PROTECTION OF ENVIRONMENTAL RESOURCES BY EFFECTIVE MINE WATER MANAGEMENT

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ABSTRACT

Mine operators are more than ever before, faced with the responsibility of controlling adverse environmental effects caused by mining and reclamation operations. In some countries, public concern has led to the formulation of guidelines and regulations aimed at promoting the implementation of schemes to prevent or minimize water pollution, soil erosion and the disruption of natural hydrological regimes by mining operations. While much attention is directed towards current wastewater treatment technology, preferential consideration should be given to the control and prevention of potential problems at their source.

Various physical and chemical methods exist, which are often used to control specific types of underground and surface mine water. These methods include diverting runoff, surface regrading, backfilling and sealing and controlled discharge. Although these techniques are the most widely used today, demand for improvement and development of better alternatives and cost-effective techniques that can be applied in different situations, is increasing.

This paper includes a review of some of the current control, treatment and preventive methods and presents examples of some planned mine water management systems.

INTRODUCTION

Historically, water control has been of concern for surface and subsurface mine operators who, faced with problems such as mine flooding, pressure containment and general safety, concentrated their efforts on controlling water entering mine workings. Mining engineering technology consequently progressed towards improving mining engineering techniques in preference to wastewater management, as the success of a mine and its economic value was the most important concern. Little attention was given to environmental issues and it was not until the sixties that the detrimental environmental effects of mine water were fully realized. Thereafter, regulatory measures were proposed to emphasize pollution control and mine owners became directly responsible. This, coupled with increasing energy costs to remove the water provided the incentive to preclude the inflow of surface and groundwater into the mines, which in turn minimized pumping, handling and treatment costs.

Of the most serious impacts posed by mine water drainage upon the environment are the effects caused by pollution of surface and underground water resources, and contamination of soils and soils erosion. Acid mine drainage for example, is a widespread and well-documented mine water quality problem and considerable literature is available detailing its adverse environmental effects which will not further be discussed here. This paper will instead be devoted to describing some of the more practical procedures and techniques which may be effectively used to control or reduce the known effects.

METHODS OF MINE WATER CONTROL

Water may enter mine workings from two sources; either surface inflow or from groundwater intrusion. Entry into an underground mine may take place through rock fractures, faults and joints or via mine shafts or boreholes. Often water enters old underground workings in areas where surface subsidence has occurred, either directly from the surface or overlying aquifers. The quantity of water which enters the mine is primarily determined by hydrogeological, climatological and hydrological characteristics of the site.

Before considering some of the alternatives available for mine drainage control, thought should be given to the many different situations with which the engineer may be faced. The designer of a drainage control system for a proposed mine usually has considerable flexibility in site selection, planning of system development and choice of hydraulic structures. In direct contrast, however, the designer faced with the problem of providing remedial measures for advanced and abandoned workings has only limited flexibility and may be obliged to improvise an improvement program as field conditions permit. In addition, the problems associated with underground drainage control may be very different to those concerning surface mines.

In any event, the designer may choose between two basic alternative lines of action; either to eliminate or minimize the amount of water entering at its source or to provide a treatment system. At-source techniques include those which prevent or control the formation or discharge of pollutants, while treatment involves the collection and processing of mine drainage to produce an effluent of a quality within desired limits. Most often the practicality and costs of implementing a suitable management system are the main constraints. Particularly in the case of abandoned workings, the cost and effort required to maintain a continuous treatment system is substantially higher than for an at-source solution.

AT-SOURCE CONTROL

Until the end of the last century, at-source drainage control was generally achieved by constructing pits or sumps at the base of mine slopes from where water was pumped to a discharge system. This method, however, which was often used for unconsolidated sediments, has many limitations and often was the cause of slumping and subsidence.

Various other methods have since been developed and their use is determined primarily by the permeability of the materials to be drained. Water can be removed effectively from perforated cased wells from which water is pumped to the surface. This method, known as the Siemens method was modified around 1920 when the well point system was introduced. Such a system requires the implementation of a series of pumping wells distributed in a linear or circular fashion around the mining area at spacings generally averaging from one to three meters [1]. A number of well points are linked to a header pipe from which water is removed by centrifugal or vacuum pumps. Because of the limited height to which water can be lifted, the water table cannot be lowered much more than about six meters below its original position. Therefore, for greater lifts a multi-level well point system may be introduced which can be particularly effective for staged open pit mines (Figure 1).

In the United States, various experimental methods for drainage control were put into practice during the 1930s when the U.S. Public Health Service began a research and demonstration program for the sealing of abandoned underground mines in the Appalachian coal fields [2]. A number of alternative procedures were realized and these are discussed briefly in the following paragraph.

Attempts were made to decrease water infiltration and mine water discharge by filling up underground voids with rocks, backfilling, compacting and grading surface materials in the areas of subsidence. Impermeable materials such as bentonite clay, rubber and cement were utilized to enhance sealing. In cases where rock fracturing was not too severe cement-bentonite grout was pressure-injected to create an impervious plug, but sound rock was required to prevent the slurry from flowing directly into the mine voids. Plastic sheeting was used to divert surface water flow. However, this could be more naturally achieved by constructing a drainage channel or ditch around the area of subsidence. Erosion of the channels was prevented by lining the base with a loose bentonite-sand mixture. In many cases, connections with the surface provided pathways for the transport of surface and groundwater into the mines or discharge from flooded workings. Exploratory boreholes and access shafts, when successfully sealed, helped alleviate this problem. Cement grout plugs, capable of withstanding the groundwater pressure were successfully used to seal openings after emplacement of rock backfill and a packer above the mine roof level.

Diversion of shallow groundwater is currently often practised in situations where a pervious shallow layer overlies an impervious layer. Construction of an impermeable slurry wall (Figure 2), usually of bentonite, soil-bentonite [3], cement or polymer grout, provides a vertical impervious barrier around which groundwater is forced to flow clear of the mine workings situated on the opposite side. Other groundwater control methods include horizontal drainage holes [4], trenches and ditches, freezing and grouting.

Water infiltration resulting from surface mining operations can be effectively controlled concurrent with reclamation procedures by regrading mined areas so as to divert water away from the mine. Upon abandonment, the regraded areas should be revegetated to prevent erosion of the newly placed fill material. Various alternative methods of regrading are currently practised (Figure 3) and are selected depending principally upon the geomorphological characteristics of the site and future land use requirements. In cases where the mine highwall may be unstable, regrading is conducted so as to return the top of the highwall to the approximate original ground level. By this method runoff is diverted away from the highwall. Where the highwall is stable, it is normally sufficient to cover the mine openings at the base of the highwall with compacted material leaving the top of the highwall in place.

Adoption of a well-planned systematic approach to water control and reclamation during the mine planning phase is needed to meet present regulations and to permit profitable operation of a mine. Particularly in the case of underground mines, detailed assessment of the hazards, mining alternatives and site conditions should be undertaken before the development commences [5][6]. What appears to be the best method of mine development at the outset may not always produce the desired results. As an example, mining updip will prevent accumulation of water at the working face and therefore the mine entry, which may not necessarily provide the best access, should be sited accordingly.

CHEMICAL TREATMENT OF ACID MINE DRAINAGE

Although many methods for treating acid mine drainage exist, those which are regularly used are chemically based and employ the basic principle of increasing the pH to a point which results in the precipitation of metal ions, which become less soluble as the acidity of the solution decreases [7][8]. The most cost-effective methods are summarized in Table 1. While other methods of treatment have been devised, their application has only been on a small scale, pilot-plant or experimental basis. Such methods include reverse osmosis, controlled dilution, sodium treatment, microbial inhibition, electrodialysis, high energy radiation, distillation, ion exchange, foam separation, use of latex, freezing and ozone oxidation.

There are many alkaline reagents that can be used to neutralize acid drainage; however, the five most commonly used compounds are listed in Table 2. Relative cost and efficiency indexes are also listed for each [9]. The efficiency ratings are dependent upon a number of factors but the principal determinant, is the solubility of the reagent in water. The efficiencies are also contingent upon the reagents being added to acid drainage in a water suspension or in solution and are considerably reduced if they are added in a dry state (for instance, the relative efficiency of limestone may be reduced to 0.25 if not in solution).

PREVENTION OF ACID MINE DRAINAGE

Current mining operations generate large volumes of refuse material which are temporarily stored or permanently disposed on the surface. This practice results in the exposure of acid-producing materials to weathering and the formation of acid drainage. Ideally, efforts should be made to counteract this problem at its source. Although numerous methods of preventing the oxidation of metal sulphides have been and are currently being studied, only three procedures (Table 3) have proved to be moderately successful and practical thus far.

Oxidation is discouraged through careful compaction of refuse materials. Compaction can be accomplished using ordinary construction equipment to travel back and forth on top of the newly placed refuse. Greater compaction can be achieved through the use of a self-propelled compactor mounted on tamping rollers. Compacted layers of refuse can also be alternated with compacted layers of impermeable material to discourage seepage. After the construction is complete, the embankment surfaces may be covered with soil or with a chemical sealant to further discourage the flow of water and oxygen through the refuse [10].

Erosion is best minimized by establishing a protective layer of vegetation on embankment slopes and along exposed ditch surfaces. The establishment of grasses in drainage ditches reduces their flow velocity and thereby protects the interior faces from erosion. It may however, not always prove practical to attempt to vegetate embankment slopes until reclamation has proceeded far enough to assure relatively stable slope conditions. Erosion control netting can also be used to stabilize freshly seeded drainage or diversion ditches, until such time that a cover of vegetation is established. Once these ditches are seeded and mulched, a biodegradable netting material can be placed along the ditch surfaces and anchored in place. This type of netting holds the mulch, seed and soil until after germination and the establishment of a root system where surface runoff would otherwise wash away the fine seedbed materials.

Runoff control is often achieved by the use of a system whereby water is collected and stored before being discharged or diverted around the mine workings to the natural drainage system. Mine water discharge is normally directed to surface impoundments or sedimentation ponds. Such ponds may be designed to serve as collecting basins or concurrently for acid neutralization and sediment removal. The quantity and timing of inflow during a design storm largely controls both the size and the cost of the hydraulic appurtenances of the system.

For any water control system, consideration should be given to maintenance. Acid mine drainage is corrosive and bacterial growth may cause plugging. This is particularly the case for screens, pumps and well points which are subject to high loads of suspended solids and insoluble chemical precipitation products. Metal alloys, stainless steel or plastic products should be used where possible to reduce corrosion. Common remedial methods include acidizing, chlorination and treatment with biocides [11].

CONCEPTS DEVELOPED FOR MINE WATER CONTROL IN THE POWDER RIVER BASIN, WESTERN UNITED STATES

This section describes two examples which illustrate some of the methods which are being considered to control surface and groundwater to minimize environmental impact during the development and reclamation of open pit coal mines of the Powder River Basin in the western United States.

Hydrogeological Description of the Area

The Powder River Basin is one of the largest structural basins of the Rocky Mountain physiographic province. The basin, which is asymmetrical, is aligned approximately north-south, the strata dipping more steeply on the western side than on the eastern side (Figure 4). Numerous coal seams of varying thickness occur in the Paleocene rocks of the Fort Union Formation. Much of the basin is covered by a thick sequence of soft siltstones and sandstones of the Eocene Wasatch Formation.

Aquifers occur in most of the main coal beds, but due to the laterally discontinuous nature of the stratigraphy, the problem of characterizing individual aquifers is extremely difficult. All of the coal aquifers display potentiometric surfaces which lie above the tops of the seams and are therefore artesian in nature except where they are in contact with alluvium or intersect the surface, where water table conditions prevail. The overburden is generally in direct hydraulic connection with the ground surface (Figure 5).

Campbell County Wyoming

Mining and reclamation plans for the development of a 16-square kilometer federal coal lease tract in Campbell County, Wyoming have been submitted to and approved by the Wyoming Department of Environmental Quality. Actions proposed for the mining of the Wyodak-Anderson coal seam (Figure 5) include:

- The removal and temporary stockpiling of enough overburden to provide an initial working surface at the seam of approximately 150 meters. As mining advances, backfilling will be begun, always maintaining the same working interval for coal removal.
- The control of surface drainage and runoff, using diversion ditches and temporary impoundments to prevent its entering the coal removal area.
- The collection of groundwater inflow to be used for dust control, in sumps or to be pumped to sedimentation ponds for required treatment to assure acceptable water quality.

- The grading of all backfilled areas to approximate original contour and drainage pattern.
- Covering the recontoured backfill with approximately 50 centimeters of acceptable topsoil, adding amendments as required to support new vegetation.
- The seeding, irrigation and protection of exposed topsoil to assure the establishment of an appropriate cover of vegetation.

No permanent streams cross the area. Surface water infiltrates to the groundwater or is trapped by impounding structures. Thus, typical surface water will not be greatly influenced by mining. Runoff from large storms or rapid snow melt will be prevented from reaching the mine by a system of diversion channels and sediment control structures (Figure 5). Sedimentation ponds will be constructed to clarify water pumped from the mine.

The flow of groundwater into the mine could be diminished by pumping from wells located outside the perimeter. Water thus collected would be of relatively high quality and probably could be used for operations or could be discharged with limited or no treatment.

Construction at the mine has already started and it is expected that development of the mine will have only limited long-term impacts. Although the removal of the coal seam aquifer will have temporary localized effect, the regional groundwater conditions will not be affected because the mine is at the discharge zone of the basin, and that the reclaimed site can be satisfactorily rehabilitated to its original pasture land use.

Tongue River Watershed, Montana

This example concerns an area for which plans have been filed for open pit mining in the Tongue River Watershed, Montana. The zone expected to be affected by mining is comprised of sediments of the Paleocene Tongue River member of the Fort Union Formation. The section is made up of moderately to poorly cemented sandstones, siltsones, shales and mudstones with several coal beds which locally reach thicknesses of more than fifty feet.

The alluvial aquifer is unconfined, containing groundwater under water table conditions. Seasonal variations in saturation are common in the alluvium, but the largest volume of water is contained in the alluvium of the Tongue River. With the exception of one of the coal seams, the potentiometric surfaces of all of the aquifers, including tributary alluvial aquifers, indicate groundwater flow from the southeast towards the Tongue River.

Plans put forward for the reclamation of the mine after extraction of the coal from the water-bearing strata at the base of the pit, include the design of a permeable drain around the entire perimeter of the mine floor, thereby allowing restricted flow of water within the drain, but at the same time preventing discharge and infiltration of mine water into the acid-forming overburden (Figure 6). Backfilling of the open pit with the poor quality overburden will return the mine to the original ground surface contour.

ABATEMENT OF ACID MINE DRAINAGE AT THE CUCUMBER RUN WATERSHED, PENNSYLVANIA, EASTERN UNITED STATES

The final example illustrates remedial measures proposed for the abatement of acid mine drainage in the Cucumber Run Watershed, Fayette County, Pennsylvania. Several abandoned mine workings in the Lower Kittanning coal seam occur throughout the watershed. Overlying the coal are varying thicknesses of shale and sandstone which dip to the southeast at approximately three degrees toward the axis of the Ligonier Syncline. History of mining in the area is not known exactly and it appears that many of the mines may be interconnected.

A complete field study of abandoned strip and deep mine workings was conducted in 1970. The studies, which included a surficial reconnaissance, subsurface exploration by borings, excavation of old mine entries, and testing of water quality from mine entries and streams, were conducted to determine the feasibility of sealing the abandoned workings.

The study showed that the workings could be effectively sealed by a combination of compacted clay seals, impervious embankments constructed against highwalls, grouting of the in-situ rock, and regrading of strip mine backfill. These seals would result in flooding of nearly all of the abandoned workings, thereby excluding oxygen from the mines and substantially reducing flow of acid mine drainage into the streams of the watershed.

Water quality sampling and testing indicated that the pollution load in Cucumber Run amounted to about 2,000 kilograms per day of acidity, 33 kilograms per day of iron and 500 kilograms per day of sulphates. It was expected that the proposed sealing program would reduce this pollution load by 80 to 85 percent.

SUMMARY AND CONCLUSIONS

A number of alternative methods and examples have been described which illustrate various aspects of mine water management currently considered for surface and underground mines. Methods for the control of mine water and prevention of acid mine drainage formation together with a brief summary of treatment methods have been included.

The argument whether to adopt a strategy for abatement or treatment depends upon each individual situation. However, much can be said for careful planning to identify and control potential problems at their source. An effective mine water management program combined with planned reclamation and revegetation throughout each phase of mine development, will usually prove to be the best approach towards protecting environmental resources.

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TABLE 1

COMMON METHODS OF CHEMICAL TREATMENT FOR ACID MINE DRAINAGE

METHOD	DESCRIPTION	LIMITATIONS
Hydrated Lime	This neutralizing agent is added to the acid drainage in either a liquid or dry form. Agitation and aeration encourages precipitation of ferric hydroxide. Flocculating agent is sometimes added to accelerate rate of precipitation. Solution diverted to settling ponds or lagoons where reaction is completed and sludge is deposited.	- Hardness of effluent due to addition of calcium ions. - Sludge handling can be difficult on small sites. - Possibility of overtreatment with some detrimental impacts. - Gypsum scale on plant equipment.
Limestone	Essentially same process as with hydrated lime; however, limestone is a weaker reagent. Additional oxidation is therefore required to complete the neutralization process. The use of limestone chips in solid form also requires the use of a rotating drum to discourage the chips from becoming coated with ferric hydroxide. Limestone is cheaper than hydrated lime and limestone sludge is easier to dewater than hydrated lime sludge.	- Limestone chips tend to coat with ferric hydroxide. - Slow rate of ferrous iron oxidation. - Lower reactivity and longer detention time.
Combined Limestone-Lime Treatment	Combination of above two techniques capitalizes upon the advantages of both, i.e. less sludge produced and reaction time decreased. This technique thus results in long-range sludge handling savings as well as reagent cost savings.	- Initial equipment and construction costs high.

TABLE 2

COST EFFICIENCY RELATIONSHIPS OF NEUTRALIZATION REAGENTS

REAGENT	CHEMICAL FORMULA	RELATIVE EFFICIENCY	RELATIVE COST
Limestone	$CaCO_3$	0.80	1
Quick Lime	CaO	0.90	4.5
Hydrated Lime	$Ca(OH)_2$	0.95	5
Caustic Soda	$NaOH$	0.99	58
Soda Ash	Na_2CO_3	0.99	16

TABLE 3

METHODS OF ACID MINE DRAINAGE PREVENTION

METHOD	DESCRIPTION	LIMITATIONS
Refuse Compaction and Sealing	Refuse facilities are planned and constructed to minimize infiltration of air and water and thereby, acid formation. This involves continuous compaction during construction and covering with soil or chemical sealer upon completion.	- Compaction applicable only to new facilities - Sealing existing facilities may not be practical or environmental-acceptable
Vegetation	Reclamation procedures are planned to facilitate continuous and final planting of vegetative cover that reduces air and water infiltration and acid formation.	- Difficult and costly on some existing areas due to site conditions
Runoff Control	The use of hydraulic structures to minimize the amount and control the direction of water discharge.	- Difficult and costly to install properly on some existing facilities

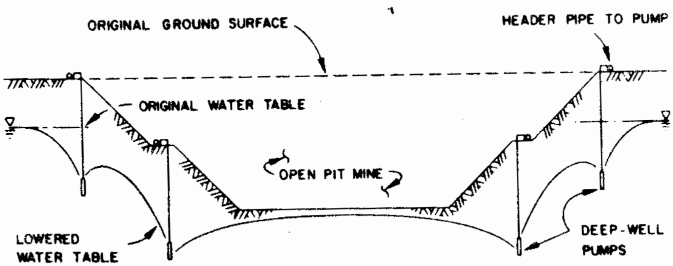


FIGURE I
MULTIPLE WELL POINT SYSTEM

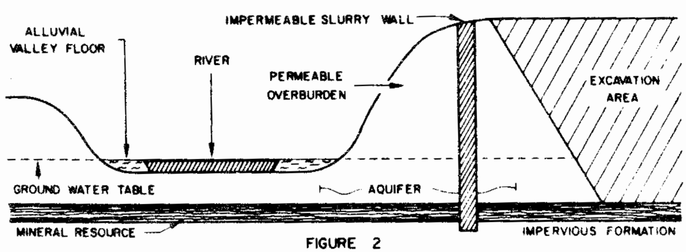
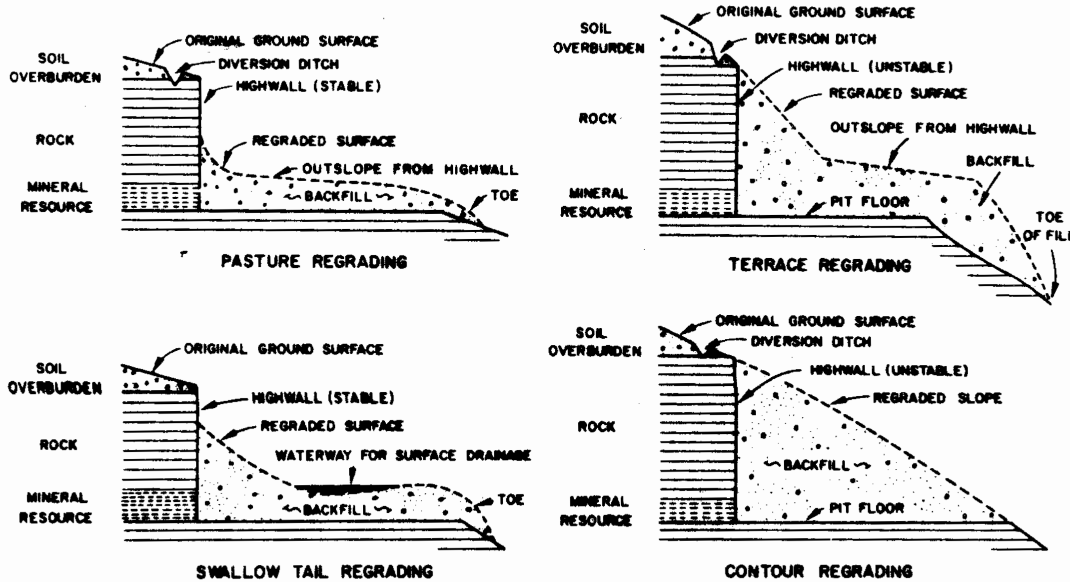


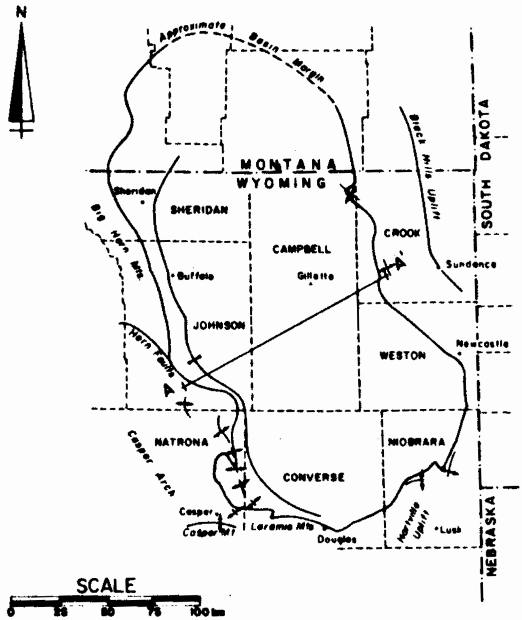
FIGURE 2
CONCEPTUAL IMPERVIOUS SLURRY WALL CUT OFF
TO PREVENT LOWERING OF GROUNDWATER TABLE IN ALLUVIUM



ADAPTED FROM REFERENCE [2]

FIGURE 3
METHODS OF REGRADING SURFACE MINE HIGHWALLS

POWDER RIVER BASIN LOCATION MAP



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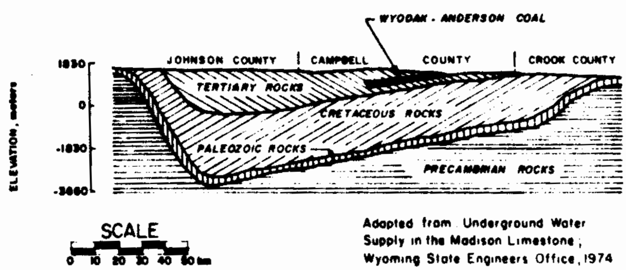

Adapted from Underground Water Supply in the Madison Limestone; Wyoming State Engineers Office, 1974

FIGURE 4

GEOLOGY OF THE POWDER RIVER BASIN WESTERN U.S.A.

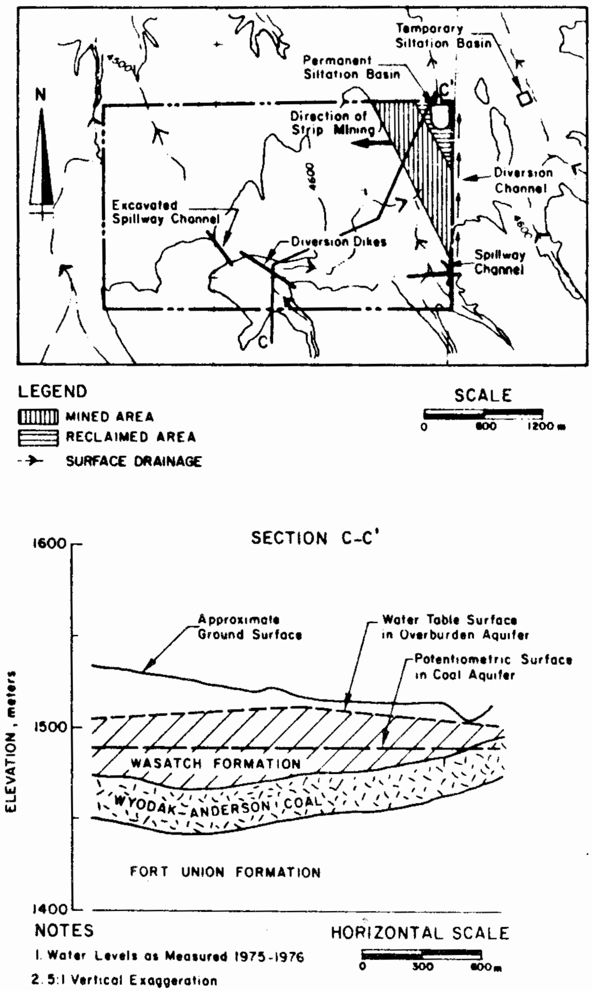

FIGURE 5

INITIAL MINE AND DIVERSION CHANNEL DEVELOPMENT

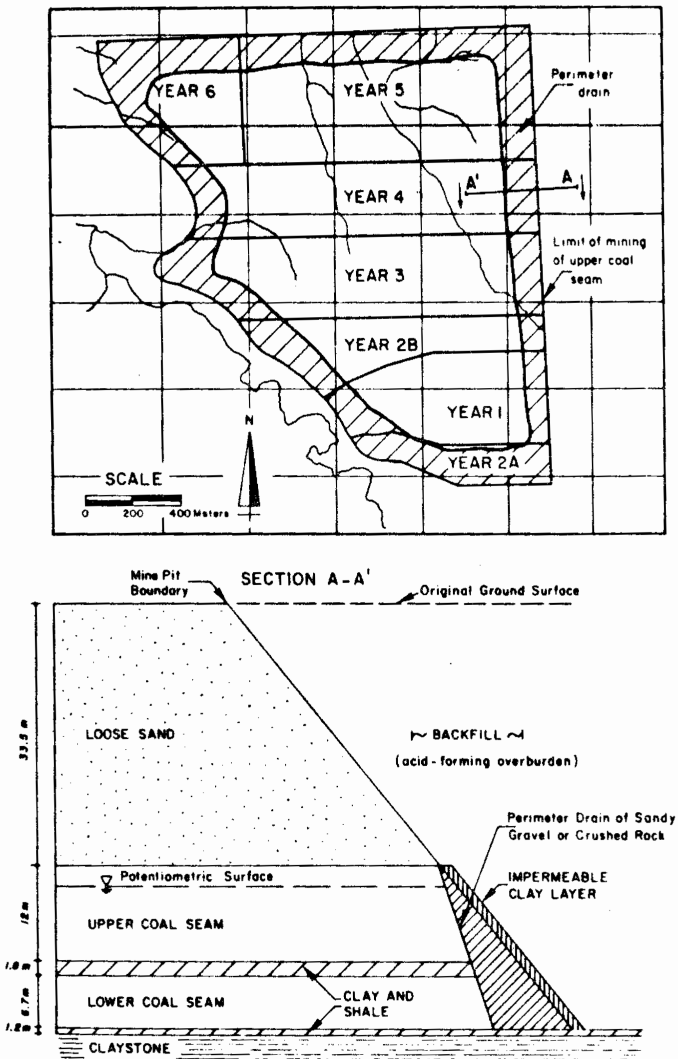

FIGURE 6
MINE PLAN AND DIVERSION OF GROUNDWATER AROUND ACID-FORMING OVERBURDEN