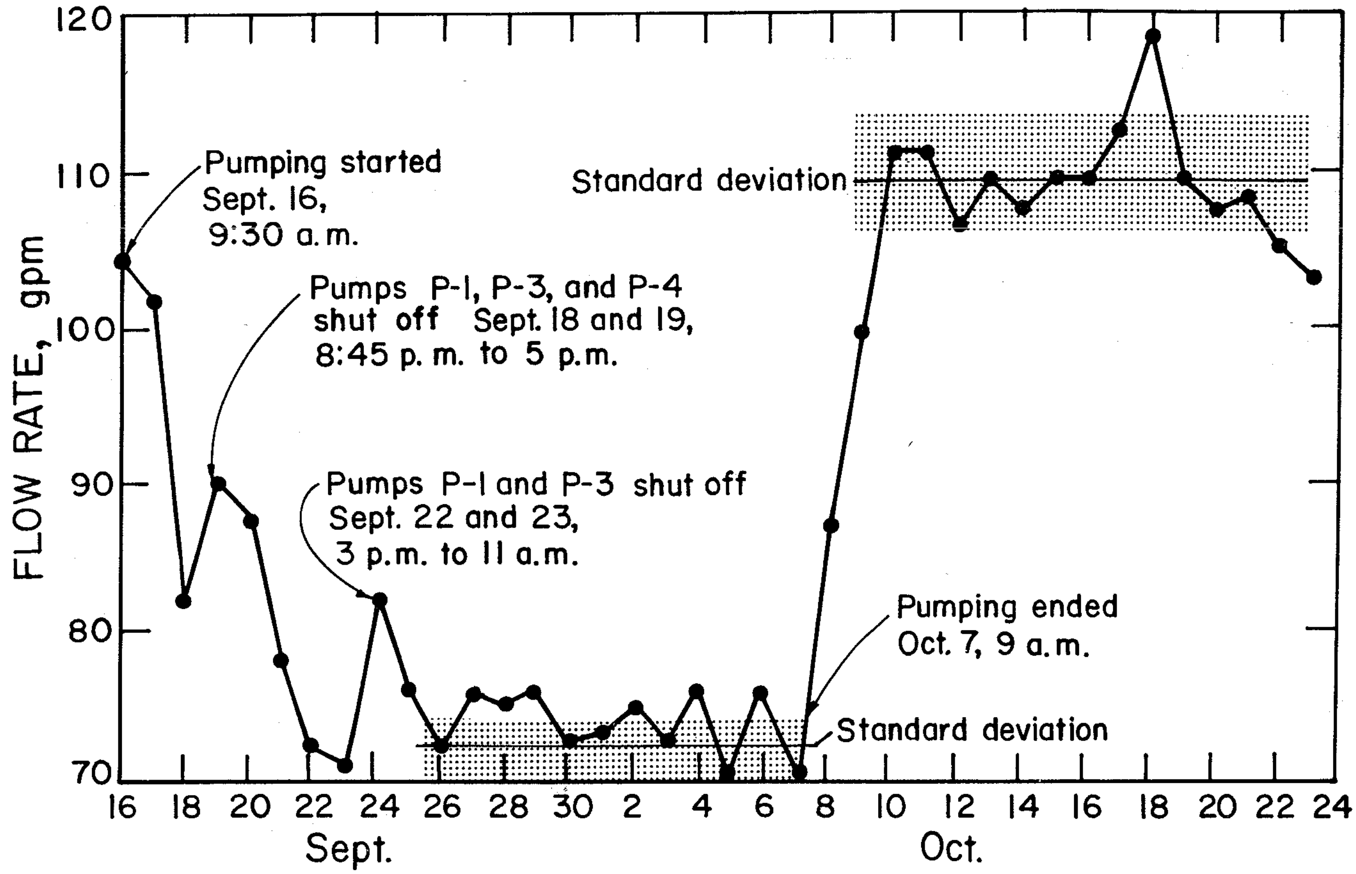


FIGURE A-9. - Average daily mine inflow, September 1977.

pumps may have been worn, reducing their capacity, or gas blocks may have developed to retard well yield. Although it was detected that all three pumping wells produced methane gas, the volume was not measured. The pumped water obviously had a large amount of gas entrained in the discharge.

For the study mine, costs for water collection and treatment were computed from company records:

Cost	Collection	Treatment
Capital investment.....	$432,000	$430,000
Operating costs:		
Annual...............	530,000	209,000
Per 1,000 gal[1].......	.468	.185

[1]Based on average flow rate of 3.1 million gpd.

Of the $530,000 annual operating cost for water collection, approximately 77 pct goes for water collection and transfer costs, and 23 pct for pumping to the surface. Major cost contributors to the $530,000 are power, 37 pct, labor, 36 pct, material, 19 pct, and other charges, 8 pct.

The computed values of treatment plant capital costs ($430,000) and annual operating expenses for treatment ($209,000) compare reasonably well with figures from published sources for other plants of similar capacity treating water with similar flow rates and acid levels.

Individually pumped wells constructed from the surface, as used in this study, do not appear to be cost effective in controlling water quality at the Lancashire No. 20 Mine, unless the average well yield can be increased three to four times the 30 gpm (1.9 L/s) used in the analyses. The cost of well dewatering at this mine appears to be, on the average, at least twice as great as present water removal and treatment costs. If the acidity of the mine water were higher (in the range of 500 to 1,500 ppm--500 to 1,500 mg/L) this dewatering system would be more cost effective. Also, if the coal seam were less than about 150 ft (46 m) deep, it appears that it would be financially feasible to dewater using individually pumped wells. Conservative well yields were used in the cost analysis based on the assumption that it would be difficult to locate wells along fracture zones, where optimum yields could be obtained. If fracture zones can be located accurately on the surface and penetrated with wells, then it is quite possible that dewatering with this type of system could be more effective. An average well yield of 30 gpm (1.9 L/s) was assumed in this analysis, but with wells located only in the more intensely fractured rocks, yields could average as high as three to four times this amount. Individual pumped wells would be cost effective if an average well yield of 90 to 120 gpm (5.7 to 7.6 L/s) could be obtained.

The cost-effectiveness analysis did not consider indirect benefits of dewatering such as reduction of production losses due to high water inflows and unstable roofs. Production losses due to poor water control can be much more expensive than the acid drainage problems that the water also creates.

APPENDIX B.--CASE STUDY 2

INTRODUCTION

Dewatering problems are of prime concern to this mine, located in Garrett County, MD. The company, Mettiki Coal Corp., has decided to mine roughly 9 mi^2 (15 km^2) of Upper Freeport Coal. Figure B-1 shows an aerial view of the planned and ongoing operations. Mining the coal will be quite difficult since the coal seam is part of the North Potomac syncline, where dips on the limbs of the syncline pitch up to 18°.

The mining complex is broken up into three mines: the Beaver Run Mine, the Gobbler's Knob Mine, and the Big George Mine. These mines will produce both metallurgical and steam coal since the quality of the coal varies within the seam itself. Each mine will use four continuous miner units in conjunction with diesel haulage equipment. Eventually, each mine will have two main sections and two working sections with a total projected production of 2 million clean tons per year.

Because of the existing conditions, the company investigated the possibility of intercepting the ground water inflow to the mines. The company felt that better mining conditions could be realized in keeping the mines dry. They hoped that this would result in higher productivity.

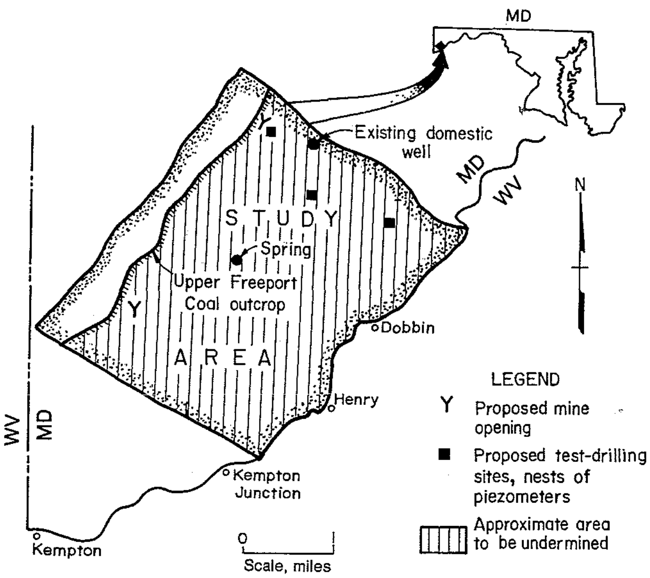


FIGURE B-1. - Planned and ongoing mine operations.

GEOLOGIC ENVIRONMENT

Surface Geology

All rocks exposed on the surface directly above the mine are of Pennsylvanian age and belong to the Conemaugh Group. This formation consists of predominantly gray and brown claystones, shales, siltstones, and sandstones. The lower part of the formation is characterized by several redbeds, calcareous claystone, and fossiliferous marine shales.

In addition to rocks, soil groups exposed on the surface include Brinkerton, Cookport, Gilpin, Ernest, Dekalb, and Stony Land. Their properties are summarized below.

	Average depth, in	Permeability, in/h
Brinkerton........	50	0.2-0.63
Cookport, Gilpin, Ernest...........	29-38	1.6-5.1
Dekalb, Stony Land	24-36	2.0+

Subsurface Geology

A generalized stratigraphic column of units encountered in the subsurface is shown in figure B-2. All rocks in the subsurface are from the Conemaugh Group (described in the previous section). The Upper Freeport Coal itself is part of the Allegheny Formation, which is of Pennsylvanian age. It is a relatively soft coal containing a shale binder 0.4 to 1.4 ft (12 to 0.43 m) thick near the middle of the seam.

The immediate roof for the Upper Freeport Coal is the Uffington Shale, which ranges from a few inches to 10 ft (3.1 m) thick. This shale is, in most places, firm and moderately hard, but it is interbedded with soft clay near the eastern corner of the property. The main roof is

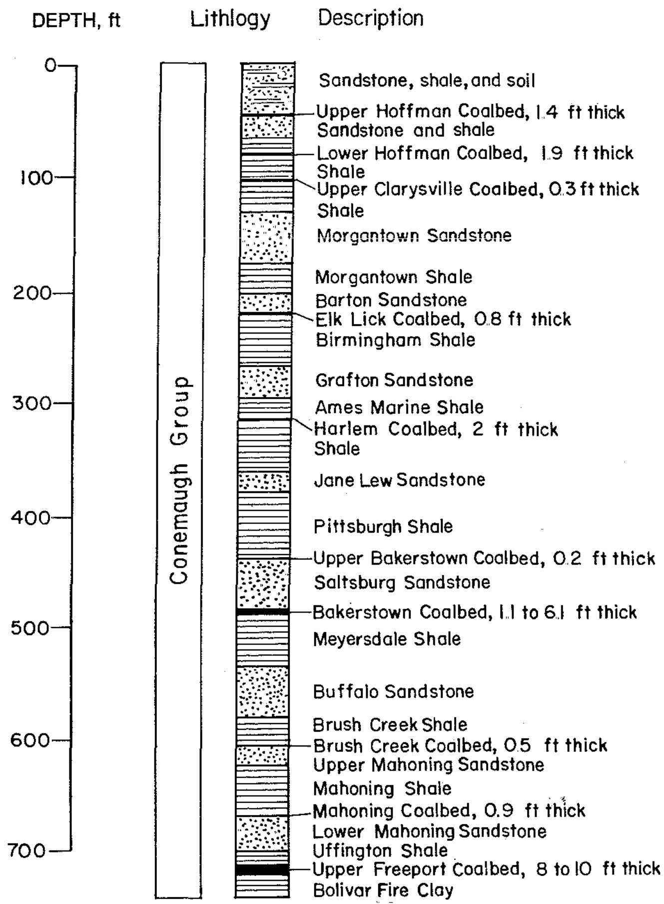


FIGURE B-2. - Generalized stratigraphic column, case study 2.

Lower Mahoning Sandstone, which ranges from 5 to 110 ft (1.5 to 33.5 m) thick, and occurs 7 to 22 ft (2.1 to 6.7 m) above the coal.

Total thickness of cover above the coal averages more than 500 ft (152 m). However, along the southeastern edge of the property, at the Potomac River, the coal is typically about 450 ft (137 m) deep.

The floor of Beaver Run Mine consist of at least 2 ft of Bolivar Fire Clay, comprised of fire clay, claystone, or soft shale. Softest areas are confined to the northwest limb of the syncline.

The principal structural feature of the mine property is the North Potomac syncline, which trends roughly northeast-southwest an average of 6,000 ft (1,829 m) north of the North Branch of the Potomac River. The basin and southeast limb are relatively flat, with dips of 0° to 3°, while dips of up to 18° exist near the outcrop of the Upper Freeport Coal on Backbone Mountain. The synclinal structure overlying the proposed mine is depicted in the schematic cross section (fig. B-3).

Joints and fractures were found to have major trends at N 7° E, N 26° E, N 74° E, and N 11° W, with a minor set at N 43° E. No true geologic faults were detected in the area.

HYDROLOGIC CONDITIONS

Surface Water

The mine area lies within the upper Potomac Drainage Basin, whose major river is the North Branch of the Potomac. This river also forms the southeast boundary of the mine area. A number of smaller streams, all of which drain into the North Branch, are also present on the mine site. These include Sand Run, Laurel Run, Chestnut Ridge Run, and Red Oak Run. No larger bodies of water, such as lakes, are present on the property, although one spring is known to exist.

Subsurface Water

General ground water flow conditions at the mine sites are artesian owing, to the synclinal structure of the site and the presence of thick, impermeable shale units that confine existing aquifers.

The following is a list of major aquifer units in the area:

Sandstone unit	Thickness range, ft	Feet above coal
Lower Mahoning....	15-110	10
Buffalo...........	15- 50	120
Saltsburg.........	0- 60	190
Jane Lew..........	15- 25	280
Grafton...........	0- 40	310
Upper Grafton.....	0- 20	370
Morgantown........	0- 50	470

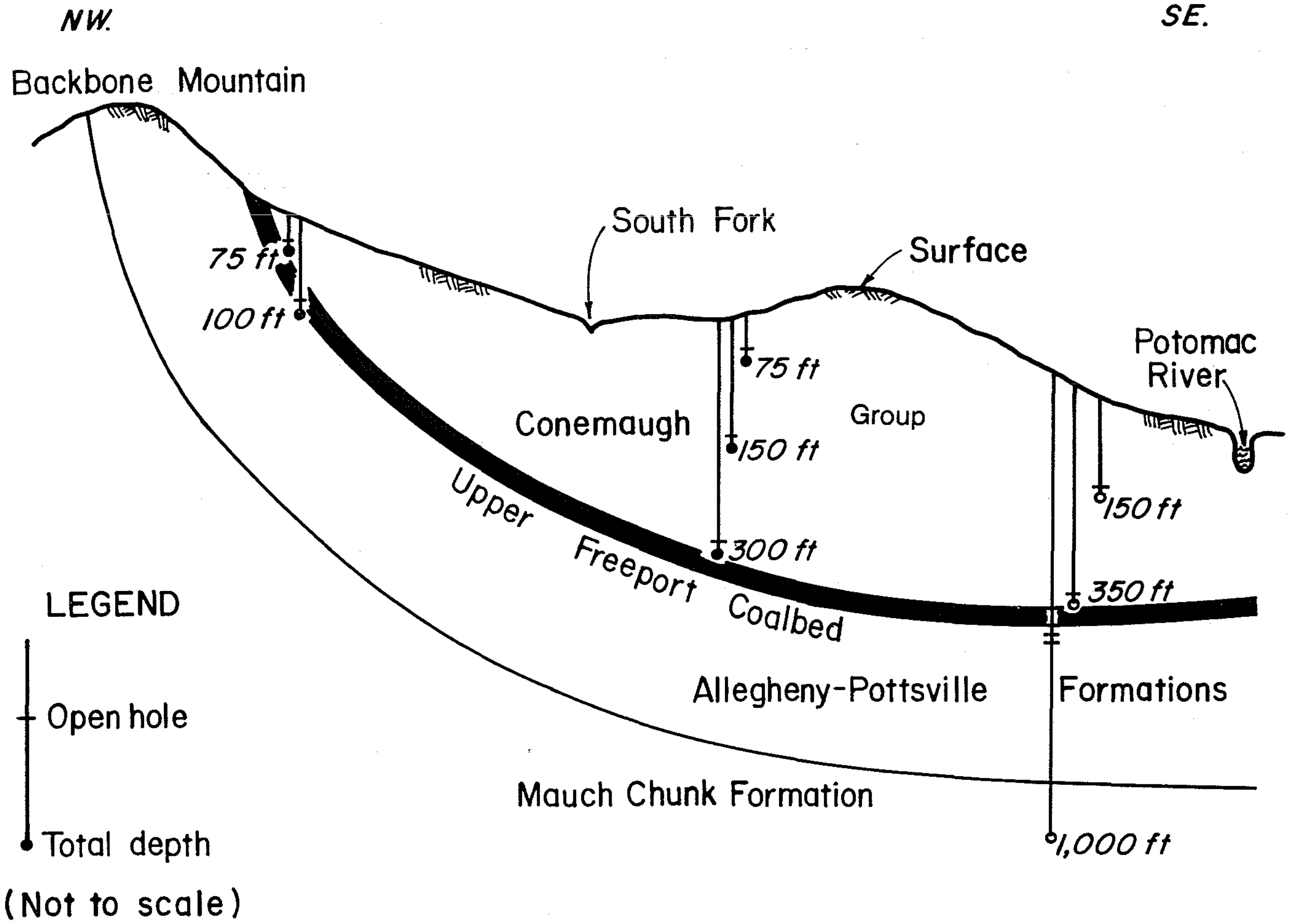


FIGURE B-3. - Site cross section.

Since 80 ft of Mahoning Shale overlie the Lower Mahoning Sandstone, most of the ground water flow into the mines will be from this sandstone. The Big George Mine differs slightly from this regime in that the Lower Mahoning Sandstone is almost entirely absent. Instead, an interbedded sandstone and shale unit overlies most of the area. This unit is extremely thick and less permeable than any of the individual aquifers.

Permeabilities are as follows:

Unit	Permeability, gpd/ft^2
Lower Mahoning Sandstone..	0.047
Uffington Shale (roof material)...............	.015

Recharge

Recharge to the Lower Mahoning Sandstone, which outcrops near the northern boundary of the proposed mine site, and to the other aquifers above the coal is contingent upon infiltration from an average annual precipitation of 48 in (122 cm). Some minor infiltration may be expected from Sand Run, Laurel Run, and the North Branch of the Potomac River.

WATER INFLOW

Dewatering Rates Versus Time of Development

Pumping rates anticipated during development of the mines, in million gallons per day, are as follows:

	5 yr	10 yr	15 yr	20 yr
Beaver Run Mine.........	0.38	0.94	1.6	1.7
Gobbler's Knob Mine.....	.83	2.7	4.1	4.9
Big George Mine.........	.32	.6	.88	.93

Expected Inflow Rates

Walton (39) derived an alternate method of predicting water inflows, which uses a variation of Darcy's law. Walton states:

$$P = \frac{QM}{\Delta ha}, \qquad \text{(B-1)}$$

where P = vertical permeability of the confining beds, gpd/ft^2,

Q = quantity of water leaking through the roof rock, gpd,

M = average thickness of the confining bed over the mine, ft,

Δh = difference between the average head in the first source bed above the mine and the mine roof, ft,

and a = mine roof area through which leakage will occur, ft^2.

Consequently, any parameter can be calculated if other parameters can be determined through prior knowledge, experimental testing, or hypotheses. In this case, Q, or expected inflow, was the quantity that was unknown and could not be assumed. Therefore, equation B-1 can be rearranged to state

$$Q = \frac{P\Delta ha}{M}. \qquad \text{(B-2)}$$

This equation could not, however, be applied to all mines or even to all areas within a mine. Values for each mine were derived on a case-by-case basis. A knowledge of the geology of each mine was imperative.

The entire area of the mine was assumed to contribute flow either directly or indirectly. The entire roof area was also assumed to continuously contribute to inflow from the moment the roof is exposed until the mine is eventually sealed.

On the basis of these two assumptions, a baseline of equal intervals was constructed across the mine area. This baseline roughly approximates a time line and can be used to extrapolate to any desired time interval. Mine advance parallel to the baseline was also assumed to be complete along the lateral width of each area. Therefore, exposed roof areas became the area of each mine segment along the baseline. This particular arrangement allows computation of inflow from any one segment or from the entire mine.

Next, the potential head for the mine was determined. By definition in equation B-1, Δh is the difference between the average head in the first source bed above the mine and the mine roof. It was assumed that the existing artesian system is, or will become, a leaky artesian system. Therefore, the total piezometric head was considered to approximate the ground surface. The value Δh then approximates the thickness of the roof material. In the Beaver Run Mine, this value was calculated to be 15 ft (4.6 m), and for Gobbler's Knob, it was calculated to be 22 ft (6.7 m).

The Big George Mine, however, had a slightly different regime. In this mine, the Lower Mahoning Sandstone was almost entirely absent. An interbedded sandstone and shale unit was present over most of the area. This unit also is extremely thick. Therefore, in the Big George Mine, the ratio of Δh to M was seen to approach 1.

Assumed permeability values were derived by reviewing existing literature on permeabilities and by visually inspecting samples of the roof shales. A value of 0.015 gpd/ft^2 (0.071 L/s per square meter) was assumed for all calculations. Tables B-1, B-2, and B-3 show the completed calculations.

DEWATERING SCHEMES

Dewatering in Advance of Mining

Dewatering in advance of mining was considered primarily because of the high cost of tramming within the mine under wet conditions. Moisture and air convert the 25-ft-thick fire clay bottom into a gooey clay. Tramming across this type of floor creates deep ruts and can lead to a loss in productivity. Favorable conditions for dewatering in advance of mining were expected since the region is artesian, with most of the ground water flow into the mines originating from the Lower Mahoning Sandstone (approximately 10 ft above the Upper Freeport Coal).

Test wells were drilled to evaluate permeability, yield, and other aquifer characteristics. Results showed that the sandstone rock unit above the Upper Freeport Coal is not permeable enough to pump. It was found to be extremely hard and highly fractured, resulting in extremely poor recharge to the drilled wells (2 to 3 gpm, 0.13 to 0.19 L/s

TABLE B-1. - Beaver Run inflows

Area	Roof area, ft^2	M,[1] ft	Inflow		Area	Roof area, ft^2	M,[1] ft	Inflow	
			gpd	Cumulative, gpd				gpd	Cumulative, gpd
1...	700,000	15	10,500	10,500	10...	6,340,000	15	95,100	940,800
2...	5,020,000	13	86,900	97,400	11...	5,970,000	12	112,000	1,052,800
3...	5,240,000	11	107,200	204,600	12...	5,840,000	9	146,000	1,198,800
4...	5,470,000	13	94,700	299,300	13...	5,840,000	7	188,000	1,386,800
5...	5,670,000	15	85,100	384,400	14...	5,970,000	10	134,300	1,521,100
6...	5,700,000	14	91,600	476,000	15...	6,570,000	13	113,700	1,634,800
7...	6,340,000	13	109,700	585,700	16...	5,290,000	16	74,400	1,709,200
8...	6,750,000	12	126,600	712,300	17...	1,170,000	17	15,500	1,724,700
9...	6,520,000	11	133,400	845,700					

[1]M = average thickness of the confining bed over the mine.

NOTE.--P = 0.015 gpd/ft^2; Δh = 15 ft.

TABLE B-2. - Gobbler's Knob inflows

Area	Roof area, ft^2	M,[1] ft	Inflow		Area	Roof area, ft^2	M,[1] ft	Inflow	
			gpd	Cumulative, gpd				gpd	Cumulative, gpd
1...	700,000	11	21,000	21,000	10...	4,720,000	6	260,000	2,718,700
2...	4,290,000	10	142,000	163,000	11...	4,710,000	8	194,000	2,912,700
3...	4,830,000	9	177,100	340,100	12...	4,690,000	9	172,000	3,084,700
4...	4,830,000	7	277,700	567,800	13...	4,670,000	7	220,000	3,304,700
5...	4,820,000	6	265,100	832,900	14...	4,650,000	5	307,000	3,611,700
6...	4,800,000	5	316,800	1,149,700	15...	4,650,000	3	512,000	4,123,700
7...	4,780,000	4	394,400	1,544,100	16...	4,100,000	3	451,000	4,574,700
8...	4,760,000	3	523,600	2,067,700	17...	2,830,000	4	233,000	4,807,700
9...	4,740,000	4	391,000	2,458,700	18...	2,520,000	7	119,000	4,926,700

[1]M = average thickness of the confining bed over the mine.

NOTE.--P = 0.015 gpd/ft^2; Δh = 22 ft.

TABLE B-3. - Big George inflows

Area	Roof area, ft^2	Inflow		Area	Roof area, ft^2	Inflow	
		gpd	Cumulative, gpd			gpd	Cumulative, gpd
1.......	700,000	10,500	10,500	9.......	2,900,000	43,500	554,700
2.......	5,270,000	79,050	89,550	10.......	2,760,000	41,400	596,100
3.......	5,560,000	83,400	172,950	11.......	2,780,000	41,700	637,800
4.......	5,020,000	75,300	248,250	12.......	3,560,000	53,400	691,200
5.......	4,770,000	71,550	319,800	13.......	3,650,000	54,750	745,950
6.......	4,510,000	67,650	387,450	14.......	3,690,000	55,350	801,300
7.......	4,240,000	63,600	451,050	15.......	5,770,000	86,550	887,850
8.......	4,010,000	60,150	511,200	16.......	2,620,000	39,300	927,150

NOTE.--Assume: $\frac{\Delta h}{M} = 1$; P = 0.015 gpd/ft^2.

maximum). These results showed that dewatering in advance of mining may be difficult and expensive.

Other factors that make dewatering in advance of mining impractical for this area are--

- The advent of new laws (Office of Surface Mining, State, etc.), which state that if the water table or hydrologic balance is altered, a potable water supply must be made available by the mining company to the area's landowners.

- The natural water in the area has a pH of 4.0 to 4.5, which is not potable. By law, this water must be treated before being returned to the environment.

- The mining cycle advances too rapidly for dewatering in advance of mining.

- The cost of drilling in hard and fractured rock is extremely high.

- The mining company has to purchase surface properties and acquire rights-of-way for access, power lines, and pipelines in the dewatering wells. The company may also get adverse reactions from preservationists.

After considering these facts, the mining company decided that dewatering in advance of mining would be technically, legally, and economically impractical.

Dewatering During Mining

As operations in the mine proceed downdip, a number of sumps will be established to collect water. The water will be pumped in three stages. Face pumps will transfer water collected at the face to a main sump, where it will be picked up and pumped out of the mine.

In approximately 10 yr, the operations will reach the base of the North Potomac syncline, where it is anticipated that wells will be drilled from the surface to main sump areas located at the syncline base. All subsequent dewatering will be accomplished through staged pumping.

The mining operations should have excellent control over water infiltration since the majority of the mine life will be spent advancing downdip. This, in conjunction with the practice of segregating flows and minimizing contact with pyritic materials, will minimize mine water contamination.

APPENDIX C.--CASE STUDY 3

INTRODUCTION

The mine used in the third case study has had a history of water problems. The Nemacolin Mine, owned by Jones and Laughlin Steel Corp. and located near Nemacolin, PA, has a total area of 11,000 acres (4,452 hectares), which generate roughly 2 million gpd (7.6 million L/d) of water. Many of the smaller areas within the mine generate between 200 and 300 gpm (12.6 to 18.9 L/s).

The Pittsburgh Coal of the Monongahela Group is the only seam mined. The coal seam averages 8 ft (0.24 m) in thickness and is located at depths ranging from 160 to 540 ft (48.8 to 164.7 m). For the most part, the seam is more than 400 ft (122 m) deep.

Most of this mine has been excavated. Only a small area of about 1-1/4 mi^2 (3.24 km^2) has remained unmined. This area is bounded by Muddy Creek on one side, the Monongahela River on another, and by worked-out sections on a third side (figure 6 in the main text). Considerable water was generated by the advancement of operations into this area. The amount of water currently being generated is so great that if left unchecked, the company would be forced to shut down the operation. This has caused the company to consider changes in the mining and water-collecting plan to reduce the water inflow.

GEOLOGIC ENVIRONMENT

Quaternary alluvium consisting of unconsolidated silt, sand, gravel, and cobbles is found in, and adjacent to, Muddy Creek and the Monongahela River. Generally, unconsolidated and poorly sorted alluvium composing the Carmichaels Formation is found in ancient, abandoned river channels and on rock terraces related to this ancient drainage network. These deposits consist of laminated clay, mixed yellowish-brown clay, silt, sand, and well-rounded pebbles, cobbles, and boulders of sandstone.

All rocks exposed on the surface are of Upper Pennsylvanian and Permian age and belong either to the Dunkard or Monongahela Groups. The formations exposed are the Waynesburg, the Uniontown, and the upper member of the Pittsburgh Formation. The Waynesburg and Uniontown Formations consists of thinly to thickly bedded sandstone, shales, siltstones, and mudstones, with numerous interbeds of carbonaceous shale, argillaceous limestone, and coal. Claystone and limestone are found less frequently. These coalbeds occur in the Waynesburg Formation; the thickest is located at the base in two and, locally, three benches separated by layers of claystone. This coalbed is 50 to 80 in (1.27 to 2.03 m) thick. An impure coalbed of less than 1 ft (0.31 m) marks the base of the Uniontown Formation (Uniontown Coalbed). In contrast, the upper member of the Pittsburgh Formation consists of four distinct units of argillaceous limestone separated by mudstone, siltstone, and sandstone units of characteristic greenish-gray color.

All rocks in the subsurface are from the Upper Pennsylvanian and the Lower Permian periods. They can be divided into two groups: the Monongahela and the Dunkard. These consist predominantly of interbedded limestone, mudstone, shale, and sandstone. The commercially mined coal bed, the Pittsburgh Coal, is 60 to 90 in (1.52 to 2.29 m) thick.

The slope of the bed does not exceed a half degree over extensive areas.

HYDROLOGIC CONDITIONS

Surface Water

The active mine area is bounded on the west by Muddy Creek and on the northeast, east, and southeast by the Monongahela River. At the most northern point of the mine area, Muddy Creek flows into the Monongahela River. In addition, the mine property has a number of intermittent streams, which flow into either the Monongahela River or Muddy Creek.

Springs of variable flows, which yield a few gallons per minute, are numerous along the outcrops of the Lower Limestone Member of the Uniontown Formation. Many of these springs are true joint or bedding plane springs supplied by a distant source and are an indication of the water-yielding capacity of the beds. Others, those springs whose flows are most variable, presumably originate locally in vadose water trapped above one of the impermeable limestone beds. Such springs are not indicative of the water-yielding capacity of the beds.

Ground Water Conditions

The Waynesburg Sandstone and the Pittsburgh Sandstone are the principal water-bearing zones of the area. There are a number of other water-bearing zones that yield limited supplies of ground water from bedding plane conduits. Although they are not deeply buried, they are impermeable beneath continuous cover. In addition, small perched water zones provide small supplies of water.

The Waynesburg Sandstone is 20 to 60 ft (6.1 to 18.3 m) thick and is commonly more than 40 ft (12.2 m) thick. The unit is light gray or buff, micaceous, and usually arkosic or feldspathic.

The upper division is typically cross-bedded and flaggy, although the lower division is generally massive and friable and locally coarse grained or even pebbly. The lower division is a bluff maker, and in many places its outcrops are somewhat cavernous.

The Waynesburg Sandstone, especially the massive and coarser grained lower portion, is by far the outstanding water-bearing member of the entire Permian series and has been extensively developed.

The coarser facies of the member yield as much as 65 gpm (4.1 L/s) where the member lies below drainage level. The specific yield of individual wells is not known precisely but is approximately 2 gpm (0.13 L/s) for each foot of drawdown in wells at the town of Waynesburg located about 10 miles west of the mine. Water is confined within the member under moderate hydrostatic pressure. It is noteworthy that wells reported to have been drilled to a depth of 200 ft (61 m) at the flour mill and at the electric light plant at Waynesburg failed to obtain water, although borings of that depth should have penetrated the Waynesburg Sandstone. This reported phenomenon has never been observed with the Waynesburg Sandstone elsewhere, and if authentic, points to considerable variations in permeability of the member from place to place.

The interval between the Redstone and Pittsburgh Coals is in many places occupied entirely or partially by the Pittsburgh Sandstone, which has been called the Upper Pittsburgh. This bed is typically coarse grained, massive to irregularly bedded, friable, and buff to dark gray or brown in color. In many localities, however, it grades laterally into flaggy or thin-bedded sandstone and into interbedded sandy shales and sandstone lentils. The Pittsburgh Sandstone ranges in thickness from 0 to 70 ft (0 to 21.3 m) and generally thickens toward the south.

The Pittsburgh Sandstone and its equivalents are highly permeable over wide areas, but they have been drained wherever the underlying Pittsburgh Coal has been mined and the roofs above the abandoned mine entries have collapsed. Consequently, this sandstone is no longer a potential source of water in many of the mining districts, especially in those that have long been worked out and abandoned. Furthermore, such drainage is likely to become more extensive in the future. In some places, the muddy water that percolates down from the surface along the larger subsidence fractures or "breaks" fills the drainage conduits so that the sandstone may become water bearing again after a lapse of several years. It is quite by chance, however, that such puddling takes place, and in most districts the water-yielding capacity of the sandstone is never fully restored. The member displays its normal water-bearing properties in those districts in which the coal has not been mined. In many mining districts there has been very little roof collapse and the member has not been completely drained. In these cases, wells of moderate yield may be obtained if care is taken to cease drilling before the well penetrates the mine entry. Where the member lies below drainage level, it is likely to be saturated, have a moderately high head, and a moderately large yield. Yields range from 0 to 35 gpm (0 to 2.2 L/s), the maximum being attained where the member lies below drainage level on the flanks of a syncline.

WATER INFLOW

Rate

The amount of water entering the whole mining operation on any given day has been estimated to be roughly 2 million gpd (7.6 million L/d). Small areas within the mine experience inflows of 200 to 300 gpm (12.6 to 18.9 L/s). In the one active section, most of the water is generated during the advance cycle of mine development, causing a considerable number of problems in production and mine development. In addition, roof bolt holes have yielded up to 50 gpm (3.2 L/s) of water in many instances.

Most of this water is found along the contact between the Pittsburgh Sandstone and a shale complex that lies directly above the Pittsburgh Coal Seam. The shale complex consists of an 8-in (0.2-m) coal seam sandwiched between two 2-in (0.05-m) shale beds. The water is held under considerable head; sprays of up to 4 ft (1.22 m) from the contact have been observed.

Water also enters the mine through certain fracture traces; however, their flow is not constant.

Source

Most of the water enters the mine through the roof and exterior faces. This water is transmitted primarily by bedding planes and roof bolt holes. A considerably smaller percentage seeps through fractures and through barrier pillars that separate abandoned parts of the mine from the active sections.

The source of the water infiltrating the mine has not yet been fully determined. Observations show that water is entering the active section along the base of the Pittsburgh Sandstone. Although this sandstone is a water supplier, it is not capable of supplying 300 gpm (18.9 L/s) of water. Water wells in the sandstone yield only up to 35 gpm (2.2 L/s), and this is only under the most optimal conditions. In contrast, roof bolt holes have yielded up to 50 gpm (3.2 L/s). In addition to this, mining operations have experienced considerable problems in the areas closest to the Monongahela River.

Based on these observations, it is believed that most of the water is originating from the Monongahela River. The water is moving along the permeable bedding planes and is entering the mine at the point where the mine operations intersect these planes.

DEWATERING SCHEME

The dewatering scheme in the active section of the underground mine complex first consisted of a conventional series of sumps with pumps transporting the water to main sumps where it was then pumped out of the mine. This system proved to be inadequate since the inflow was so great that it disrupted face operations. As a consequence, mine engineers thought that the water inflow could be decreased by changing the direction of mining by 90°. This had only limited success.

Since most of the water flowing into the mines was coming from the direction of the Monongahela River, mine engineers decided that in order to prevent disruption of face operations, the water would have to be intercepted before it reached the face. This technique is currently being implemented by second-mining the part of the operation closest to the Monongahela River, thereby creating a huge sump. It is hoped that the water will drain into the sump before reaching the face. The water in the sump will then be pumped out of the mine. This system is a modification of the gravity drainage and mine pumping system to dewater above a mine. Instead of using drilled holes to collect water, the water is collected by fracturing the confining bed and part of the source bed so that the water will run along the fractures into the mine.

☆U.S. GPO: 1985-505-019/20,062

INT.-BU.OF MINES,PGH.,PA. 27979