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Environmental Monitoring Series

RATIONALE AND METHODOLOGY FOR MONITORING GROUNDWATER POLLUTED BY MINING ACTIVITIES

NATIONAL ENVIRONMENTAL RESEARCH CENTER
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
LAS VEGAS, NEVADA 89114

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RATIONALE AND METHODOLOGY FOR MONITORING GROUNDWATER POLLUTED BY MINING ACTIVITIES

by

Don L. Warner
Consulting Geological Engineer

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Project Officer

George B. Morgan
Monitoring Systems Research and Development Laboratory
National Environmental Research Center
Las Vegas, Nevada

NATIONAL ENVIRONMENTAL RESEARCH CENTER
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ABSTRACT

The principal objective of the report is to document the rationale and related methodology for monitoring groundwater pollution caused by mining and mineral processing.

The various mining methods and the ways in which they interact with groundwater are analyzed. Because of the broad range of mining activities and diversity of geologic and hydrologic settings, monitoring programs for mineral operations must be individually considered.

Some mines and waste disposal areas will continue to be pollution sources long after the mines have closed. This important fact must be taken into account when designing a monitoring program.

Technology for at-source control of water pollution from mining is reviewed, including factors that influence groundwater. In some cases, methods that effect an improvement in surface water quality may cause deterioration in groundwater quality; therefore, observation of groundwater quality may be necessary when such methods are used.

Existing State and Federal laws for control of mine drainage pollution are discussed. An important defect of most such laws and regulations is their inability to influence the design, permitting, or abandonment of underground mines on the basis of water pollution considerations.

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The following officials of the Environmental Protection Agency were responsible for administration and technical guidance of the project:

<u>Office of Research and Development</u> (Program Area Management)

Dr. Henry F. Enos

Mr. Donald B. Gilmore

Mr. John D. Koutsandreas

<u>NERC—Las Vegas</u> (Program Element Direction)

Mr. George B. Morgan

Mr. Leslie G. McMillion

* General Electric Company—TEMPO, Center for Advanced Studies, P. O. Drawer QQ, Santa Barbara, California 93102

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION I
CONCLUSIONS

The production of minerals and mineral fuels by mining has long been the basis for much of the American economy. Many mining activities will increase in the future, some of them very substantially.

New mining technologies are receiving greater emphasis.

Mining will move into new geographic areas, such as those where the western coal fields and oil shale deposits occur.

Like other industries, mining creates environmental impacts, of which one may be groundwater pollution. Many documented cases show how groundwater pollution can result from mining and related activities. Other as-yet undocumented possibilities can be anticipated, partly because some of the new technologies have a greater potential for polluting groundwater.

Because groundwater is also a valuable natural resource, every effort should be made to anticipate and prevent or minimize groundwater pollution during mining. Monitoring, in the broadest sense, is a means for achieving this objective.

Mining and mineral processing operations include an extremely broad range of activities that occur in diverse geologic and hydrologic settings; therefore, it is necessary to consider each mineral operation individually in order to devise the most cost-effective monitoring scheme.

Groundwater pollution from mining operations may be caused by the discharge of pollutants into the hydrologic system, just as with other industrial plants. On the other hand, groundwater pollution may result from natural chemical reactions that occur in underground mines, the spoils of surface mines, or mine and mill waste-disposal areas.

An important characteristic of mining operations is that some mines and waste-disposal areas will continue to be pollution sources long after the mines and processing plants have closed.

These characteristics are such that a philosophy of monitoring different from that applied to other pollution sources is required. In particular, it is desirable to anticipate the potential for water pollution problems and to plan for closing of underground mines and the reclamation of surface mines and waste-disposal areas in advance of the opening of new mines. If predictions indicate that water quality problems may occur and mining is nevertheless initiated, then changes in water quality can be followed to provide information on the location and intensity of pollution for use in groundwater management.

Some methods for surveillance of groundwater quality during the operation of a mine and its auxiliary facilities are water sampling, measurement of groundwater levels, geophysical measurements, remote sensing, monitoring of storage tanks and pipelines, monitoring of solid and liquid waste-disposal areas, and maintenance of material balances.

Sampling points used in a monitoring program should be located on the basis of the hydrogeologic framework of the areas. Mathematical models may provide a means for optimizing the location of sampling points, by reducing the number of points and helping to determine the frequency of sampling required. The frequency of sampling required will depend not only on site hydrogeology, but also on other factors such as the nature of the pollution source and the hazard of the pollutants involved. Analyses performed on water samples should be for specific pollutants because of their hazard, persistence, concentration, ease of identification, or other characteristic features.

The various techniques for control of water pollution from mining may generally be classified as either at-source or treatment methods. Insofar as groundwater pollution is concerned, the at-source techniques are of interest because such techniques may involve modification of the groundwater system in either a beneficial or detrimental way, and observation of quality changes may be needed to verify the effect on groundwater of the controls that are applied.

A variety of different statutory means are available by which the States and Federal government can control water pollution from mining activities. Perhaps the most important defect of such laws and regulations is their inability, in most cases, to influence the design, permitting, or abandonment of underground mines on the basis of water pollution considerations. A particular defect in Federal laws in the inability to regulate the environmental aspects of mining done under the general mining law of 1872.

SECTION II
RECOMMENDATIONS

More attention should be given to the actual and the potential effects of mining activities on the quality of groundwater resources. Water-quality inventories in mining areas should routinely consider groundwater as well as surface water.

Provisions should exist in State and Federal laws for requiring the potential effect of mining activities on groundwater to be examined prior to opening of a new mine, so that impacts may be considered and mine design influenced where necessary. Pre-mining plans should include the anticipated method of mine closing and site reclamation. Groundwater quality observation should be a part of the environmental program of the mining company whenever groundwater quality changes are possible. After mining is completed, continued surveillance of groundwater quality may be desirable or even essential in some mining areas.

A monitoring program should be based on the geology and hydrology of the individual mine site. Analysis and modeling of the groundwater flow system should be considered as a possible means for optimizing a monitoring system by minimizing cost and maximizing the effectiveness of monitoring.

Research is needed to better define the effect on groundwater of some of the newer mining technologies, such as in-situ leaching and combustion. Also, the particular groundwater problems that may develop in potentially large new geographic mining regions, such as those where the western coal and oil shale deposits occur, should be very carefully studied now, before substantial mining begins, to avoid creation of extensive and perhaps irreversible water quality damage. The Appalachian coal fields provide a vivid and eternal example of the water quality damage that can result when mining is undertaken without adequate prior consideration of and adjustment for impacts on water resources.

SECTION III
INTRODUCTION

This report, concerning the monitoring of groundwater pollution from mining activities, was prepared under a contract between the Environmental Protection Agency and General Electric—TEMPO, for formulation of a concept and methodology for monitoring the quality of the nation's groundwater resources, in support of developing and enforcing groundwater quality standards.

The principal objective of the report is to document methodology for monitoring of groundwater pollution from mining and mineral processing. Monitoring of groundwater is often thought of as the observation of groundwater quality by the sampling of wells and springs. In this case, monitoring is meant to include the full spectrum of considerations given to determining the effects of a mine and its associated facilities on groundwater quality, from planning through operation and finally abandonment. A secondary objective of the report is to organize and present the subject matter in an integrated form, a task that has not been previously undertaken.

Because mining and mineral processing encompass such a broad field of activities and these activities occur in diverse geologic and hydrologic settings, the report includes discussion of the various mining methods and their extent and the observed and potential mechanisms for groundwater pollution related to each. Known methods for control of water pollution from mining are generally discussed, because some of the methods involve interaction with the groundwater system. A brief review of existing laws and regulations for control of water pollution from mining is presented.

SECTION IV
MINING METHODS

To obtain an organized view of the potential for groundwater pollution from mining activities, the various mining methods must be understood sufficiently to determine how the mines will interact with groundwater systems. Mining is broadly classified as surface or underground mining, but there are methods that are in use today, or which may be in use in the future, that do not fit into the conventional concept of mining, and are sufficiently different to warrant individual discussion. Such methods include solution mining, leaching, and in-situ retorting or combustion of fossil fuels. Furthermore, in the case of leaching and in-situ retorting or combustion of fossil fuels, the use of nuclear explosives as an energy source is sufficiently different from other methods to warrant separate consideration.

CONVENTIONAL UNDERGROUND MINING

Conventional underground mining methods are considered here to be those in which underground entry is made by a drift, slope, or shaft (Figure 1), the rock broken by drilling and blasting or with mining machines, and the broken rock removed from the mine for processing. Underground mining methods are usually discussed by the type of extraction process and the means of support of the roof and walls. Underground openings created by the extraction of ore are called stopes. Stoping methods are classified as those in which stopes are open or naturally supported, those in which stopes are artificially supported, those in which stopes are allowed or encounraged to cave, and combinations of supported and caved stoping methods.

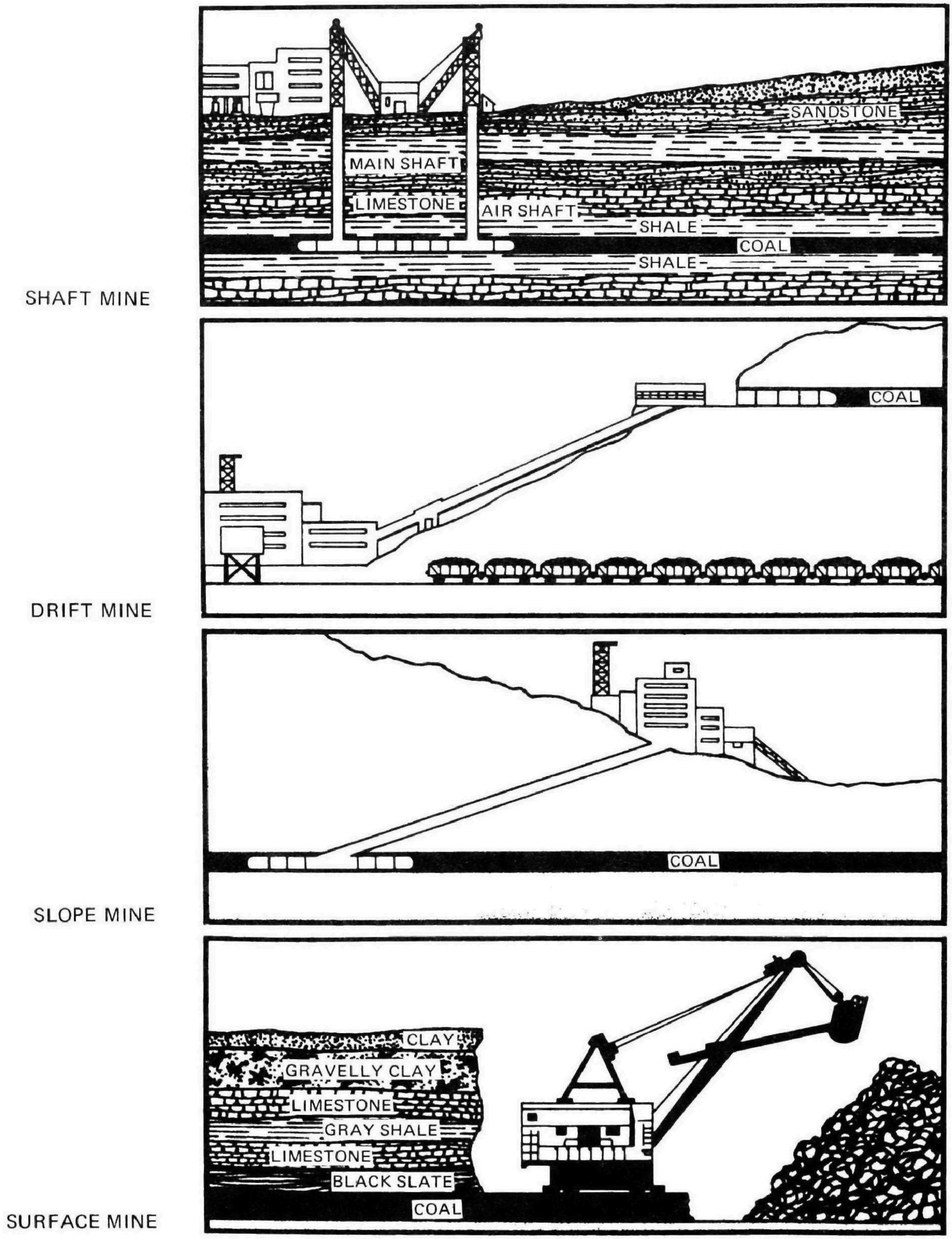


Figure 1. Means of entry to underground bituminous coal mines.

An example of the open or naturally supported stoping method is room and pillar mining of coal, oil shale, limestone, and other bedded minerals (Figure 2). Such methods are used where the openings are sufficiently stable so that little or no artificial support is needed during mining. In coal mining, however, it is usually planned to ultimately remove as many pillars as possible and collapse of the mine roof will then occur after mining is completed.

Supported stoping methods are those in which materials such as waste rock, timber sets, steel sets, jacks, liners, and roof bolts are used to support the openings. The square-set timbering method, which is used under conditions requiring maximum support, is an example (Figure 3). The openings in the timber sets are filled, so that after mining is completed, only a minimal amount of collapse of the mine workings can occur. A number of metal mines in the United States have used this and similar mining methods.

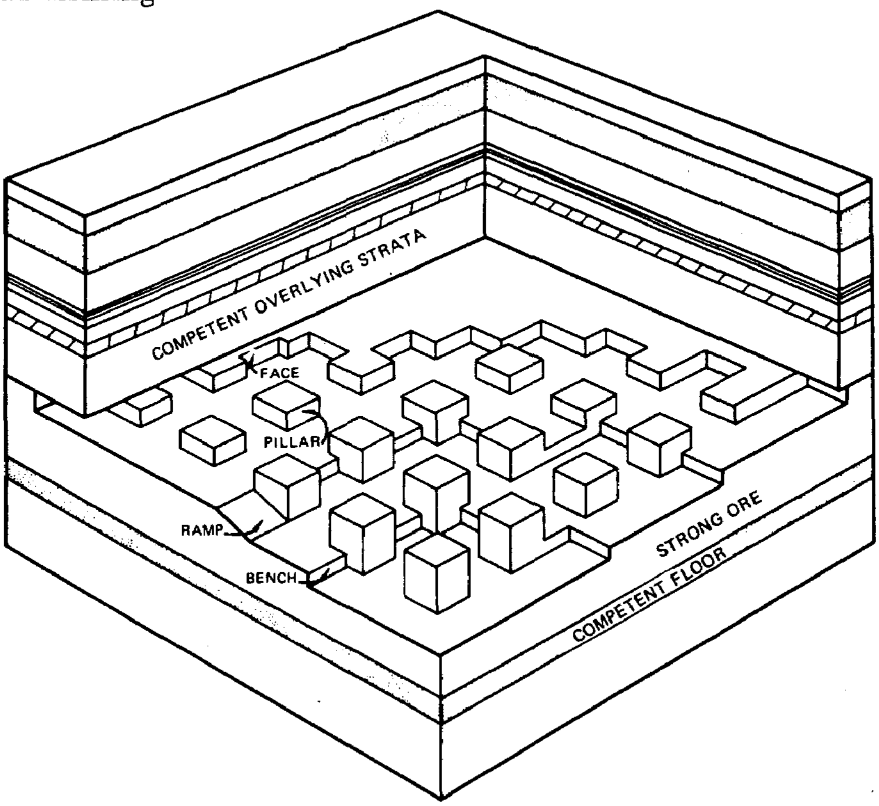


Figure 2. Room and pillar mining method with regular pillars (Lewis and Clark, 1964).

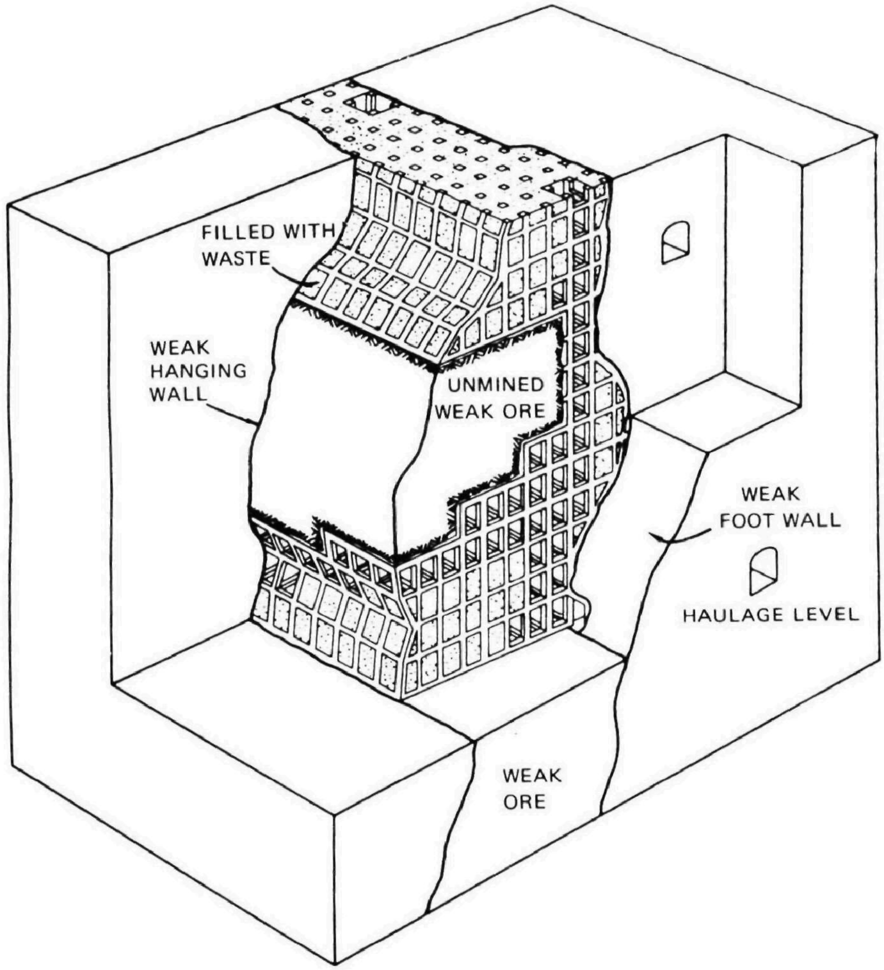


Figure 3. Square-set mining methods used under conditions requiring maximum support for ore and walls (Lewis and Clark, 1964).

Caving methods are used where ore bodies are large and have a capping which may be caved. Block caving (Figure 4) exemplifies caving methods. When caving methods are used, subsidence is an inevitable consequence, and a large collapsed area, open to the surface, may be the final result. A number of large copper deposits in the western United States have been mined by block caving.

SURFACE MINING

"Surface methods employed to recover minerals and fuels are generally classified as (1) open pit mining (quarry, open case); (2) strip mining (area, contour); (3) auger mining; (4) dredging; and (5) hydraulic mining" (U.S. Department of Interior, 1965).

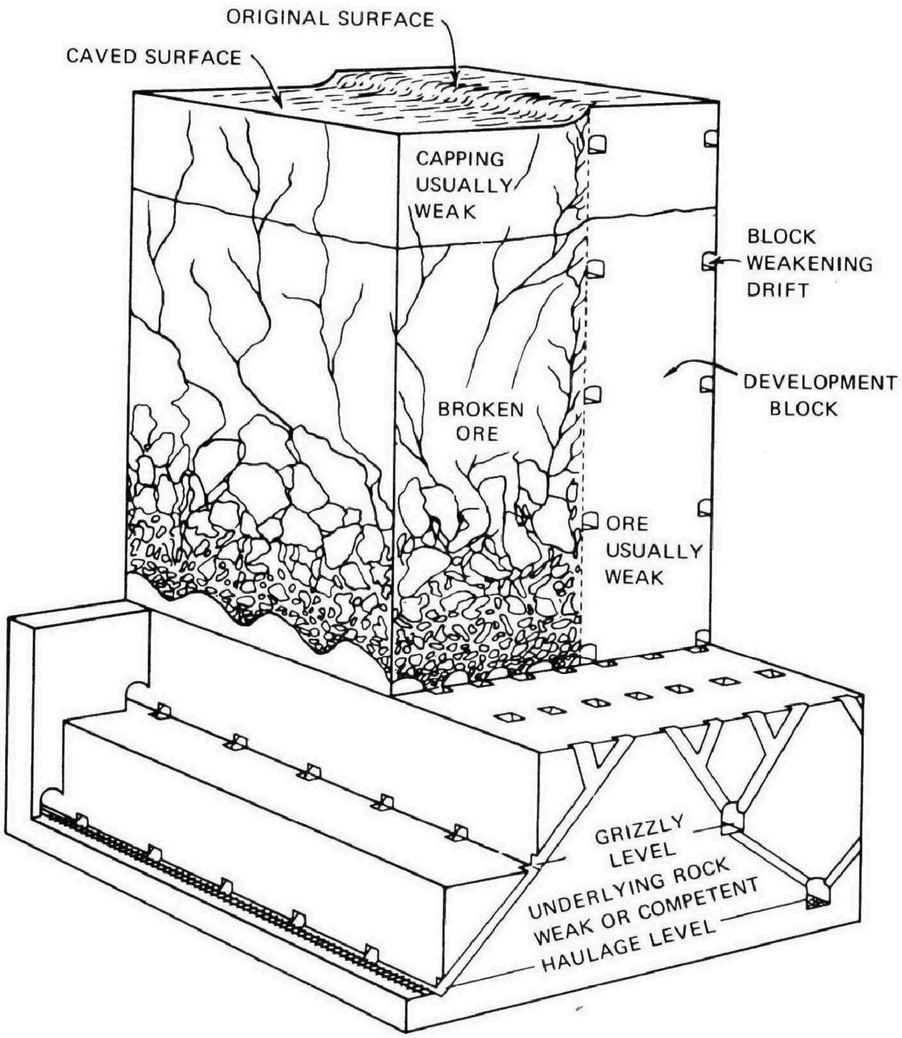


Figure 4. Diagram illustrating principles involved in application of block caving method (Lewis and Clark, 1964).

Open pit mining is exemplified by quarries producing limestone, sandstone, marble, and granite; sand and gravel pits; and large excavations opened to produce iron and copper. Usually, in open pit mining, the amount of overburden removed is proportionately small compared with the quantity of ore recovered. Another distinctive feature of open pit mining is the length of time that mining is conducted. In stone quarrying, and in open pit mining of iron ore and other metallics, large quantities of ore are obtained within a relatively small surface area because of the thickness of the deposits. Some open pits may be mined for many years—50 or more. However, since coal beds are comparatively thin, the average surface coal mine has a relatively short life.

Area strip mining (Figure 5) usually is practiced on relatively flat terrain. A trench, or "box cut," is made through the overburden to expose a portion of the deposit, which is then removed. Succeeding parallel cuts are then made, with the spoil (overburden) deposited in the cut just previously excavated. The final cut produces an open trench as deep as the combined thickness of the overburden and the ore recovered, bounded on one side by the last spoil bank and on the other by the undisturbed highwall. Such a strip-mined area may encompass several square miles and will, prior to grading during the reclamation resemble a gigantic washboard. Coal and Florida phosphate account for the major part of the acreage disturbed by this method, but brown iron ore, some clays, and other commodities are also mined in a similar manner.

Contour strip mining (Figure 6) is most commonly practiced where deposits occur in rolling or mountainous country. Basically, this method

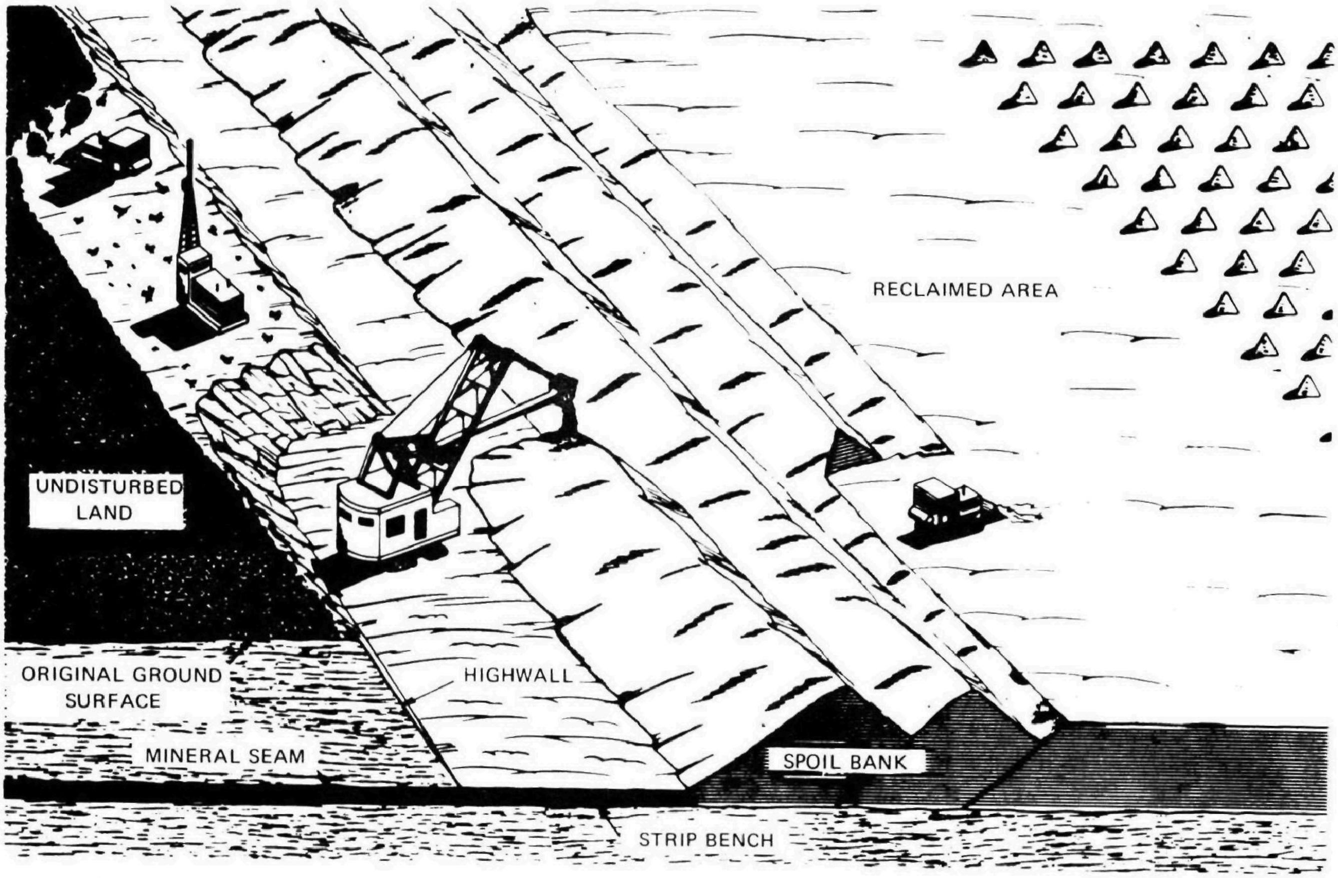


Figure 5. Area surface mining method (U.S. Department of Interior, 1965).

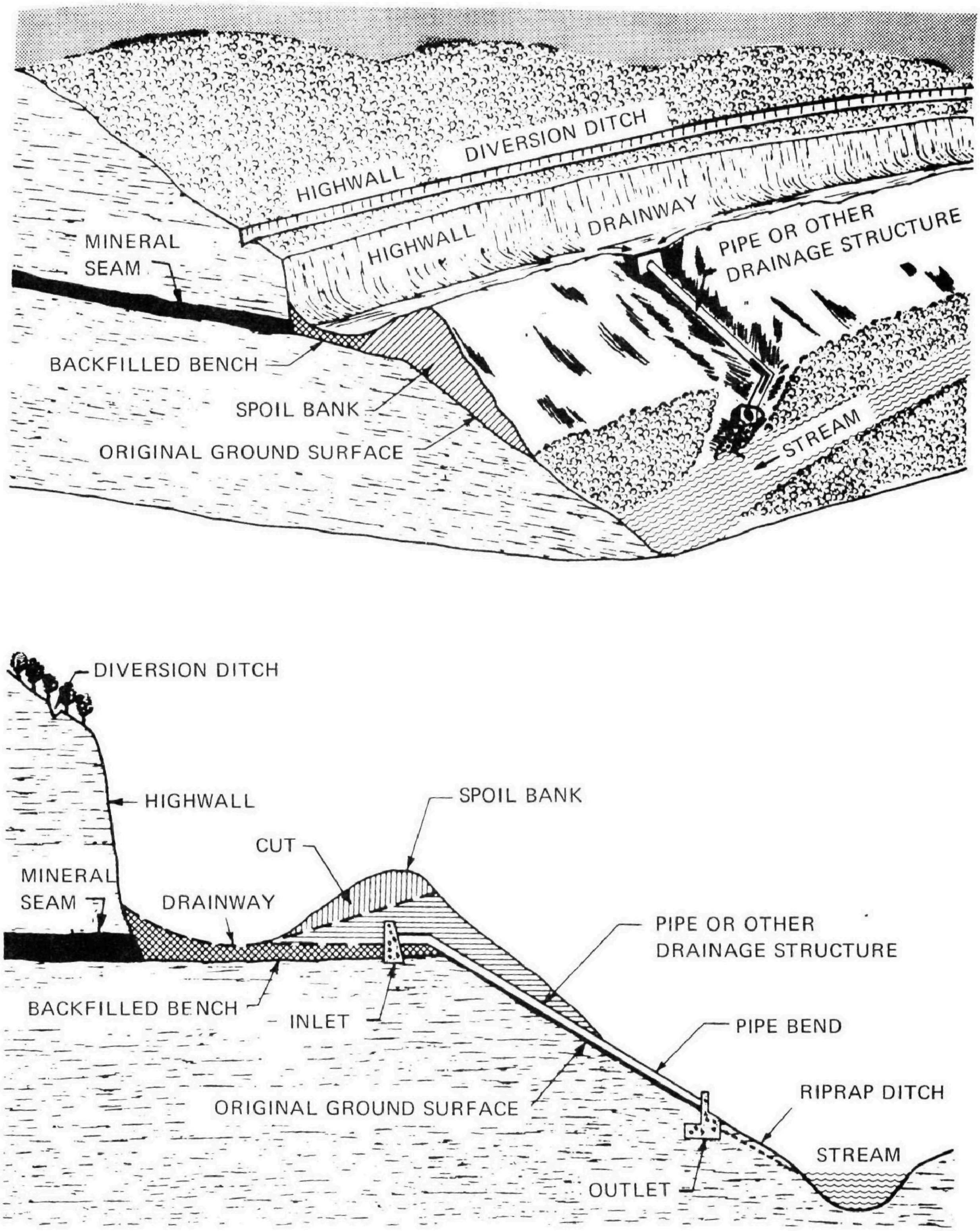


Figure 6. Contour strip mine after regrading (U.S. Department of Interior, 1965).

consists of removing the overburden above the bed by starting at the outcrop and proceeding along the hillside. After the deposit is exposed and removed by this first cut, additional cuts are made until the ratio of overburden to product brings the operation to a halt. This type of mining creates a shelf, or "bench," on the hillside. On the inside it is bordered by the highwall, which may range from a few to perhaps more than 100 feet in height, and on the opposite, or outer, side by a rim below which there is frequently a precipitous downslope that has been covered by spoil material cast down the hillside. Contour mining is practiced widely in the coal fields of Appalachia and western phosphate mining regions because of the generally rugged topography.

Auger mining is usually associated with contour strip mining. In coal fields, it is most commonly practiced to recover additional tonnages after the coal-overburden ratio has become such as to render further contour mining uneconomical. As the name implies, augering is a method of producing coal by boring horizontally into the seam, much like the carpenter bores a hole in wood. The coal is extracted in the same manner that shavings are produced by the carpenter's bit. Cutting heads of some coal augers are as large as seven feet in diameter. By adding sections behind the cutting head, holes may be drilled in excess of 200 feet. As augering generally is conducted after the strip-mining phase has been completed, little land disturbance can be directly attributed to it. However, it may induce surface subsidence and complicate surface and groundwater flow when underground workings are intersected.

Dredging operations utilize a suction apparatus or various mechanical devices, such as ladder or chain buckets, clamshells, and draglines mounted on floating barges. Dredges have been utilized extensively in placer gold mining. Tailings piles from gold dredging operations usually have a configuration that is similar to spoil piles left by area strip mining for coal. Dredging is also used in the recovery of sand and gravel from stream beds and low-lying lands. In the sand and gravel industry most of the dredged material is marketed, but in dredging for the higher priced minerals virtually all of the mined material consists of waste that is left at the mine site.

In hydraulic mining a powerful jet of water is employed to wash down or erode a bank of earth or gravel that either is the overburden or contains the desired ore. The ore-bearing material is fed into sluices or other concentrating devices where the desired product is separated from the tailings, or waste—by differences in specific gravity. Hydraulic mining was extensively used in the past to produce gold and other precious metals, but it is practiced only on a limited scale today.

SOLUTION MINING

Solution mining, as the term is used here, refers to the extraction of minerals soluble in water or salt solutions by injecting the water through wells or shafts into the deposit, then extracting the injected water through the casing of the injection well or through separate extraction wells (Figure 7). Solution mining has been used or proposed for common salt (NaCl), potash, borax, phosphate, and trona (Hunkin, 1971). Sulfur is mined by the Frasch Process in which the sulfur is melted with injected hot water and brought to the surface through wells (Figure 8). About 57 percent of the 1968 production of salt and 76 percent of the sulfur was obtained by solution mining. Principal salt-producing States are Louisiana, Texas, Ohio, New York, and Michigan. Louisiana and Texas are the nation's primary sulfur-producing States.

Commercial salt deposits in Louisiana and Texas occur in the salt domes that are present in the Gulf Coast geologic province of those States. These salt domes are also important sources of solution-mined sulfur. In other geographic areas of the United States, salt and the other minerals listed above occur in bedded deposits.

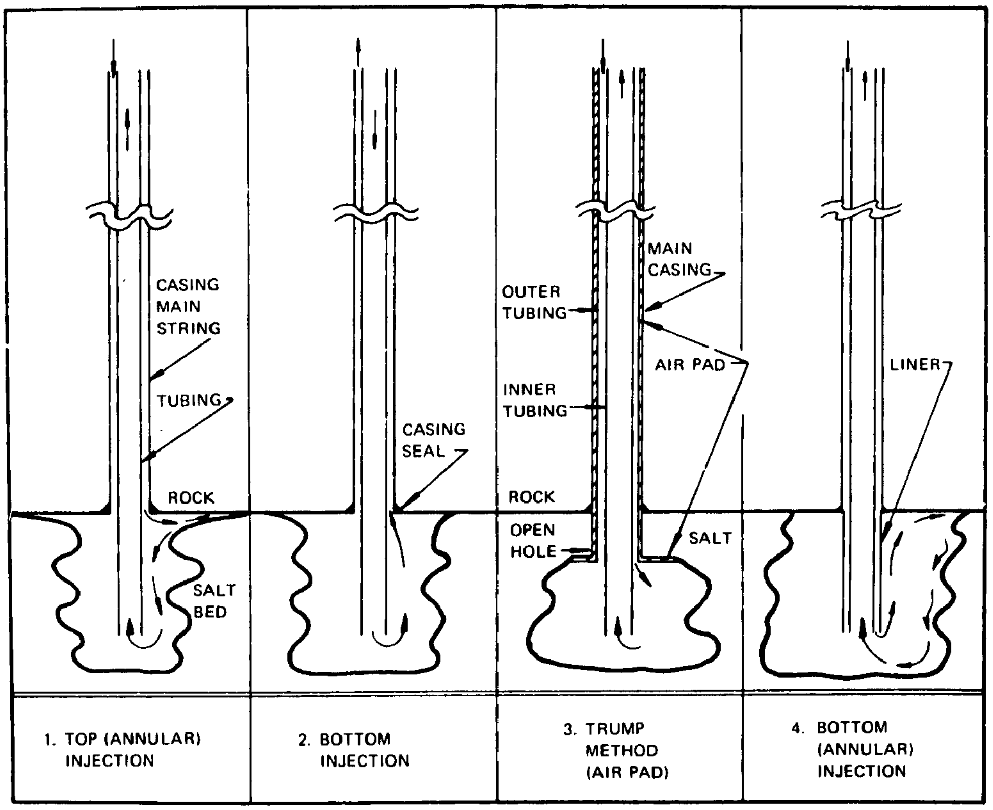


Figure 7. Single-well systems for solution mining of halite (Jacoby, 1973).

Hydraulic fracturing is widely used to increase the permeability of salt deposits and to develop communication between injection and production wells. Controlling the location, direction, and extent of hydraulic fractures is difficult because of mechanical problems and the anisotropic nature of rock layers. Henderson (1963) lists the principal reasons for failure of attempts to connect two wells by fracturing as:

1. A poor primary cement job of the well casing
2. A fracture in the crystalline structure of the salt which causes the fluid to follow an indeterminant path
3. Natural vertical fractures, generally in the formation immediately below the salt, allowing the fluid to escape into a heavily fractured or permeable formation
4. The fracturing well being at a different geological depth than the target well.

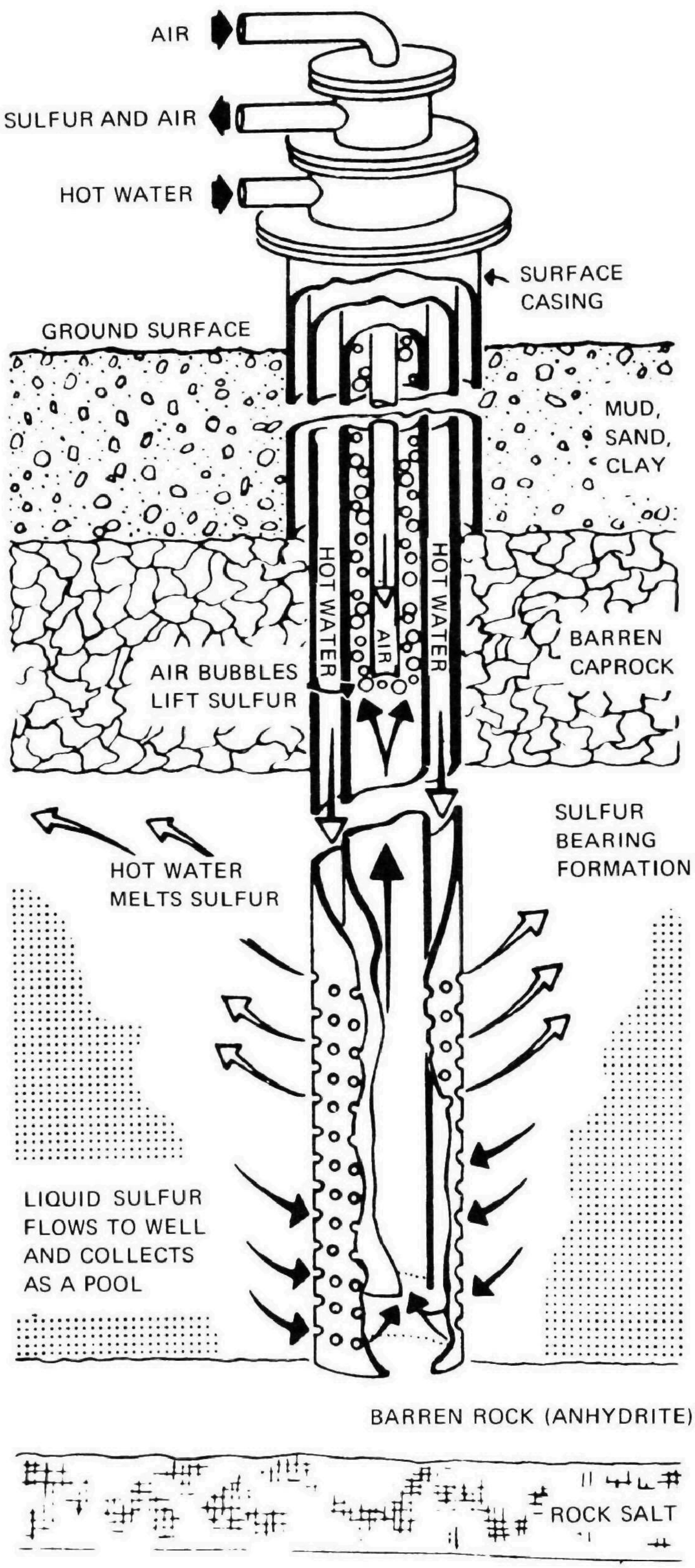


Figure 8. Operation of a sulfur well during solution mining of sulfur by the Frasch Process (Donner and Wornat, 1973).

Control of fracturing is difficult, yet is clearly essential if the technique is used in situations where highly mineralized fluids used for solution mining might inadvertantly be introduced into and damage the quality of groundwater bodies.

Another significant problem in solution mining is the collapse of solution-mined caverns. In 1971, the Michigan State Department of Natural Resources issued an order restricting hydraulic mining of salt at Grosse Isle following the development of two large sinkholes on property owned by a salt company on an island in the Detroit River. The caved areas, 100 to 200 feet in diameter and 30 to 40 feet deep, were believed to have been caused by removal of salt from beds lying about 1,100 feet beneath the surface. A study of the problem was planned by State officials before deciding upon a course of action (MacMillan, 1973).

In many cases, caverns formed by solution mining are used for storage of liquid petroleum gas, natural gas, and other hydrocarbons, storage of radioactive wastes, and surge vessels for air compressed by electric utilities during off-peak hours (Jacoby, 1972). In the development of solution-mined caverns for storage purposes, and in solution mining of minerals, there is often a need for disposal of waste brines. Many of the industrial wastewater injection wells inventoried by Warner (1972) in Kansas, Texas, Michigan, and New York are for disposal of brines produced by solution mining.

LEACHING

Leaching is the term applied to the selective dissolution of a mineral from an ore using a solvent, such as sulfuric acid. Leaching methods are dump, heap, in-place or in-situ, and vat leaching.

Some metallic minerals that have been recovered or considered for recovery by leaching include copper, uranium, mercury, molybdenum, silver, gold, aluminum, and zinc (Hunkin, 1971; Nichols and Peterson, 1970; McKinney, 1973; and Sheffer and Lamar, 1968). Leaching has become a very important method of extracting copper in the United States. According to Pernichele (1973) about 20 percent of the domestically produced copper is obtained by dump and heap leaching. Because of economic, environmental, and other reasons, in-situ leaching is receiving increasing attention (Pernichele, 1973; Hunkin, 1971).

Choice of the leaching method depends upon the chemical and physical characteristics of the specific material to be treated. The grade of the ore, the solubility of the ore minerals, the amount of solvent-consuming material in the host rock, the size of the operation, and the mode of occurrence of the ore-bearing minerals are some of the important factors to be considered.

Dump leaching is used to extract copper from waste material produced during the large-scale open-pit mining of copper ore deposits. Nearly all the copper-mining companies employ some form of leaching for recovery of trace amounts of copper from the mine overburden or waste. The mine waste dumps are made up of mine-run material with no attempt to prepare the material as to size, type or elimination of deleterious gangue minerals. In the majority of mining operations, the waste is moved as rapidly and efficiently as possible with no consideration for subsequent leaching of the copper.

Heap leaching is used for ores that are too low in grade to be processed by conventional means or by vat leaching, and also for complex ores that are not suitable for conventional processing. In heap leaching, pads are prepared for the ore by clearing an area and emplacing a layer of compacted clay, with a collection dam or reservoir at the topographically low end of the pad. Pads have been constructed with concrete, asphalt, or plastic membranes, but according to Malouf (1973) these have proven unsuitable because they are invariably ruptured by the weight of the ore.

Vat leaching of copper is used primarily for high-grade oxide or mixed oxide-sulfide ores. Ore is crushed, screened, and placed in large leaching tanks, where the leaching solutions are circulated through the crushed ore.

In-situ leaching of copper ore has been practiced in the United States since 1922 (Hardwick, 1967). All of the examples cited by Hardwick (1967) of mines in which in-situ leaching had been used prior to 1967 are ones in which extensive underground mining and block caving preceded the solution mining. In such cases, the ore body is already broken and collapsed, so that the leaching solutions have easy access to the ore-bearing rock (Figure 9). In stiuations where mining has not been so extensive or where there has been no previous mining and the ore occurs in relatively impermeable igneous and metamorphic rocks, fracturing may be with conventional explosives as in the case of the Old Reliable copper mine (Malouf, 1973), by hydraulic fracturing (Pernichele, 1973), or possibly by nuclear fracturing in the future (Hardwick, 1967). In-situ leaching of uranium in a permeable sandstone ore body has been carried out, apparently without any fracturing of the ore-bearing deposit (Anderson and Ritchie, 1968; Sievert and others, 1970).

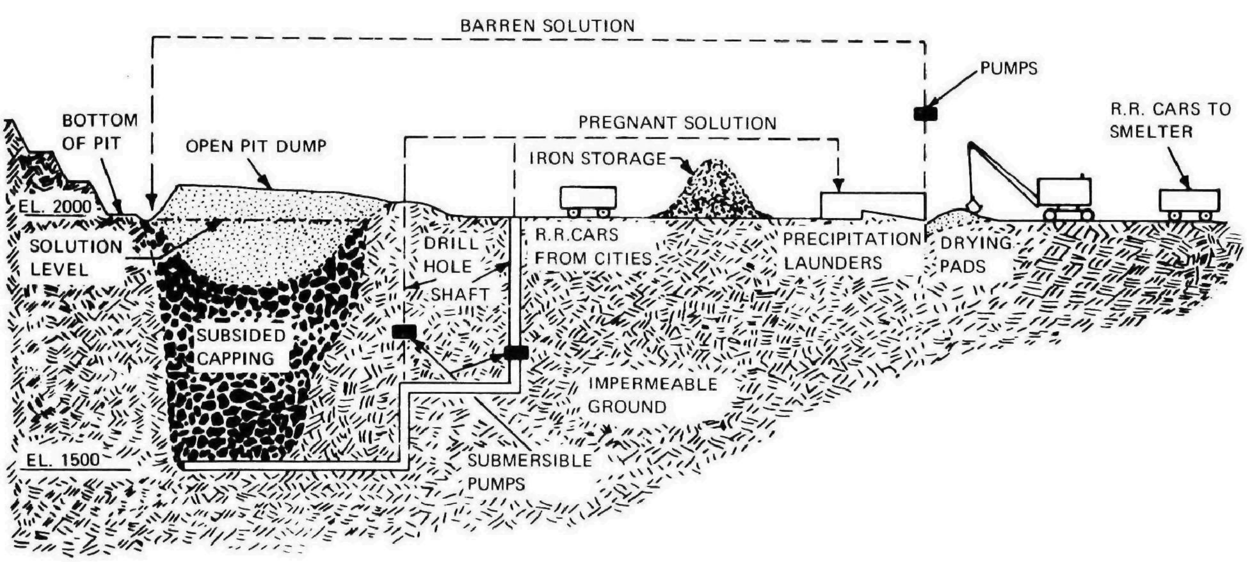


Figure 9. Flood-leaching mining system (Hardwick, 1967).

IN-SITU COMBUSTION

In-situ combustion for secondary recovery of liquid hydrocarbons has been practiced for some time, and the in-situ combustion of various solid fossil fuels has been discussed and experimentation with it conducted by industrial companies and the U.S. Bureau of Mines. However, the technology has apparently not yet been developed to the extent that there are any commercial operations of this type.

In the case of oil shale, a key problem is the creation of permeability within the shale formation. Two major approaches are in early stages of investigation. One approach proposes limited fracturing by conventional means, the other proposes massive fracturing by a nuclear explosion (Williams and others, 1969).

Figure 10 presents a design concept for in-situ retorting based on contemporary petroleum technology (U.S. Department of Interior, 1973). The essential steps include: (1) well drilling, (2) fracturing to permit heat transfer and movement of liquids and gases, (3) application of heat, and (4) recovery of products. The two Wyoming sites proposed for leasing in the prototype oil shale program would be best mined by in-situ methods (U.S. Department of Interior, 1973).

WASTE DISPOSAL

Solid Wastes

In the mining and processing of most minerals, some rock is mined that is barren of the minerals that are being sought or contains the minerals but in concentrations too low to be economical. Waste rock or low-grade ore that is not mixed with the ore-bearing rock may be immediately discarded, but some waste rock is so intimately mixed with the ore-bearing rock that it must be separated by some mechanical means before it can be discarded, or perhaps it may be necessary to process it metallurgically with the ore to achieve separation.

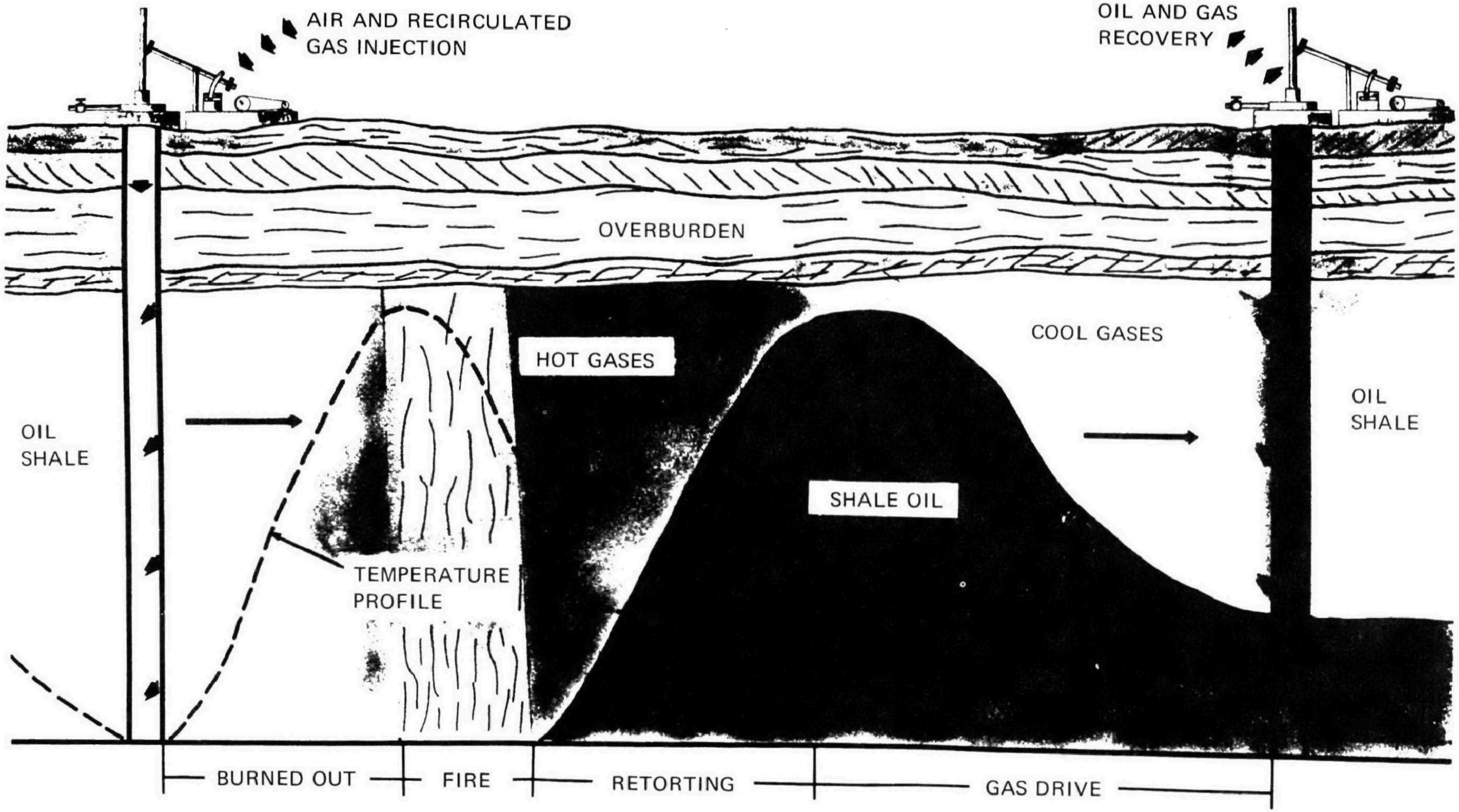


Figure 10. Schematic representation of an in-situ retorting operation (U.S. Department of Interior, 1973).

In any event, very large volumes of solid wastes result. These wastes range in particle size from boulders to colloids. The larger material may be conveyed to the disposal site by truck or conveyor belt. Most material fine enough to be suspended in water is carried to the disposal site in pipes or channels, where the solids are separated from the liquid in tailings ponds. Some appreciation of the volume of solid wastes produced can be obtained by realizing that the average grade of copper ore mined in the United States is now about 0.5 percent, so 99.5 percent of the rock mined is waste. It has been estimated that 1.7 billion tons of solid wastes were produced by the mining industry in 1971 and that 20 billion tons have been produced in the last 30 years (National Commission on Materials Policy, 1973).

The wastes may be piled in open areas, in the heads of valleys, on alluvial plains, or other locations, or they may be used to construct dams across valleys. Mine wastes may also be used to backfill the worked-out areas of underground mines to prevent collapse of the workings and subsidence and to minimize the need for surface disposal.

Liquid Wastes

Liquid wastes produced in mining and mineral processing range in character from high-quality unpolluted groundwater pumped to dewater mines to the effluent from mineral preparation plants which may contain acids, alkalis, heavy metals, radioactive elements, etc. Unpolluted groundwater pumped during dewatering will usually be discharged directly into a surface drainage system. Mine water polluted with acid produced by pyrite oxidation or mill effluents has, in the past, also been discharged into surface drainages or into holding ponds where it eventually seeped into the subsurface or overflowed into surface drainages. In some cases, physical and chemical changes that occur in holding ponds are sufficient to produce an acceptable discharge; but, in many cases, the effluent will require treatment before it can meet the water quality requirements that have and will be imposed on operators.

SECTION V
EXTENT OF MINING ACTIVITIES

A large part of American economic life is mirrored in the record of materials production and population growth. The pattern of materials use has changed dramatically over the past 70 years. The amount of materials used has increased in both absolute and per capita terms. Overall growth has been remarkably steady in spite of two world wars and a world depression. Energy materials head the list of greatest growth. No major raw material has become obsolete. A host of new products are made today that were not conceived in 1900.

From 1900 to 1969, the U.S. population increased by 166 percent, the GNP by almost 900 percent (in constant 1967 dollars), and total materials consumption by more than 400 percent (National Commission on Materials Policy, 1973). Many of these materials have been obtained by mining. Further, it is probable that the production of materials, including mined products, will continue to increase in the future.

It is not possible to determine how many mines of all types have been opened and their associated refuse and tailings disposal sites created in the past. In a detailed study of the Appalachian coal-mining region, it was found that at least 5,570 sources of acid mine drainage existed, including 405 associated with active coal mines, and 5,165 associated with inactive or abandoned coal mines (Federal Water Pollution Control Administration, 1969). The U.S. Department of the Interior (1965) estimated that, in 1965, past surface mining had affected 3.2 million acres of land and that about 20,000 active surface mines were disturbing in excess of 150,000 acres annually. It has been estimated that more than 20,000 prospect holes and mine and mill dumps exist in the State of Colorado alone, most of them abandoned (Federal Water Pollution Control Administration, 1968).

According to the U.S. Department of the Interior (1972) there was a total of 25,148 active mines, quarries, pits, dredges, brine, well, and other mineral-extractive operations in 1969. The largest numbers of mines were in Pennsylvania (1,733), Kentucky (1,576), West Virginia (1,507), and California (1,380). There were 5,168 active mineral preparation plants. Information is available in publications such as that cited above and from State agencies to permit fairly accurate determination of the number, location, size, and nature of all existing mining operations in the United States.

Future projections of the demand for minerals and mineral fuels are available from many different sources. In particular, the 1973 report of the National Commission on Materials Policy and the annual reports of the Secretary of the Interior under the Mining and Minerals Policy Act of 1970 (P.L. 91-631) provide current information on this subject. Regardless of the source of figures used, all estimates indicate a continuously growing need for mineral commodities. In particular, the nation's present and future dependency on mineral energy sources was brought into focus during 1973 and 1974; but many knowledgable authorities have warned of the danger of comparable problems with other minerals.

Thus, it seems inevitable that mining and related activities will not only continue, but will increase. Also, newer mining technologies, such as in-situ combustion and leaching will probably receive greater emphasis as lower grade and less accessible mineral deposits are exploited, and mining will move into new geographic areas such as those where the western coal fields and oil shale deposits occur.

SECTION VI

MINING HYDROLOGY AND GROUNDWATER POLLUTION

Most underground mines will in some way measurably interrupt the existing hydrologic system at the location where they are developed. In the case of an underground mine that reaches below the water table of an unconfined aquifer or intersects a confined aquifer, groundwater will have to be pumped to allow the mine to be worked, and pumping will have to be continued as long as the mine is being operated. During this time, the mine will be a sink, toward which groundwater will flow, and groundwater levels will be lowered in the surrounding area (Figure 11). LeGrand (1972) briefly outlined the physical effects of mining on groundwater systems, particularly in the case of underground mines.

Two well-known and widely discussed examples of the problem of mine dewatering and the resultant effect of the dewatering on the hydrologic system of the surrounding area are the Hershey Valley, Pennsylvania (Foose, 1953) and Friedensville, Pennsylvania (Childs, 1957). In the Hershey Valley, pumping of up to 6,500 gallons per minute was necessary to dewater an underground limestone mine. This pumpage was sufficient to lower the groundwater table drastically over an area of 10 square miles, to dry up many springs and wells, and to cause about 100 new sink holes to develop. At Friedensville, dewatering of a zinc mine caused numerous springs and wells to dry up, and required the development of a pipeline to supply water to residents of the affected area.

Dewatering of underground mines may also affect the quality of groundwater. The most serious water quality problem associated with past and present mining in the United States is the formation of acid mine water. Acid mine water is formed when pyrite (FeS_2) and perhaps other

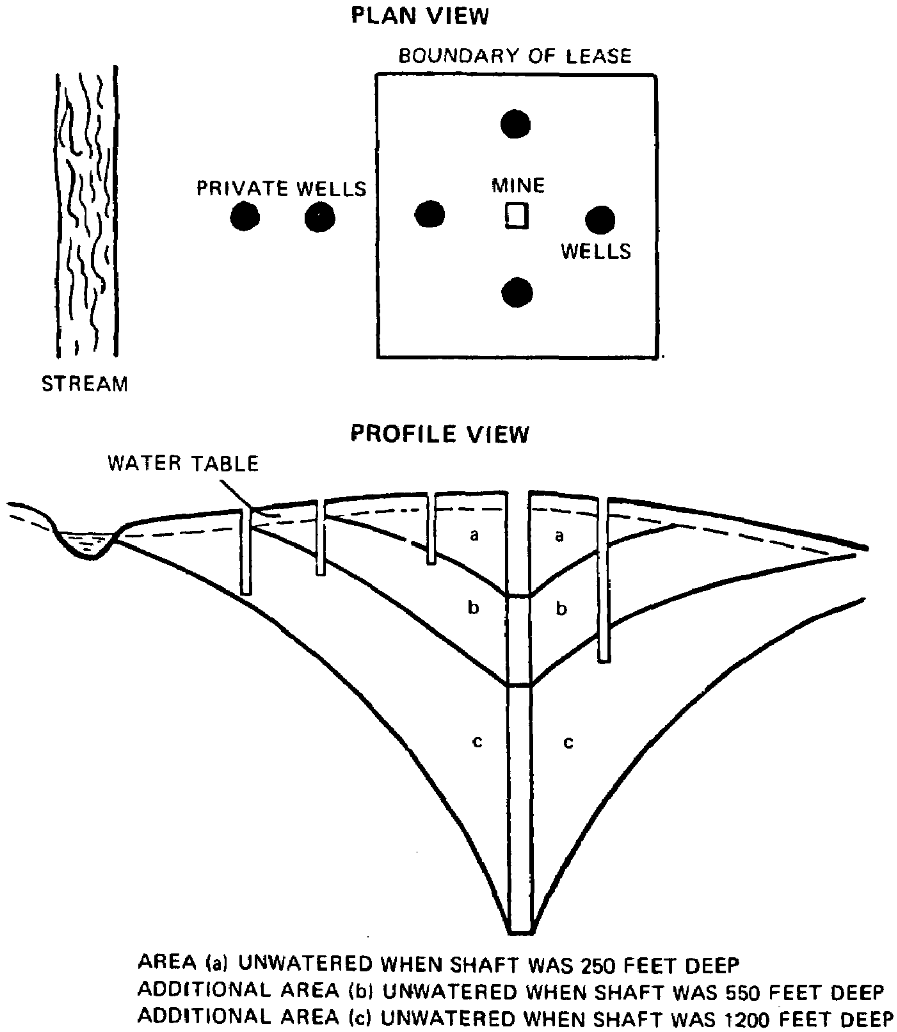


Figure 11. Cone of depression resulting from mine dewatering (LeGrand, 1972).

sulfide minerals are exposed to the atmosphere as a result of the mining operations.

Although the exact reaction process is still not fully understood, the formation of acid mine water from pyrite is generally illustrated by the equations shown below. The initial reaction that occurs when iron sulfide minerals are exposed to air and water produces ferrous sulfate and sulfuric acid.

$$2FeS_2 + 7O_2 + 2H_2O \longrightarrow 2FeSO_4 + 2H_2SO_4$$

(pyrite) (ferrous sulfate) (sulfuric acid)

Subsequent oxidation of ferrous sulfate produces ferric sulfate.

$$4FeSO_4 + 2H_2SO_4 + O_2 \longrightarrow \underset{\text{(ferric sulfate)}}{2Fe_2(SO_4)_3} + 2H_2O \quad .$$

Depending on physical and chemical conditions, the reaction may then proceed to form ferric hydroxide or basic ferric sulfate.

$$Fe_2(SO_4)_3 + 6H_2O \longrightarrow \underset{\text{(ferric hydroxide)}}{2Fe(OH)_3} + 3H_2SO_4$$

and/or

$$Fe_2(SO_4)_3 + 2H_2O \longrightarrow \underset{\text{(basic ferric sulfate)}}{2Fe(OH)(SO_4)} + H_2SO_4 \quad .$$

Pyrite can also be oxidized by ferric iron as shown below.

$$FeS_2 + 14Fe^{+3} + 8H_2O \longrightarrow 15Fe^{+2} + 2SO_4^{-2} + 16H^+ \quad .$$

Regardless of the reaction mechanism, the oxidation of one molecular weight of pyrite ultimately leads to the release of two molecular weights of sulfuric acid (acidity).

Other constituents found in mine drainage are produced by secondary reactions of sulfuric acid with minerals and organic compounds in the mine and along the stream valleys. Such secondary reactions commonly produce concentrations of aluminum, manganese, calcium, and sodium in the drainage waters from coal mining areas. In metal mining areas, other constituents such as copper, lead, zinc, nickel, silver, fluoride, uranium, antimony, mercury, chromium, selenium, cadmium, and arsenic have been found in excessive concentrations. In fact, copper has long been commercially extracted from natural mine waters; and, as has been explained, leaching of copper from copper ore and waste rock using sulfuric acid is an important mining method.

Articles by Emrich (1965), Emrich and Merritt (1969), Merritt and Emrich (1970), Dutcher and others (1967), Parizek (1971) and Parizek and Tarr (1972) discuss the groundwater hydrology typical of many underground coal mines in the Appalachian coal-mining area and also deal specifically with groundwater pollution from underground coal mining in that area or depict situations that could obviously result in groundwater pollution.

Many of the underground coal mines in Appalachia are above-drainage drift mines (Figure 1). In many if not all cases, the coal seam and the overlying beds are saturated prior to mining. As a result of mining, these strata are dewatered, either by gravity flow or pumping (Figure 8). After the groundwater table has been lowered, the pyrite that was previously below the water table is exposed to oxygen in the air and oxidation of the pyrite occurs. The sulfate and iron become soluble as a result of the oxidation and are taken into solution by water percolating through the partially saturated soil and rock above the mine. The acid water then enters the mine workings and flows out by gravity, is pumped out, or percolates through the mine floor and enters the groundwater system (Figures 12 and 13). The acid drainage that directly enters the groundwater system through the mine floor, will, of course, act as a pollutant. Water that flows or is pumped from mines first becomes part of the surface water, but may enter the groundwater system by infiltration at some point as shown in Figure 14. It was determined that, as of 1969, 10,500 miles of Appalachian streams were significantly affected by coal-mine drainage pollution, including entire drainage basins and several major streams (Federal Water Pollution Control Administration, 1969). In a U.S. Environmental Protection Agency sponsored survey of groundwater pollution in the northeastern United States, four instances of groundwater pollution from acid mine water have been identified in Maryland and 18 in Pennsylvania (written communication, D.W. Miller, Geraghty and Miller,

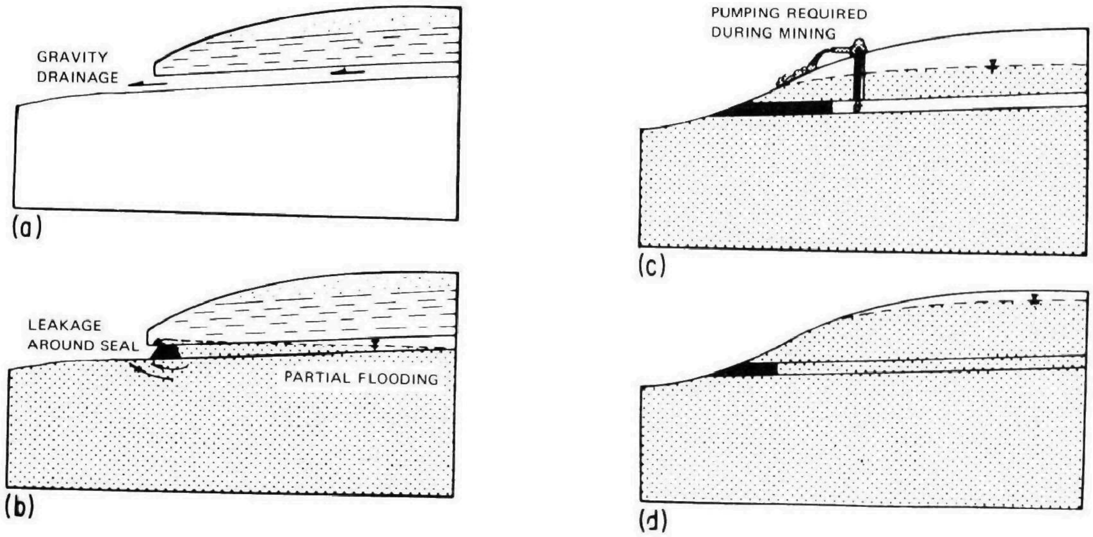


Figure 12. Drift mining of coal to provide free gravity drainage during mining (a) and partial flooding of mine after sealing (b). In (c) coal is mined downdip and requires pumping during mining but in (d) the mine floods completely when abandoned (Parizek and Tarr, 1972).

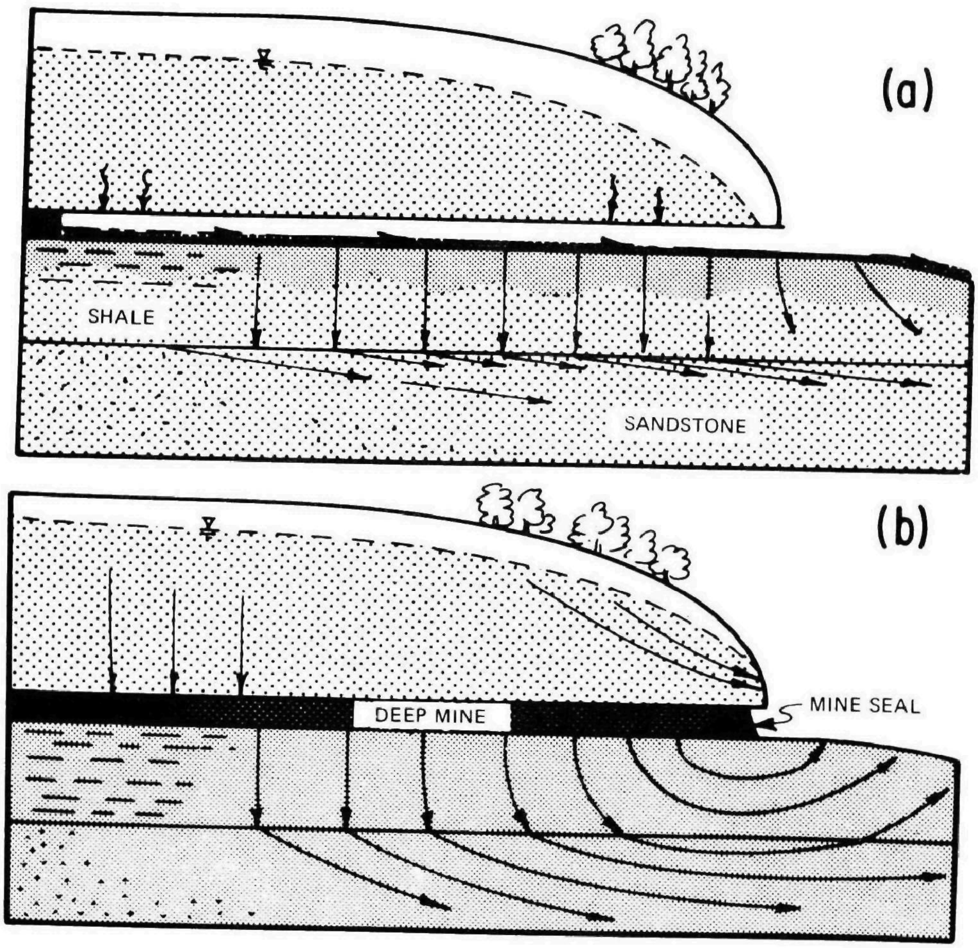


Figure 13. Relationship of underground coal mines to groundwater flow systems before mine sealing (a) and after sealing and flooding (b). In (b), a greater proportion of mine drainage is diverted to the regional groundwater flow system (Parizek and Tarr, 1972).

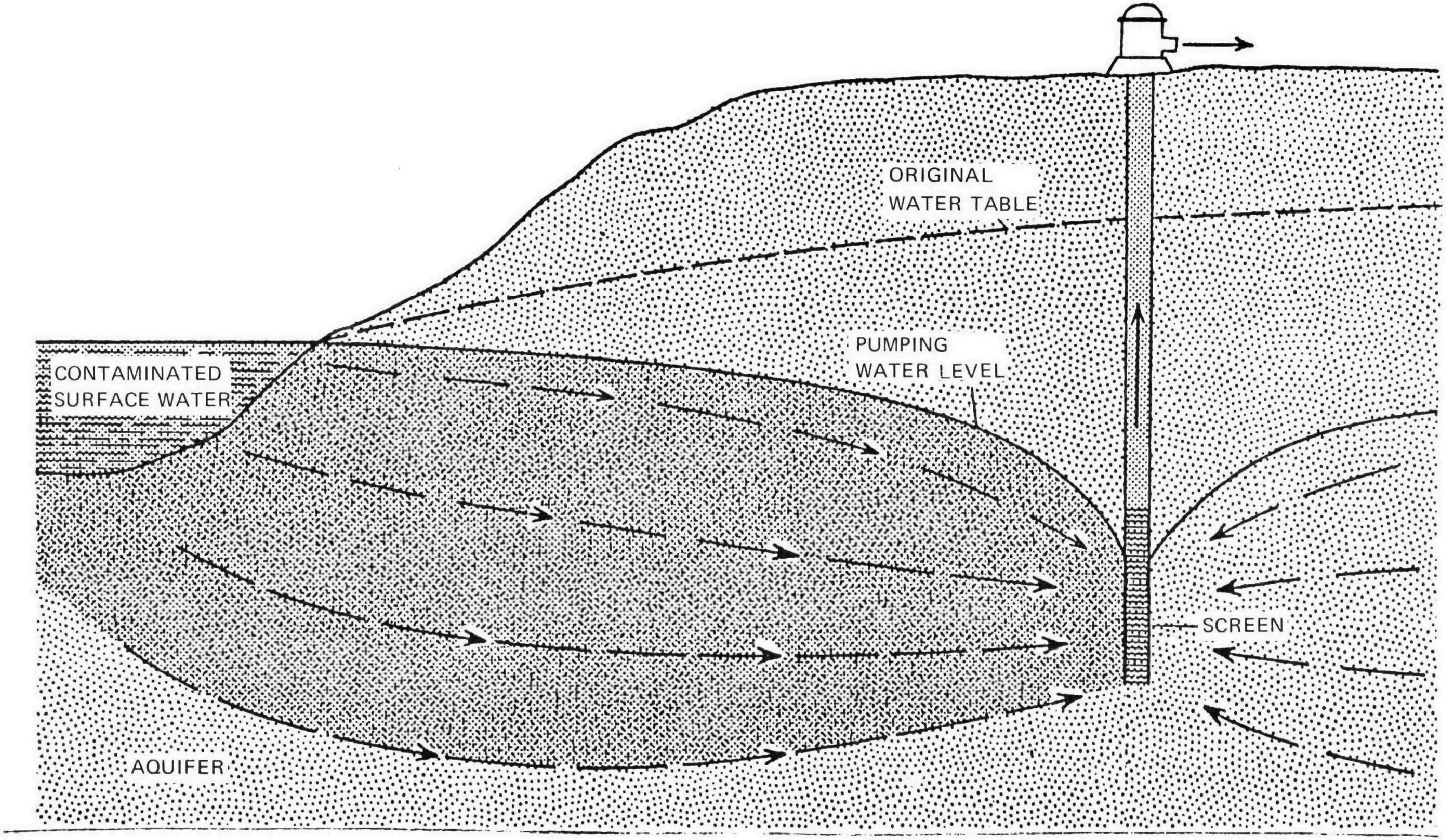


Figure 14. Diagram showing how contaminated water can be induced to flow from a surface source to a well (Deutsch, 1963).

Inc.). These are undoubtedly only examples of the effect of acid mine water on groundwater in that area.

Deutsch (1963) gave an example of the pollution of a shallow gravel aquifer by infiltration of water pumped to the surface from an underground iron mine. The contaminants were dissolved solids and hardness.

One method of controlling the production of acid water from abandoned above-drainage drift mines is sealing off the mine in an attempt to flood the mine and thus stop the oxidation of pyrite. Figure 13 shows how such sealing may increase the amount of acid water entering the groundwater system. The principles discussed above with reference to above-drainage coal mines also will apply to metal mines that occur in a similar topographic and hydrologic setting and where oxidizable sulfide minerals are present. Many metal mines in the western United States are in this category.

Acid water is also formed in underground mines that are below the level of the local drainage system. Mines of this type must be continuously pumped during their operation to allow them to be worked. The mine thus becomes the center of a cone of depression in the groundwater table (Figure 11). Pyrite in the rocks that are drained during the operation of the mine is thus subject to oxidation and the water being pumped from the mine may be acid. As long as the mine is being operated and the water discharged at the surface, groundwater pollution would occur principally from infiltration of the pumped water back into the groundwater system. However, when the mine is abandoned, the workings will fill with water, which will take the already oxidized minerals into solution. This polluted water will then enter the flowing groundwater system. No detailed study of such a situation was found in the literature, but the water in many abandoned deep coal mines is known to be acid and it would be expected that water in some flooded underground metal mines might also be acid and contain higher than usual concentrations of the metals that occur in the local rocks. Proctor and others (1973) have found unusually high concentrations of zinc and other metals in shallow groundwater in the Joplin, Missouri, area and they believe that it is probable the shallow aquifers are connected with abandoned mines in that area or that groundwater percolates through brecciated and mineralized areas associated with mines resulting in the high metal contents.

In addition to the types of groundwater pollution mentioned above, the pumping of underground mines may result in the upward flow of saline groundwater in the vicinity of the mine, thus inducing saline water intrusion, as shown in Figure 15. The hazard of this happening may be particularly great in some areas of Appalachia where saline water occurs at depths of only 100 to 300 feet (Wilmoth, 1971). This type of groundwater quality deterioration is anticipated as a potential problem in the mining of oil shale at the two proposed prototype Colorado tracts (U.S. Department

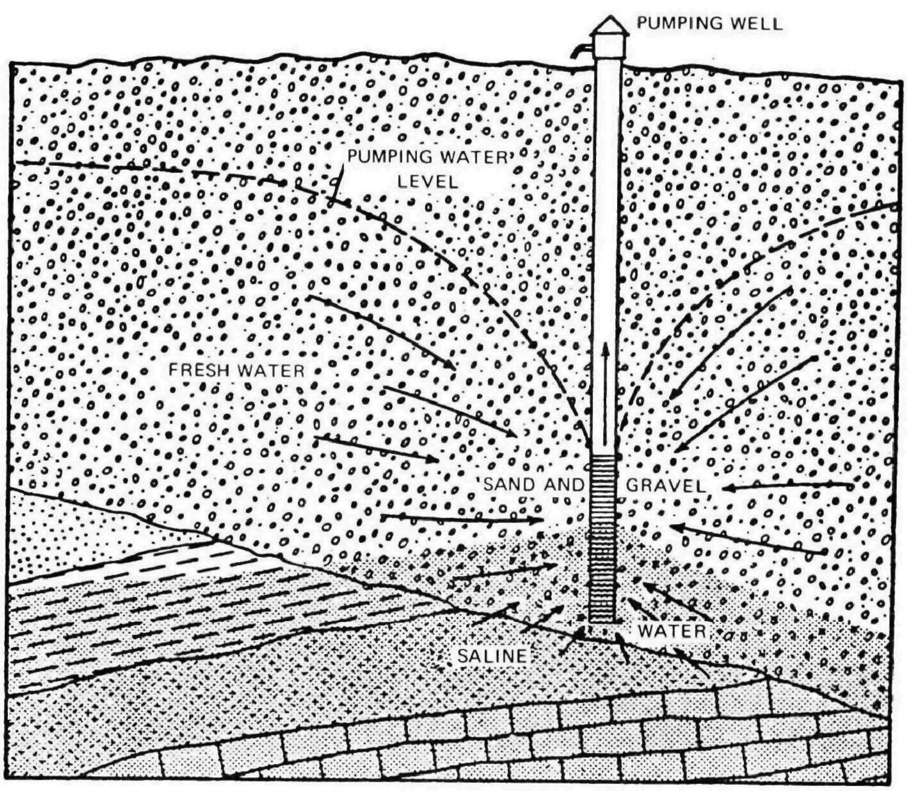


Figure 15. Diagram showing how a pumping well can cause a fresh-water aquifer to be contaminated by saline water from underlying rocks (Deutsch, 1963).

of the Interior, 1973). The hydrologic situation in the Piceance Basin oil shale area is shown in Figure 16. Interaquifer flow, leading to groundwater contamination, could also be induced by unplugged exploratory drill holes or even abandoned oil and gas wells that may intersect mines containing contaminated water (Emrich and Merritt, 1969; Merritt and Emrich, 1970; Thompson, 1972). One method that is suggested for the disposal of the large volume of saline water that would eventually be pumped from the underground oil shale mines in Colorado is reinjection into a slightly deeper aquifer (U.S. Department of the Interior, 1973). A result of such extensive injection would be to increase upward flow of saline water from the injection zone into the shallower fresh-water aquifers.

The same chemical reactions that create acid mine water during underground coal mining occur in the spoils from area-strip and contour-strip coal mines. Rainwater that infiltrates into acid-bearing spoils dissolves the sulfate, iron, and other minerals, then continues downward into the groundwater system or until it contacts an impervious layer where it will migrate laterally and emerge as seepage at the perimeter of the spoil pile. Groundwater that flows laterally into and through strip-mine spoils may also become mineralized. Probably the most detailed study of the influences of coal strip mining on groundwater and surface water quality was that performed by the U.S. Geological Survey in the Beaver Creek basin, Kentucky (Collier and others, 1970), during which it was found that mining has significantly increased the acidity and mineralization of groundwater and surface water. Emrich and Merritt (1969) reported that polluted drainage from coal strip mines in the Thoms Run drainage basin, Pennsylvania, entered deeper aquifers along joints, fractures, and especially through abandoned oil and gas wells.

Corbett (1965) and Cederstrom (1971) have pointed out that the spoils from area-strip mining have a large capacity for retention of water and may have the beneficial effect of reducing runoff and increasing the base

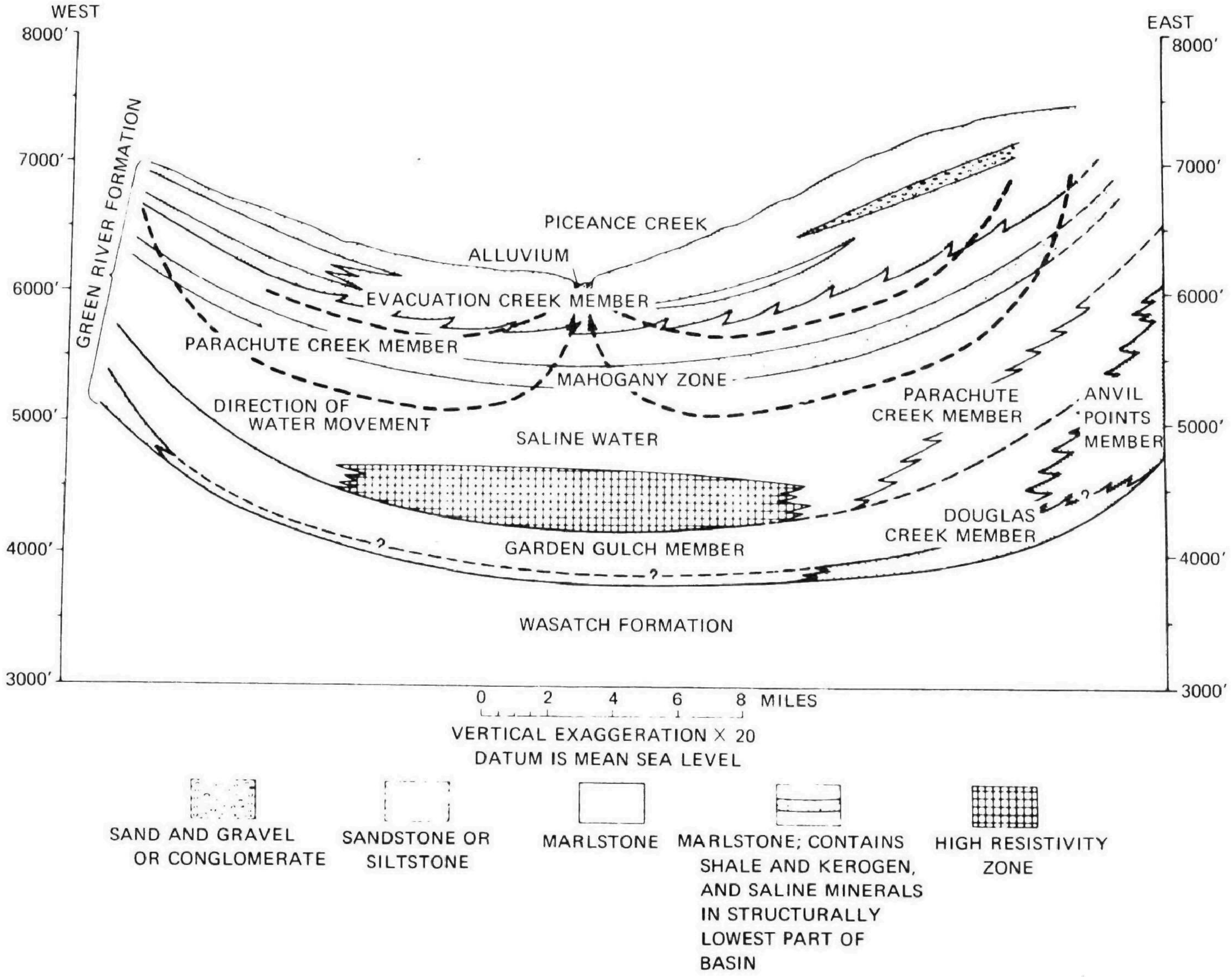


Figure 16. Diagrammatic section across the Piceance Basin (after Coffin, and others, 1971).

flow of streams, However, if the spoils contain appreciable soluble minerals, the water that they store may be of poor quality and contribute to surface water and groundwater pollution.

Considerable concern has been expressed about the possible effect of area-strip mining of coal in Wyoming, Montana, North Dakota, and other western States on the groundwater resources of those States (The Ground Water Newsletter, 1973). In a recent environmental impact statement for the Peabody Coal Company Big Sky Mine, southeastern Montana (U.S. Geological Survey, 1973), it was concluded that the mine would inevitably destroy parts of certain aquifers, interrupt the local groundwater flow pattern, and probably lower the quality of shallow groundwater in the immediate vicinity. The one mine is projected to disturb only about 4,300 acres, but surface mining of western coals has only recently become of significant magnitude and the potential for growth is very great. It has been estimated that the amount of coal mined in the western States in 1985 will be more than 10 times that mined in 1970 (Coal Age, 1973). The western States contain about 60 percent of the nation's strippable coal reserves, about two-thirds of which is in the three States mentioned above.

Strip mining of minerals other than coal could be expected to have similar adverse effects on the quality of groundwater resources where circumstances are conducive. Clay mining in Pennsylvania creates many of the same problems as coal mining. Phosphate mining and milling have recently been found to be the source of extensive radiochemical pollution of groundwater in Florida (U.S. Environmental Protection Agency, 1974; Rouse, 1974). Uranium mining in the western States would be expected to have had some adverse effects on groundwater quality through leaching of the spoils, but no documentation of such problems was located.

In some cases it is necessary to dewater strip mines and open-pit mines. Extensive pumping of groundwater at a surface mine of any kind could lead to vertical intrusion of saline water or even lateral intrusion of sea water if the mine were very near the sea. Deutsch (1963) reported a case where dewatering of a limestone quarry appeared to have accelerated the normal upward encroachment of mineralized water and contributed to pollution of the shallow fresh-water zone (Figure 17). A situation where the potential exists for both vertical and lateral intrusion as a result of pumping 60 mgd from a phosphate mine in eastern North Carolina is described by Peek (1969) and Hird (1971). According to Peek, water levels in the affected aquifers were rapidly lowered to below sea level in an area of about 800 square miles and to more than 100 feet below sea level in the immediate vicinity of the mine. However, Hird reported that no water quality change had yet been observed in monitor wells in 1970.

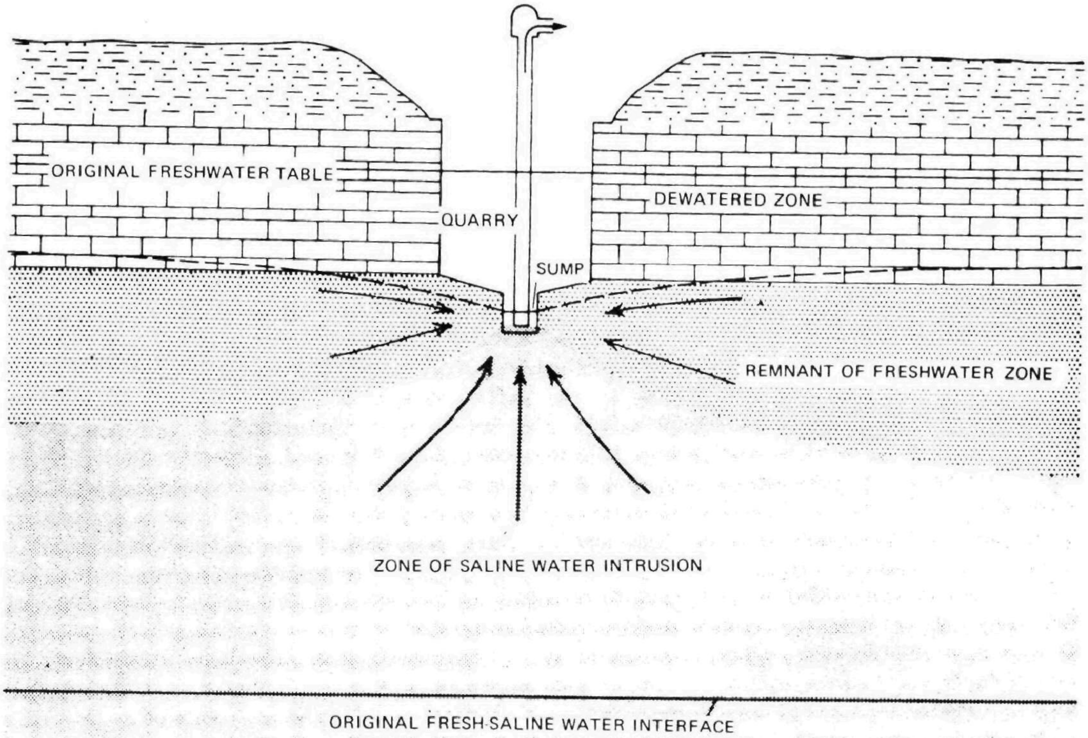


Figure 17. Diagram showing migration of saline water caused by dewatering in a fresh-water aquifer overlying a saline-water aquifer (Deutsch, 1968).

Auger mining is generally carried out in conjunction with contour-strip mining of coal, as has been described. Probably the greatest effect of augering on water quality results from the connections between strip mines and underground mines that are caused by auger holes that are driven from the highwall of the contour mine into the workings of underground mines. Such holes allow water from strip mines to flow into underground workings and vice versa. This situation complicates the hydrology and makes some in-situ control methods impractical.

Dredging of sand and gravel and placer minerals would tend to disrupt the alluvial aquifers that are being mined, but it is not obvious that any chemical pollution of the aquifers would result from dredging. Hydraulic mining is little practiced today, except for a few gold mines in Alaska; and, while such mining may greatly affect the quality of adjacent streams, there should not be much effect on groundwater quality.

Disposal of solid wastes into abandoned quarries, gravel pits, and strip mines has long been practiced. Although such practice is not part of surface mining itself, it is closely enough related to be worthy of mention. The potential for groundwater pollution from disposal of waste into the cavities left by surface mining is obvious. Emrich and Landon (1971) investigated the effects of disposal of urban solid wastes in coal strip mines on groundwater quality and found that in four of the five sites that were studied groundwater pollution had occurred or would be expected to occur.

Strata in which solution mining is practiced (Figures 7 and 8) inherently contain highly mineralized water, because the salt or other minerals being mined are water soluble. The potential for groundwater pollution from solution mining would be from interaquifer flow of the saline water as a result of:

1. Escape of saline water through a well bore into a fresh-water aquifer because of insufficient casing, by corrosion, or by other failure of the well casing

2. Vertical escape of saline water, outside of the well casing, into a fresh-water aquifer
3. Vertical escape of saline water through aquicludes that are leaky because of high primary permeability, solution channels, joints, faults, or induced fractures
4. Vertical movement of saline water through other nearby deep wells that are improperly cemented or plugged, or that have insufficient or corroded casing.

Fracturing of aquicludes could be caused by the high injection pressures used to fracture the salt or other minerals being mined or by subsidence over mined cavities. When surface collapse results from subsidence, the potential for groundwater contamination is increased because polluted surface water can be funneled into aquifers.

Leakage of ponds used to hold brine solutions is also a potential pollution mechanism. Although there are a large number of solution mining operations in the United States, and there is obviously a significant possibility of groundwater contamination from such mining, no published examples were found.

Groundwater pollution from in-situ dump- and heap-leaching of metallic ores could occur as a result of loss of the leaching agent into the groundwater system (Figure 9). As Rouse (1974)(a) points out, there is an inherent, risk of spills and leakage during the handling and storage of large volumes of leach solution and recovered pregnant liquor. He further comments that this risk is greatly enhanced by less than adequate construction methods that are all too common around leach-mining operations. Cederstrom (1971) mentions that contamination of groundwater supplied has occurred as a consequence of leaching of pyritic copper ores. He cites an example of pollution of an alluvial aquifer by waste leach water discharged into the stream course that recharged the aquifer.

On the positive side, Longwell (1974) reports that no evidence of lateral migration of leach solutions has been observed in conjuction with in-situ leaching at the Old Reliable copper mine, Arizona, after one year of operation. Similarly, Pizarro and others (1974) report no evidence of groundwater pollution in monitor wells at Carlin Gold Mining Company's Carlin, Nevada heap-leaching facility after several years of operation.

Sites for the disposal of solid and liquid wastes from mining and mineral processing are potential groundwater pollution sources much the same as sanitary landfills and lagoons for other liquid wastes. In addition, mine refuse, mill tailings, or coal preparation plant wastes are frequently used to construct dams and the reservoirs formed by these dams may be used to contain pumped mine water or wastewater from mineral processing.

Piles of waste from coal mining and refuse from coal preparation plants are frequent sources of acid water, since this material often contains very high concentrations of pyrite. Wastes from many metal mines and their associated mills are also acid producing and the drainage may contain many other minerals, as has previously been mentioned. Mink, Williams, and Wallace (1971) describe the pollution of an alluvial aquifer in the Canyon Creek basin in the Coeur d'Alene mining district of Idaho as a result of previous mining. The pollutants are cadmium, copper, lead, and zinc leached from the tailings left by the concentrating of ore from metal mines. Mink and others (1971), Galbraith and others (1972), Williams and Wallace (1973), and Sceva (1973) reported further on groundwater pollution from mining in the Coeur d'Alene mining district of Idaho, much of which is caused by tailings piles. This example is probably typical of what would be found in other mining districts in western States, if they were examined. The potential for groundwater pollution from a proposed tailings dam and settling pond for the Homestake gold mine is briefly described in the environmental impact statement for that project (U.S. Environmental Protection Agency, 1972).

Groundwater pollution from leaching of uranium mill tailings is another problem that is known to exist, but for which the magnitude has not been defined. The Federal Water Pollution Control Admininstration (1966) reported that "industry-owned observation wells in the near vicinity of tailings and uranium mills have been reported to indicate radiation levels well above background." The FWPCA report cited one example of a contaminated domestic well and speculated that other groundwater pollution could result in the future by recharge of alluvial aquifers from polluted streams. At the time that the report was written ten operating and seven inactive uranium mills and concentrating plants were located in the Colorado River basin and only one had attempted to prevent downward percolation of water by placing a bentonite base beneath the tailings pile of the plant.

There are no commercial in-situ combination mining projects (Figure 10) at the present time. Some information on the effect of in-situ mining of oil shale on groundwater quality has been obtained by the U.S. Bureau of Mines in pilot-scale tests in Wyoming. At one site, the dissolved solids content in water taken from wells approximately 200 feet from the burned zone increased from about 500 ppm at the beginning of the experiment to 20,000 ppm within two months after the experiment (U.S. Department of the Interior, 1973).

The volume of the spent oil shale that is produced during retorting is greater than the volume of the original shale as extracted from underground. Disposal of the spent shale is a major problem. Possibilities for disposal include backfilling mines or depositing the spent shale in the deep gullies and canyons that are often characteristic of the regions in which oil shale is found. Water percolating through the spent shale in surface disposal sites might be intercepted, although this is a major undertaking. It would be quite difficult to prevent groundwater pollution from backfilled underground mines. The potential for water pollution by circulation of water through spent shale was evaluated by Colorado State University (1971).

The study showed that substantial quantities of soluble salts, particularly sodium, calcium, magnesium, and sulfate are present in spent shales and that concentrations of these ions in water percolated through spent shale exceeded 100,000 mg/liter in the initial samples of leachate. These experiments are not sufficient to determine what the magnitude of the problem from a full-scale operation would be; however, it is apparent that groundwater contamination might occur from leaching of organic and inorganic minerals in spent shale.

Water pumped from underground mines and released into tailings ponds may increase greatly in dissolved solids in arid areas as a result of evaporation. This water then becomes a pollutant, if it infiltrates back into the groundwater system.

An unusual mechanism for water pollution from tailings piles is that which may occur when fine tailings are distributed by wind and carried into surface waters or leached by rainwater. The potential for pollution from this source was recognized in the previously discussed studies of uranium tailings and pollution from windblown tailings has been observed in the Coeur d'Alene mining district (Sceva, 1973). An example of this type of groundwater pollution is shown in Figure 18.

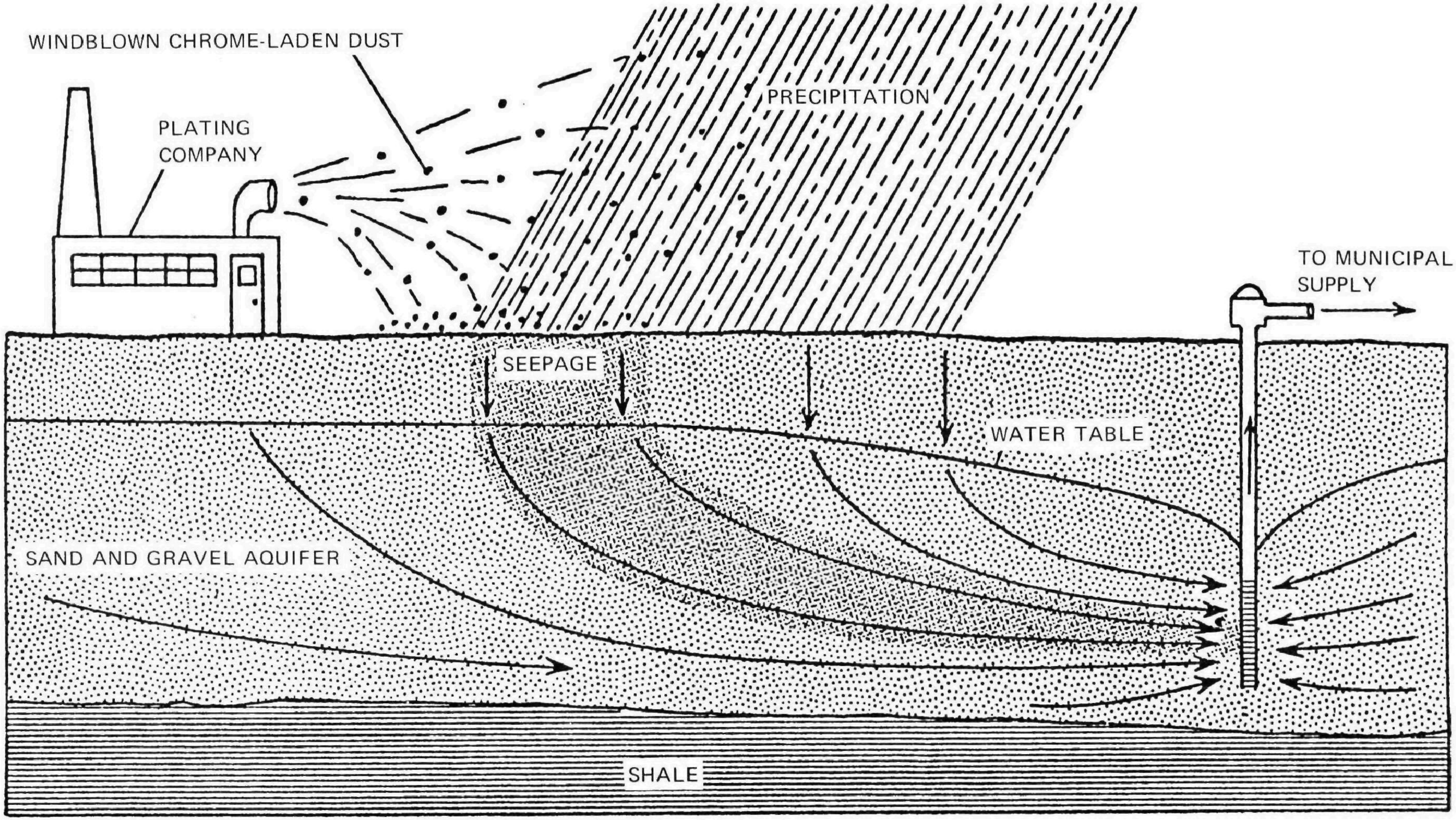


Figure 18. Diagram showing possible mode of entry of windblown wastes into an aquifer (Deutsch, 1963).

SECTION VII

METHODS FOR CONTROL AND PREVENTION OF GROUNDWATER POLLUTION

A recent comprehensive U.S. Environmental Protection Agency publication (U.S. Environmental Protection Agency, 1973) provides a summary of currently available processes, procedures, and methods for the control of water pollution from mining activities. The methods listed for underground mines include controlled mining procedures, water infiltration control, wastewater control, mine sealing, and treatment. Techniques for surface mines are similar, but also include erosion control, regrading, and revegetation. All techniques have potential for reducing both surface and groundwater pollution, but their discussion is beyond the scope of this report, except where the technique may directly relate to groundwater pollution and its monitoring. The various techniques may be classified as either at-source or treatment methods. The at-source control methods deal with the mine site and its hydrology and are of interest here.

As is noted in the introductory chapters of the sections of the EPA report dealing with control of water pollution from both underground and surface mining, effective mine site studies and preplanning of the entire mining operation from the opening to the closing of a mine are fundamental to effective pollution control. Site hydrology is important, because water passing through the mine site and its vicinity provides the mechanism for transfer of pollutants into the groundwater system. The details of such site studies could be discussed here or in the monitoring section, but the latter has been selected because of the emphasis of this report. The discussion of at-source control techniques that follows has been modified from that presented in the EPA publication. Original references are not cited here, but may be obtained from the EPA report.

UNDERGROUND MINES

Preplanned Flooding

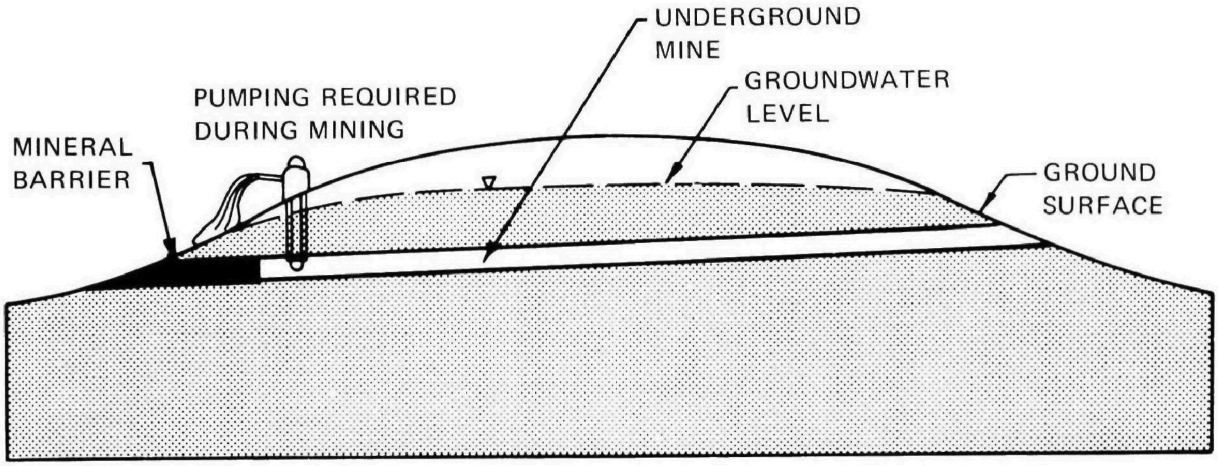
As previously explained, the principal cause of polluted mine water is the oxidation of sulfide minerals exposed during mining. Flooding of a mine upon completion of mining will greatly reduce further oxidation. The most effective method of achieving flooding is by mining downdip and leaving a barrier at the outcrop, so that flooding will occur naturally (Figure 19). Although flooding will control further oxidation of sulfide minerals, it may contribute to groundwater pollution in some cases by dissolving previously oxidized minerals and by increasing the rate of flow into groundwater aquifers (Figure 13).

Roof Fracture Control

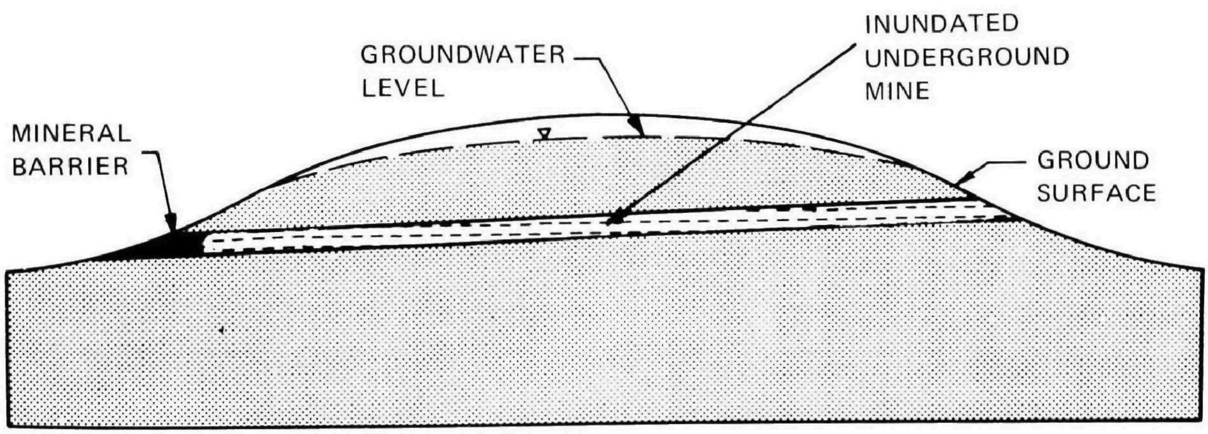
Most of the water entering many underground mines passes vertically through the mine roof from overlying strata. The original source of this water is infiltrating rainfall. Collapse of a mine roof is sometimes responsible for increased vertical flow, particularly in coal mines. Roof collapse causes widespread fracturing in the strata around a mine roof, and subsequent joint separation far above the roof. These opened joints can tap overlying perched aquifers and provide flow paths to the mine. Roof collapse in shallow mines will often cause surface subsidence. Subsidence fissures collect and then funnel surface runoff directly to the mine.

Roof collapse and fracturing of overlying strata can be reduced by using the roof support techniques discussed in Section IV, Mining Methods. In review, these are:

1. Methods of natural roof support, such as the room and pillar system
2. Artificial support methods, such as square-set stoping
3. Combinations of 1 and 2.



DOWNDIP MINE–DURING MINING



DOWNDIP MINE–AFTER MINING

Figure 19. Preplanned flooding of underground drift mines (U.S. Environmental Protection Agency, 1973).

In order for this technique to be useful in pollution control, the resultant decrease in flow must not be accompanied by a proportionate increase in pollution concentration. If such a tradeoff should occur, the pollution load could remain essentially the same. This tradeoff is not an entirely unlikely possibility.

Coal mine drainage will be used as an example of how this could occur. Coal mine drainage pollutants result from the oxidation of pyrite. Oxygen and water are required for this oxidation reaction in a nonflooded mine. The relative humidity in an underground coal mine is usually at or near saturation (100 percent relative humidity). Mine walls are normally damp. Water required for the pollution-forming reaction is almost always available. Flushing of the oxidation sites is not even required. Salts resulting from oxidation are hygroscopic, meaning that they will draw water from the atmospheric humidity. The salts will seep downward from the accumulated humidity, exposing the reaction sites to further oxidation. The point of this discussion is that the availability of oxygen is the oxidation rate controlling factor, and the amount of water flowing through the mine does not control the oxidation rate. Pollution production may be constant within the mine regardless of the flow of water through the mine. Decreasing flow may result in increased pollution concentrations.

Therefore it is possible that decreasing mine drainage could have little or no effect in controlling pollution. Decreased flow may result in decreased water pollution if the amount of drainage is reduced sufficiently to prevent pollution transportation from the mine. In this case, decreases in water pollution coming out to the surface could also result in increases in groundwater pollution.

Increasing Surface Runoff

With objectives similar to those in roof fracture control, water infiltration can be decreased by increasing surface water runoff. This technique involves elimination of depressions and grading the surface to increase water velocities. Subsidence depressions often collect and convey large quantities of surface water to underground mines. The amount of water collected depends on size of drainage area tributary to the depression, and annual rainfall and runoff rate. Subsidence holes in stream channels can cause entire streams to enter underlying underground mines. Uneven surfaces caused by agricultural, logging or other surface activities can cause increased infiltration.

Surface runoff can be increased by grading an overlying area to a smoother, better draining configuration. Surface depressions can be filled in and leveled with clay. Stream channels can be flumed, reconstructed with impermeable liners, or diverted around water loss areas. Channel stability under increased flows must be assured.

As with roof fracture control, the overall effect of increased surface runoff should be appraised to insure that the objective of decreased pollution loads is achieved and that groundwater pollution is not accelerated.

Regrading Surface Mines

Surface mines are often responsible for collecting and conveying large quantities of surface water to adjacent or underlying underground mines. Nonregraded surface mines often collect water in an open pit where no surface exit point is available. Many abandoned underground mine outcrop areas have been contour stripped. These surface mines often intercepted underground mine workings, providing a direct hydrologic connection. The surface mine does not have to intercept underground mine workings in order to increase infiltration. Surface mines on the updip side of underground mines collect water and allow it to enter a permeable coal seam. It then flows along the coal seam to underground mines. Overlying surface mines that collect and entrap water can also be significant sources of infiltration. These surface mines facilitate entry of surface runoff to the groundwater system, which eventually works its way into an underground mine. Regrading techniques are discussed under control techniques for surface mines in the EPA report.

Sealing Boreholes and Fracture Zones

Boreholes and fracture zones act as water conduits to underground mines. They are usually vertical, or near vertical, and tap overlying aquifers. They collect and transport groundwater.

Boreholes are commonly present around underground mines and usually remain from earlier mineral exploration efforts. These boreholes can be located and plugged to prevent passage of water. Concrete can be inserted hydraulically to form a seal. Boreholes can be easily sealed from below in an active underground mine. Difficulty can be encountered if sealing has to be performed from the surface. Abandoned holes are often difficult to locate on the surface, and many times they will be blocked by debris.

Fracture zones are often major conduits of water. They increase vertical movement of water and can cause large lateral movements. Fracture zones are usually vertically oriented planar type features. Their location can be plotted by experienced personnel using aerial photography. Permeability of these zones can be reduced by drilling and grouting. Holes are drilled into the zone and grout is inserted hydraulically. Care must be taken to ensure that the boreholes are located in the fracture zone at the point of grouting. There are various types of grout available; however, concrete is commonly used.

Interception of Aquifers

This technique takes advantage of the natural geologic and hydrologic systems surrounding a mined area. It involves use of boreholes, casing, and pumps to transfer water from one point to another in order to reduce water flow into an underground mine. The techniques are theoretical and will require development and demonstration to establish feasibility.

A complete hydrogeologic site evaluation of a mined area to determine aquifer characteristics and water flow systems is required prior to implementation. Most underground mines receive water from overlying aquifers. Several techniques can be employed to tap these aquifers and reduce the amount of water entering a mine. Overlying aquifers can be drilled and the water pumped to the surface (Figure 20). Boreholes can also be drilled

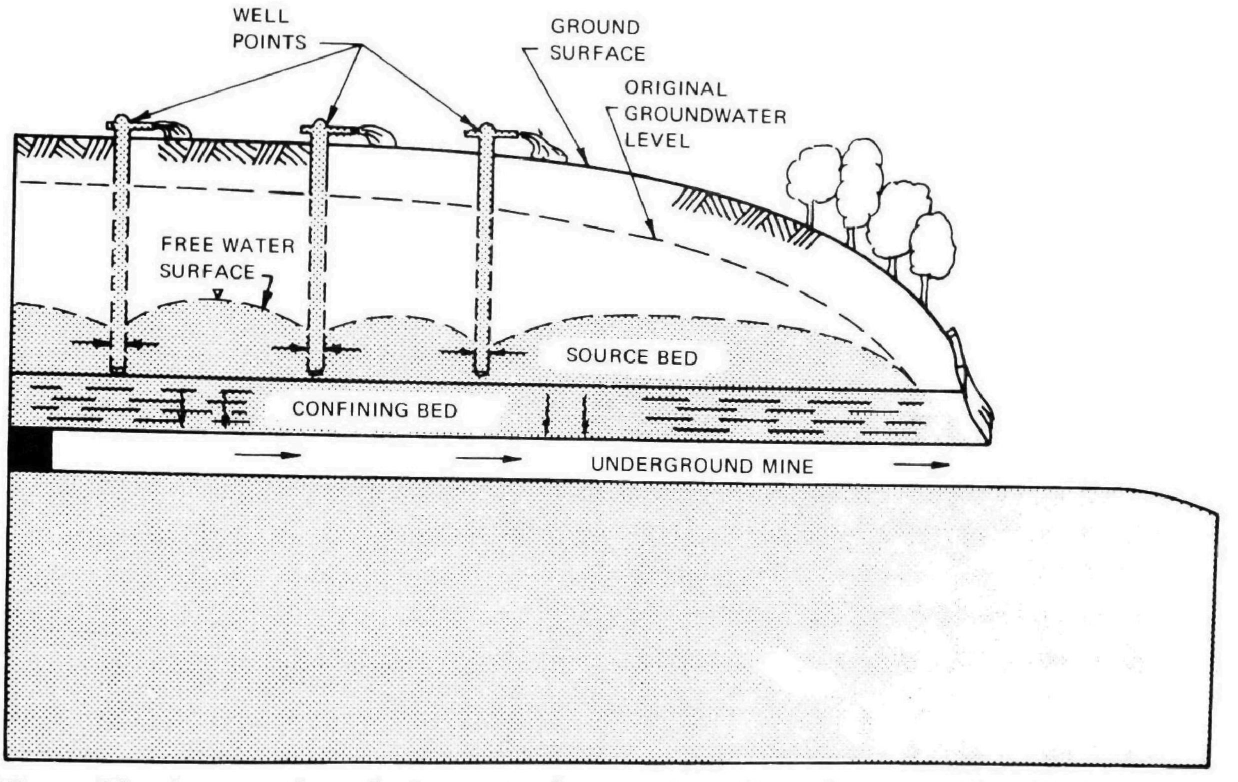
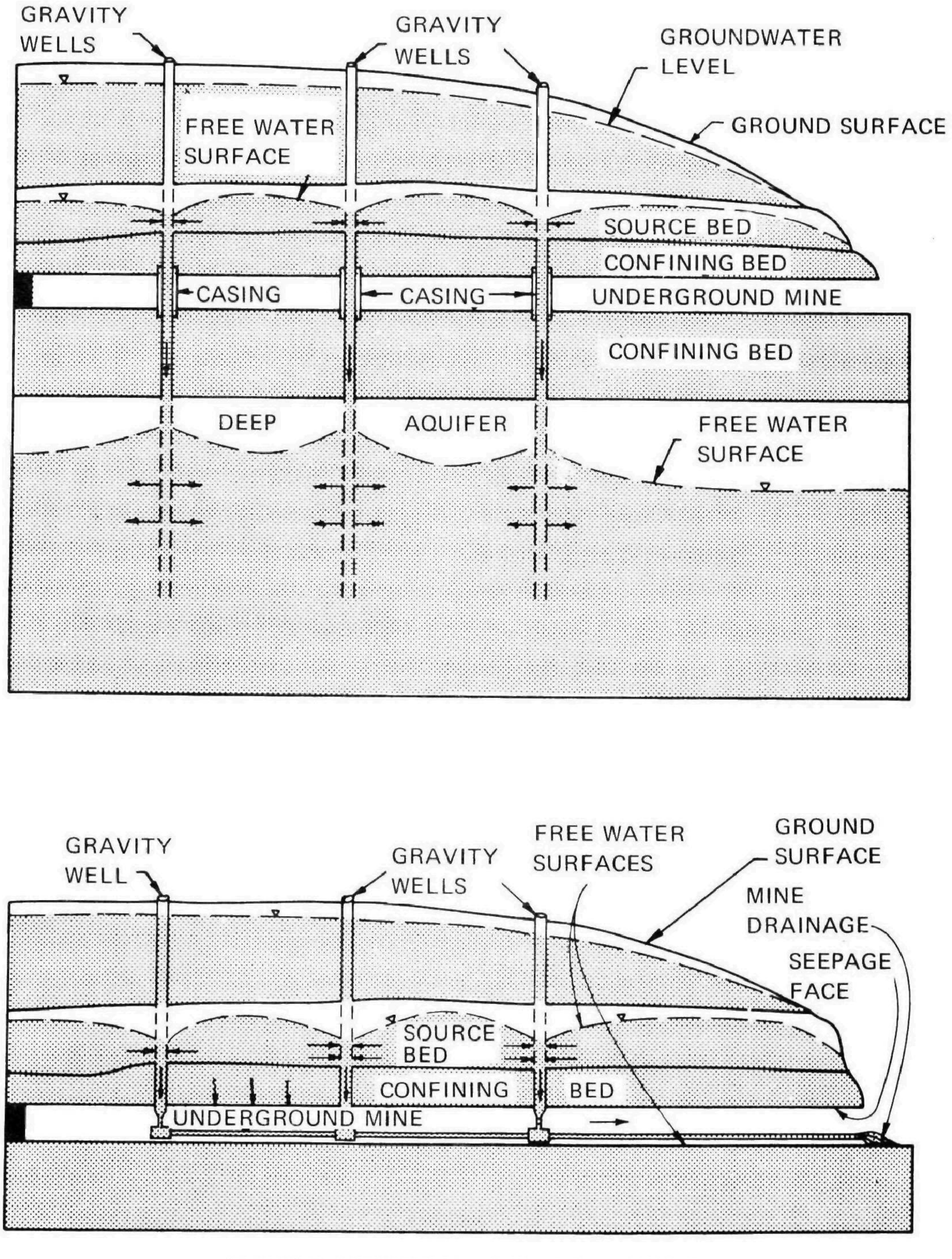


Figure 20. Interception of mine water by pumping of overlying aquifers (U.S. Environmental Protection Agency, 1973).

through aquifers, passing through an underground mine and into underlying aquifers (Figure 21-a). The boreholes must be cased through the mined zone (it collects water from the overlying aquifer, passes it through the mine zone for discharge to an underlying aquifer). The underlying aquifer must be capable of accepting the anticipated flow.

A variation on this technique is to drill holes into the underground mine, casing and grouting the borehole through the zone forming the roof. The boreholes are then connected by pipes and the water carried outside the mine. The uncased or perforated-casing portion of the borehole collects water from overlying aquifers and passes it into the piping system for conveyance out of the mine, never contacting pollution-forming materials (Figure 21-b).

Boreholes, pumps and piping systems can also be used to convey acid mine drainage to a nearby alkaline aquifer, or alkaline underground mine, to encourage mixing, neutralization and settling of precipitates.



INTERCEPTION OF AQUIFERS

Figure 21. Interception of mine water by gravity wells (U.S. Environmental Protection Agency, 1973).

Mine Sealing

Mine sealing is used to promote mine flooding as was previously discussed under preplanned flooding. Mine sealing for purposes of inundation involved construction of a physical barrier in a mine opening to prevent passage of water. A barrier must be designed to withstand the maximum expected pressure (head) of water that will be exerted against it. Sealing underground mines is somewhat analogous to creating a surface water impoundment: a major portion of the dam structure would already be in place and the seal merely closes the opening. Engineering considerations are also similar to these for surface impoundment design. The entire dam structure must be capable of withstanding exerted pressure, and leakage rates must be determined. Underground mine seals have seldom been successful due to lack of consideration of leakage rates and weak points. Seals can be designed to withstand a large amount of pressure, but the seal is only a small part of the impoundment structure. The perimeter of the mine forms most of the impoundment, and often it is not capable of withstanding any significant amount of pressure.

As with preplanned flooding, there is potential for increased groundwater pollution, and such operations should be carefully monitored to determine their overall effect.

SURFACE MINING

The general methods of controlling water pollution from surface mining were previously listed. Within the general methods, a large number of variations are discussed in the EPA publication, of which only selected ones can be reviewed here.

Controlled Mining Procedures

Ten controlled surface mining procedures are discussed in the EPA report. As an example, one of these, the use of mineral or low-wall barriers will be included.

Mineral or low-wall barriers are portions of the mineral and/or overburden that are left in place during contour strip mining (Figure 22). The barrier is intended to retain surface water in the mine during mining and retain groundwater in the base of the regraded spoil bank after reclamation. If pollution-forming materials are buried at the base of the spoils they can thus be covered with water and oxidation of pyrite retarded. A possible negative effect of such barriers would be to increase infiltration of polluted water into the groundwater system.

Water Infiltration Control

Chemical pollution of surface water and groundwater that results from surface mining is caused by leaching of the pollutants from the spoil material. Much of the leaching occurs during infiltration of water into the spoils.

Controlling water infiltration from rainfall and subsurface sources can be accomplished by placing impervious barriers on or around the waste material, establishing vegetative cover, or constructing underdrains. Impervious barriers, constructed of clay, concrete, asphalt, latex, plastic, or formed by special processes such as carbonate bonding, can prevent water from reaching the waste material. Figure 23 shows the reduction of surface water infiltration by implacement of impermeable material.

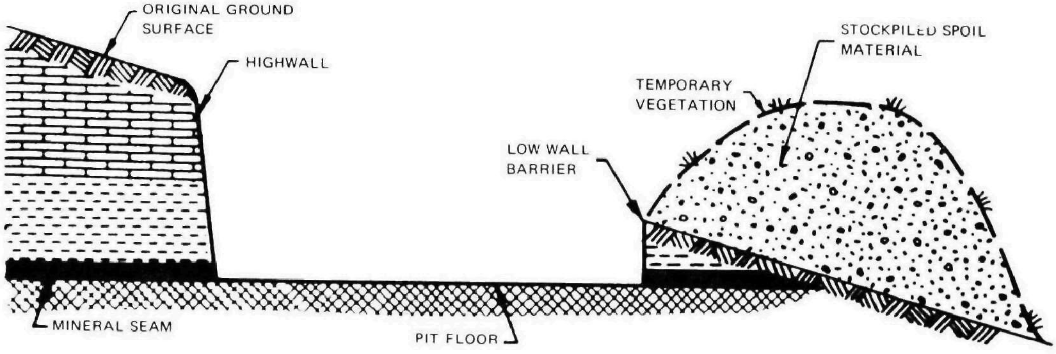


Figure 22. Impoundment of water in a contour strip mine by use of a low-wall barrier (U.S. Environmental Protection Agency, 1973).

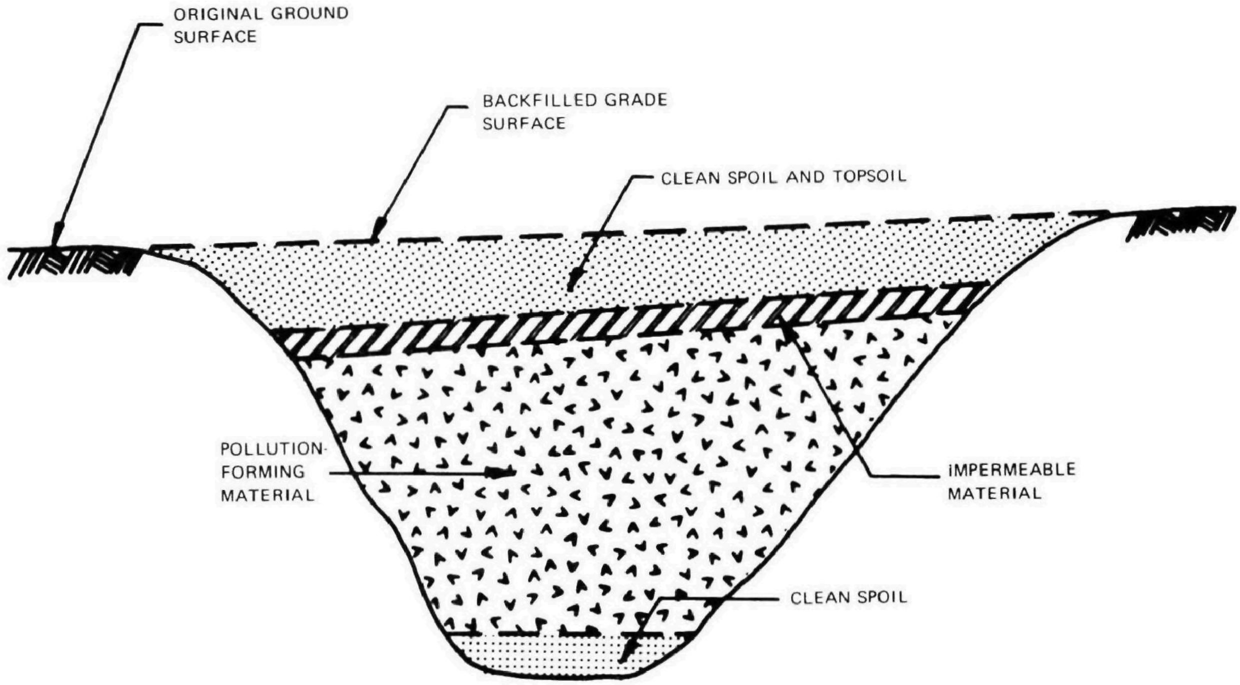


Figure 23. Control of infiltration by implacement of impermeable material (U.S. Environmental Protection Agency, 1973).

Pollutants may also be leached by groundwater flowing laterally through spoils. Such pollution can be controlled by placement of impermeable barriers to restrict groundwater flow. As an example, an impermeable barrier can be placed against the highwall of a surface mine to prevent flow of water from an adjacent underground mine through the spoils of a regraded strip mine (Figure 24).

Handling of Pollution-Forming Materials

Pollution-forming materials originated by mining or mineral preparation include all solid wastes that contribute to water quality degradation as surface or groundwater percolates through or flows over them.

One method of handling such pollution-forming materials is to remove them to a more suitable location such as is shown in Figure 25. Another possible handling method with multiple objectives is backfilling of underground mines. In this method, the pollution-forming materials are removed to an isolated location, the use of surface space is minimized, and support for the mined-out area is provided. Backfilling of underground

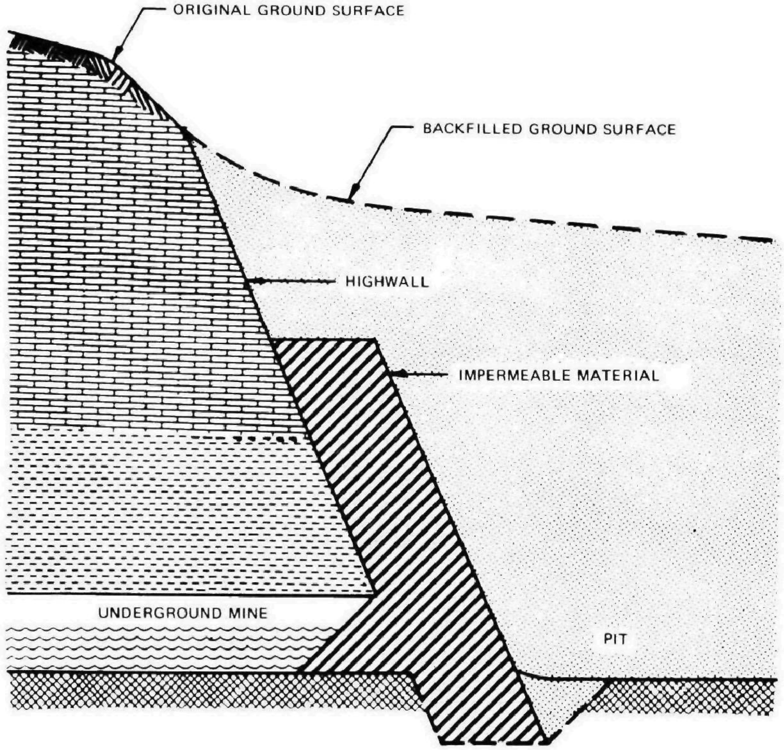


Figure 24. Control of lateral flow through strip mine spoils by implacement of impermeable material (U.S. Enfironmental Protection Agency, 1973).

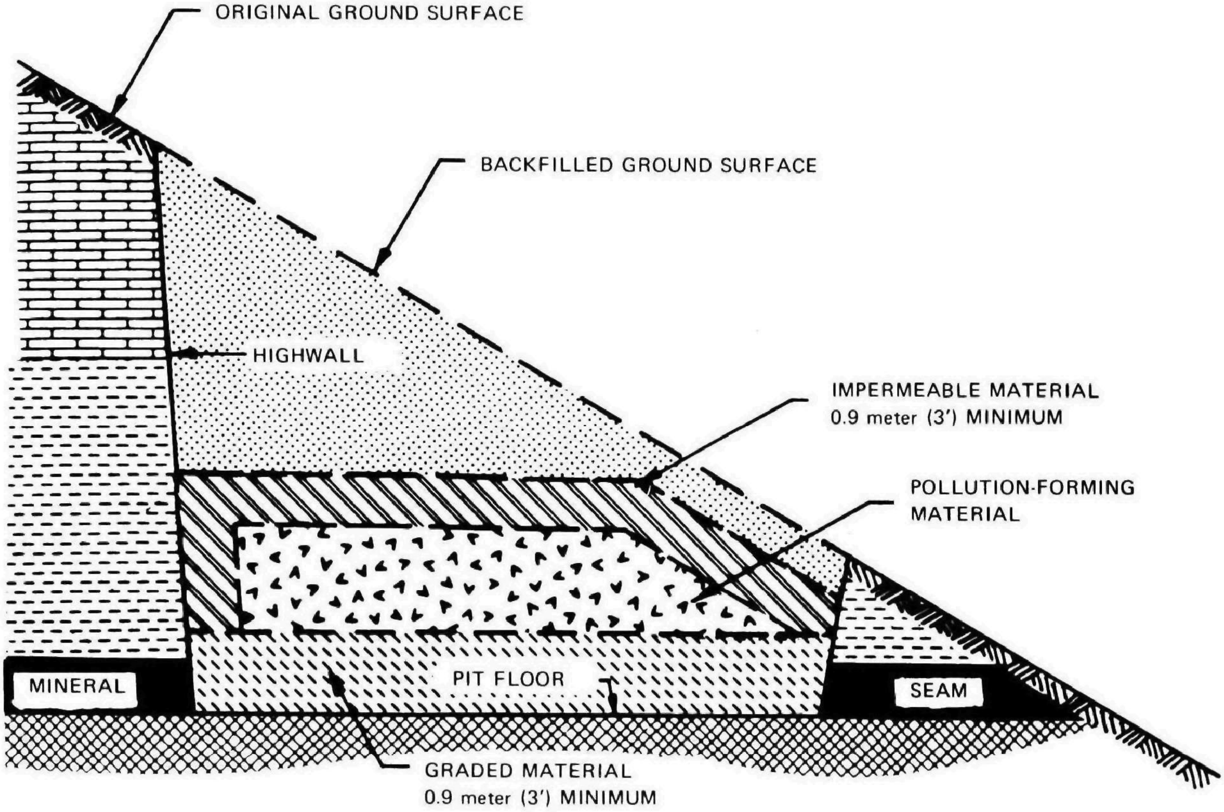


Figure 25. Relocation of pollution-forming material in the spoil bank of a contour strip mine (U.S. Environmental Protection Agency, 1973).

oil shale mines with spent oil shale is contemplated as a possible method of disposal of those wastes, which will be a major problem as that industry develops. A possible problem that could result from backfilling of underground mines would be pollution of groundwater during its percolation through the backfilled areas. An excellent example of this pollution mechanism was described by Trexler and others (1974) in their discussion of the Bunker Hill Mine in Idaho.

Wastewater Control

Once mine or mill water becomes polluted, it can only be treated or handled in some way to minimize its polluting effect on the water resource as a whole. Wastewater control methods include recycling and reuse, holding and evaporation, holding and controlled discharge, and spray irrigation. All of these techniques may pose some hazard to groundwater if improperly practiced, since they either involve impounding of the wastewater with an inherent potential for loss by seepage or spreading on the surface with its potential for introduction of pollutants by infiltration. Subsurface injection, rerouting, and mineral recovery are also discussed under the heading of wastewater control in the EPA publication.

SECTION VIII
MONITORING

Monitoring of water quality might be defined as a scientifically designed program of continuing surveillance; including direct sampling and remote quality measurements, inventory of existing and potential causes of change, and analysis of the cause of past quality changes and prediction of the nature of future quality changes.

Unfortunately, monitoring of groundwater is often thought of only in the context of sampling of wells and springs. Such sampling is a dominant or sole practice in most surveillance programs; however, sampling can be minimized and perhaps even eliminated in some cases by thorough inventory of possible causes and prediction of anticipated quality changes. For example, a situation in which direct sampling could be eliminated would be one where a planned activity is analyzed, major groundwater pollution predicted, and the planned activity is cancelled because of the unacceptable level of predicted pollution. An alternative outcome if the planned activity were implemented after analysis of the anticipated effects would be that the location and number of sampling points and the quality parameters analyzed would be minimized by anticipating the location of the source(s) and nature of pollution and by making predictions of rates and direction of pollution travel. The entire process described is thus considered to be monitoring.

EVALUATION OF PROPOSED MINING ACTIVITIES

An important key to monitoring the effect of any mining activity on groundwater quality is the development of an adequate understanding of the local geology, hydrology, and geochemistry. Gathering the necessary geohydrologic information should be a normal activity during the exploratory steps prior to the initiation of mining.

Experience obtained from evaluating the water pollution potential of surface and underground coal mines during their permitting is valuable in establishing the detailed list of required information. The State of Pennsylvania has developed a manual for this purpose, the Mine Drainage Manual (Pennsylvania Department of Health, 1966). Below is a modified list of some of the information requested in applications for mine drainage permits in Pennsylvania.

1. Type of mine.
2. Geologic column, indicating seams to be mined and amount and location of coal to be extracted from each seam.
3. Maps showing:
    a. geology of mine area
    b. topography and surface drainage
    c. boundaries of mining operation
    d. points at which drainage is likely to exit from mine
    e. locations of interconnected deep and strip mines, extent of workings, existing mine water impoundments, and present mine water discharge points.
4. Strike and dip (pitch) of coal seam(s).
5. Mining method and proposed development plan.
6. Mine drainage:
    a. anticipated amount and chemical character
    b. will drainage discharge by natural flow or will it be pumped?
    c. how will drainage be handled in the mine?
    d. details of any proposed treatment including final quality of treated effluent.
7. Proposed mine waste-handling plans.

8. Groundwater:
    a. water-bearing strata in the area, configuration of water table(s), and quality of water(s)
    b. location, discharge, and quality of water for any springs in area
    c. location, depth, construction, and use of all wells in the area to be mined and of any proposed wells.
9. Plans for mine abandonment.

When the coal mine is a new one, an estimate of the quality of drainage from the mine may be made by examining existing mines in the area. For cases where no other coal mines are present in the immediate area, Emrich (1966) and Renton and others (1973) have suggested laboratory procedures for determining the acid-producing potential of coals, and the University of West Virginia (1971) recommended field and laboratory methods for recognizing the pollution-forming potential of coal strip mine overburden prior to mining.

The procedures described in the references given above provide for prediction of the acid-forming potential of coal and overburden materials, but the means of relating this to the amount of surface or groundwater pollution from a mining operation is not developed.

If, for example, it were desired to predict the extent of groundwater pollution from surface coal mining as a result of pyrite oxidation, the variables that would have to be considered are:

1. The amount and distribution of oxidizable sulfide minerals
2. The kinetics of pyrite oxidation
3. The rate of transport of the oxidation products to the groundwater system and their concentration in the transporting water
4. The mechanics of mixing and transport of pollutants within the groundwater system.

In spite of the obvious complexity of the problem, a group of researchers at Ohio State University has published the description of a model for the prediction of the discharge rates and acid loads from a single underground coal mine (Morth and others, 1972) and the same group is presently working on a model for an entire small drainage basin, including surface and underground mines. If a model could be developed during the planning for a new mine that would yield reasonable values of the probable extent of pollution that would occur, the prediction could be used as one basis for determining whether or not the mine should be opened and what monitoring should be done if the mine is opened. The present models do not yet appear to have this capability.

Hunkin (1971) compared the engineering of an in-situ uranium mining operation with the secondary recovery of oil by waterflooding and suggested that the feasibility of an in-situ leaching project requires a three-stage evaluation. The environmental considerations in the first stage include:

1. An ore body confined by natural or artificial means in such a way that dilution or fluid losses may be restricted to an acceptable level
2. An aquifer with low groundwater velocity that is not used for water supply.

If these and other criteria in the first-stage evaluation are satisfied, then Hunkin recommends the following for the second stage:

1. Regional hydrology survey including seasonal variation, water usage, and regional groundwater flow.
2. Local hydrology survey, say for 10,000-ft. radius around proposed site. Groundwater contours, terrain, geological features (in particular, faults, dikes, and sills which may indicate local variation in permeability), and surface drainage features must be included.

3. Geophysical surveys to substantiate hydrological and geological interpretations. Minimum requirements are gamma log, self-potential, and resistivity logs, spaced with due regard to heterogeneity of formation.
4. Detailed water sampling program covering all seasons to determine quality of water in adjacent aquifers, streams, lakes and springs. This is essential in order to establish contamination levels existing prior to commencement of operations and to set standards for a continuous monitoring system during later operations.

The third stage is detailed site investigation, including core drilling and injection and bail testing of boreholes.

Rouse (1974) states that requirements for monitoring of an in-situ leaching operation are very similar to those for wastewater injection wells. He suggests the Environmental Protection Agency's recommended data requirements for environmental evaluation of subsurface injection wells as a basis for evaluating leaching operations.

In cases where the magnitude of the mining operation and the environmental hazard warrant the effort, it may be desirable to develop a mathematical model of the groundwater system in the area to determine as accurately as possible the rate and direction of flow and concentration of pollutants in the system (Tinlin and others, 1973). Modeling of this type has been used, for example, to predict the rate and direction of spread of radioactive wastes at the National Reactor Testing Station, Idaho (Robertson and Barraclough, 1973), and for estimating the effects of dewatering an oil-shale mine on groundwater in western Colorado (Coffin and Bredehoeft, 1969). Such models can, to a certain extent, take into account dispersion, radioactive decay, chemical reaction, adsorption, ion exchange, and density stratification of pollutants as they flow through the aquifer. Mathematical models may, as they are developed and verified, serve to reduce the number of sampling points, help to determine how frequently samples should be taken, and indicate constituents which should be considered in chemical and biological analyses.

MONITORING DURING OPERATION

Some means of surveillance of groundwater quality during the operation of a mine and its auxiliary facilities are water sampling, measurement of groundwater levels, geophysical measurements, remote sensing, monitoring of storage tanks and pipeline, monitoring of solid and liquid waste-disposal areas, and maintenance of material balances.

Water Sampling

SAMPLING POINTS.

1. Monitor wells—These may be specially constructed or may be existing wells converted to use as monitor wells. A monitor well may be pumped or unpumped. An unpumped well samples only the water that passes directly through the well bore. A pumped monitor well produces an integrated sample from an area whose size depends on the local geohydrology and the rate of pumping.
2. Water supplies—Samples of groundwater pumped for water supply can be periodically taken and analyzed to detect quality changes. Such samples are representative of the well or wells in the system and the area or areas of influence.
3. Springs—Since springs are outlet areas for groundwater, samples taken from them are similar to ones from pumped wells, in that they reflect the quality of water within an area of influence.
4. Streams—Because many streams derive most of their flow from groundwater drainage for a substantial part of each year, samples from gaining streams can be used to measure groundwater quality. Similarly, samples from losing streams can yield

information on pollution entering the groundwater from surface water sources. A gaining stream might be thought of as representing the composite quality of a number of springs.

LOCATION OF SAMPLING POINTS. As LeGrand (1968) has stated, haphazard plans for the location of monitoring sites are almost certain to result in excessive cost and to fail in their objective. He further points out that such sites must be located on the basis of the hydrogeologic framework, and provides some useful general guidelines for planning their location. Rouse (1974) also comments on the need for designing an observation well system based on site geology and hydrology, rather than routinely placing such wells in a circle around the operation to be monitored. The concept of using modeling methods for optimizing the location of monitoring points has previously been discussed.

FREQUENCY OF SAMPLING. Under natural conditions the quality of groundwater will typically change imperceptibly with time. Rates of change are related to rates of flow, which in turn are governed by the hydrogeologic situation. Some groundwater basins unaffected by man show annual fluctuations in quality produced by seasonal variations in recharge, level changes, and discharge.

The influences of man can and do cause significant changes in groundwater quality. Two common effects are an increase in amplitude of annual changes in quality and a progressive deterioration in quality over a period of many years.

The frequency of monitoring groundwater quality depends upon its sensitivity to natural and manmade influences. For effluent wastes to the ground which are subject to rapid changes in composition, continuous, daily or weekly sampling may be appropriate. To characterize changes which might occur annually in groundwater, a bimonthly or quarterly frequency should be adequate. In general where prior background information is insufficient to define periodic changes, a surveillance program should include at least two years of observation at this frequency. Thereafter, the frequency can be reduced to monitor long-term rates of change of various constituents, but probably not less than semiannually.

Monitoring near or downstream from a known pollution source may require a frequency of the order of semimonthly, monthly, or bimonthly. Monitoring of groundwater flowing toward wells or being pumped from wells should be conducted perhaps semiannually, while background quality control sites for groundwater basins may be as infrequent as annually. Wherever and whenever a pollution hazard develops, such as a toxic constituent affecting an underground water supply source, the frequency of monitoring must be increased in accordance with the importance or seriousness of the situation.

POLLUTANTS MONITORED. Groundwater quality monitoring should focus on specific pollutants because of their hazard, persistence, concentration, ease of identification, or other characteristic features. In the case of most mining activities, the specific pollutants that may be present can be identified through knowledge of the source. Many of the pollutants that will be found associated with particular types of mining activities have been discussed in Section VI, Mining Hydrology and Groundwater Pollution.

Groundwater Levels

Although measurement of groundwater levels does not provide quality data directly, it can yield valuable indirect information. From a map of water-level contours, the groundwater flow pattern of a region can be defined. This will show the areas of groundwater recharge and their relation to possible pollution sources. Changes with time of flow patterns due to mining activities may be apparent so that the influence of pollution sources as well as the location of polluted groundwater areas may be shown by such maps.

Geophysical Measurements

Geophysical measurements made in bore holes or on the ground surface can provide valuable supplementary information in a monitoring program. A wide variety of bore hole logging methods have been developed. Keys and MacCary (1971) provide an extensive discussion of the use of bore-hole geophysics in water-resource investigations.

Bore-hole geophysical devices may be designed to examine only the fluids in the bore hole or to examine a volume of the aquifer around the bore hole. Two fluid properties that are directly measured in the bore hole are temperature and conductivity. Two aquifer properties that are commonly measured are conductivity (resistivity) and natural radioactivity. The conductivity and radioactivity of the aquifer water contributes to the overall reading, and changes in the conductivity or radioactivity of the water can thus be detected, even though the instruments are viewing a section of the aquifer rather than the water alone.

Of the surface geophysical methods, electrical resistivity surveying is the most useful for groundwater quality studies. Many types of pollutants will increase the conductivity of groundwater and, under favorable circumstances, such changes may be detected by resistivity surveying. Merkel (1972) describes the use of electrical resistivity surveys to delineate groundwater pollution from acid mine drainage. A number of other publications discuss the use of electrical resistivity to detect groundwater pollution from other sources, principally sanitary landfills. Barr (1973) reported on the feasibility of using seismic reflection for monitoring the distribution of wastes in the vicinity of industrial injection wells. Because of the small contrasts in seismic reflectivity of wastewater as compared with formation water that will exist in most cases of groundwater pollution, seismic techniques probably offer very limited monitoring potential.

Remote Sensing

Remote sensing is the technology of remotely collecting and interpreting data generated by electromagnetic energy from the earth's surface and near surface. This definition includes conventional black and white photography as well as the many newer methods that utilize other parts of the electromagnetic specturm. Barr and James (1973) summarized many of the uses of remote sensing including aerial monitoring of surface-water quality. Monitoring of groundwater quality will probably be, in most cases, indirect. In an example of the use of remote sensing for mining problems, Ahmad (1973) described the use of satellite imagery for study of strip-mined areas in Ohio. Remote sensing has been widely used for agricultural studies and has been found useful for detection of drainage and salinity problems (Meyers and others, 1963). This suggests the use of remote sensing for indirectly inferring groundwater quality problems based on soil conditions and on the response of vegetation to changes in groundwater quality.

Monitoring of Storage Tanks and Pipelines

Storage tanks and pipelines associated with mining operations are potential pollution sources and should be routinely inspected for leaks. Pressure testing of tanks and pipelines would be an additional monitoring method.

Monitoring of Solid and Liquid Waste Disposal Areas

Some examples of groundwater pollution problems associated with the solid and liquid waste-disposal areas of mining operations have been mentioned previously. Such areas should be designed to prevent water pollution to begin with; but nevertheless, waste-disposal sites require periodic inspection. For example, the lining of a waste storage pond or the dike around a solid waste storage area could fail, thus releasing polluted water to the environment.

Maintenance of Material Balances

In mining by leaching, chemical solvents are introduced into mines, ore heaps, and mine dumps, as has been previously discussed. The maintenance of an accurate material balance of introduced versus recovered chemicals would provide a means of quantitatively determining the amount of pollutants lost to the environment. The detection of such losses might also point to the existence of groundwater pollution before it could be detected by other monitoring means. Material balances could also be used for tailings ponds and evaporation basins to detect seepage losses.

POST-OPERATIONAL MONITORING

One characteristic of mining operations that distinguishes them from many other industrial operations is the fact that some mines and waste disposal areas will continue to be pollution sources long after the mines and processing plants have closed. In fact, some will be pollution sources indefinitely; that is, for geologic time. Sources of this type will obviously require a monitoring philosophy different from that applied to sources with finite lives. The range of possible schemes is great; but, in general, the procedure would be to identify the source, to predict the rate of production and distribution to pollutants, and then to periodically verify the predictions. Such a procedure would provide continually updated information on the location and intensity of pollution for use in groundwater management.

SECTION IX
LAWS AND REGULATIONS

There are a variety of different statutory means by which the States and the Federal government can control water pollution from mining activities. Water resources are directly protected by water pollution control laws. In addition, there are provisions in a variety of other laws, such as surface mine reclamation laws that may contribute to water quality protection.

All States and the Federal government have water pollution control laws that can be used directly, in one way or another, to control water pollution from mines and mineral preparation plants. However, major differences between mines and the usual industrial plants exist which require special consideration. Such differences include the fact that, for effective pollution control, planning must often begin during the location and design of the mine. Another important difference is the fact that pollution may continue after abandonment of a mine. Only two States, Pennsylvania and West Virginia, are known to formally recognize the need for advance planning by requiring a permit be obtained prior to the initiation of underground mining. In most other cases, it would only be necessary for a mining company to obtain a permit when it became apparent that there was a polluted discharge. Also, the requirement for a permit before opening of an underground mine allows an opportunity for denial of a permit if it appears impossible to effectively control water pollution after abandonment by some at-source technique such as flooding. Control of water pollution from mining on Federal land can be effected through the State, directly by the Federal agency having jurisdiction, or both. However, in the case of mines developed under the general mining law of 1872 there is probably no way of influencing the mining process or requiring site restoration upon abandonment.

The main concern of surface mine reclamation laws is not water pollution control and the enforcement agencies are not viewed as water pollution control agencies. However, an important secondary consideration in such laws, whether expressed or implied, is water pollution control. At least 22 States have reclamation laws, including all of the major coal-producing States. In many cases, the laws or the regulations developed to complement them require a complete mining and reclamation plan to be specified prior to issuance of a permit. In some cases it is possible for a State to deny a permit if the environmental effects of mining are judged to be too great. A Federal surface mining law was recommended in 1965 (U.S. Department of the Interior, 1965), but as of the date of this report such a law has not yet been passed. In the meantime, surface mining on Federal land is subject to regulation except for mining done on claims acquired under the general mining law of 1872, which has no provisions for environmental control.

The National Environmental Policy Act of 1969 has proven to be a very important means of identifying the potential environmental impact of proposed mining operations on Federal land. When such impacts are identified, then it is possible for the agency with authority to specify the necessary controls for minimizing those impacts as a provision of the lease. Several examples of such impact statements are included in the reference list. Unfortunately, mining claims developed under the general mining law of 1872 are not subject to the provisions of the National Environmental Policy Act.

SECTION X

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16. ABSTRACT

Analyzes and documents the rationale and related methodology for monitoring groundwater pollution caused by mining and mineral processing. Notes that some mines and waste-disposal areas will continue to be pollution sources long after the mines have closed, and that because of the broad range of mining activities and diversity of geologic and hydrologic settings, monitoring programs for mineral operations must be individually considered. Reviews technology for at-source control of water pollution from mining and points out that some methods used to improve surface water quality may cause deterioration in groundwater quality. Discusses existing State and Federal laws and regulations for control of mine drainage pollution and the inability of most to influence the design, permitting, or abandonment of underground mines on the basis of water pollution considerations.

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