GROUND-WATER REACTIONS TO SURFACE COAL MINING IN SEMIARID LANDS

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ABSTRACT

Coal beds that will be mined in southeastern Montana are aquifers that provide essential local water supplies. Mine cuts along aquifer outcrops create almost imperceptible piezometric changes. Mine cuts between outcrops induce rapid storage depletion and associated piezometric depressions. One such cut near Decker induced 1250 m^3/day of flow from storage and has created a piezometric depression of 5 m or more as far as 4000 m from the mine. Effluents from active mines are chemically similar to other area waters because they are mixtures of ground waters entering the mine cuts. Occasional high concentrations of nitrate do occur, however, as residuals from explosives.

Spoils commonly contain mine-floor aquifers of wasted coal and coarse rubble at their bases, confirmed beneath finer-grained sand, silt, and clay. Hydraulic conductivities are comparable with those of undisturbe confined aquifers. Water quality in mined lands is highly diverse because of diverse spoils lithologies and poorly established ground-water circulation. Ground water in spoils is more mineralized than in the coal beds; post-mining dissolved solids concentrations are 2- to 3-fold increases over pre-mining concentrations.

Before-mining predictions of post-mining ground-water quality are very rough, at the present time relying upon saturated-paste analyses to determine available volumes and species of soluble salts. Efforts to improve the predictions by using column leach tests have not been very successful. Geochemical equilibrium between spoils and ground water apparently does not become established in the early years after mining.

INTRODUCTION

More than 13.3 billion metric tons of subbituminous coal are present within Montana's portion of the Fort Union Coal Region (Matson and Blumer, 1974). The region occupies the northern end of the Powder

River structural basin (Figure 1). Twenty-six coal beds have been identified there, having thicknesses between 1 meter and 25 meters. The coals are lignite with heating values less than 4,600 kcal/kg (kilocalories per kilogram), and subbituminous with heating values between 4,600 kcal/kg and 5,500 kcal/kg. Thus far, the subbituminous beds have been the primary objects of development because of thickness, areal persistence, low-sulfur content (generally less than 1 percent), and shallow depth. Matson and Blumer estimated that the strippable subbituminous reserves underlie an area of approximately 123,000 hectares. Their figures do not include additional but less known reserves under the Northern Cheyenne and Crow Indian Reservations.

Coal has been mined in the region by individuals and small concerns for many years. Most of these operations were underground mines, and have had little noticeable effect on the land. Larger scale surface mining has now come to the subbituminous fields. Since 1968, six surface mines have been opened; numerous others are in planning stages. Production is currently more than 30 million metric tons per year.

Energy is not the only resource that southeastern Montana coal provides The coal beds are the most accessible and widely used aquifers of the region; they are extensively fractured and have significant areal continuity. In this semi-arid climate, many residents are almost totally

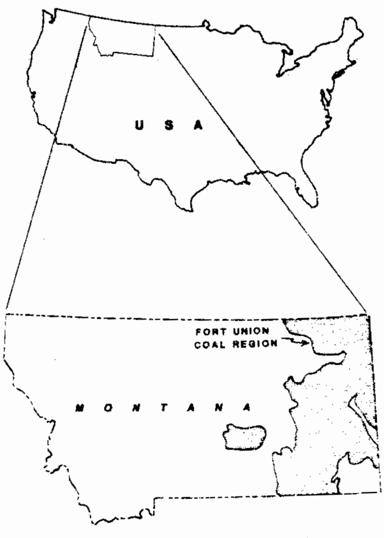

Figure 1. Index map showing location of the Fort Union coal region within Montana and the United States.

dependent upon ground water for stock and domestic supplies, and in many places they obtain it from coal beds that will be removed by mining. Concerns logically arise over the possible impacts of mining upon water supplies that are vital for agriculture.

The dual role of the coal as a source of both energy and water was realized by the Montana Bureau of Mines and Geology in 1971, shortly after the beginning of large-scale development. Since then, research into the hydrologic effects of surface mining has proceeded with the objectives of (a) determining pre-mining conditions; (b) determining hydrogeologic characteristics of mined land; and (c) developing techniques to assist planners, developers, and regulators in assessment and prediction of mining impacts.

Acknowledgements

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Physiography and Climate

The coal region of Montana lies within the High Plains physiographic province, and includes both gently rolling and rugged terrain. Land surface altitudes range from about 800 meters to about 1,500 meters above sea level. Local relief along watercourses is commonly 100 meters or more. Stream valleys tend to be long and narrow, in many places flanked by escarpments; minor watercourses are characteristically steep-sided gulches, locally known as coulees.

The area is semiarid; the climate is the continental steppe type, common to most of the northern Great Plains. Annual precipitation averages about 380 millimeters, most of which normally falls during spring and early summer. Mean annual temperature is about 7°C; temperatures exceeding 38° in summer and below -34° in winter are common.

Most streams of the region are ephemeral, flowing only during periods of snowmelt or heavy precipitation. Mean annual runoff reflects strong evapotranspirative demands, and is less than 15 millimeters in most small basins of the region (Ferreira, 1981). A correspondingly small (but not quantified) portion of the annual precipitation recharges the ground-water system, thereby becoming the life-blood of the region's agricultural community. Ranching (raising of livestock) is the traditional land use in the region, made possible only because of the presence of ground water, obtained from thousands of wells penetrating beds of sandstone and coal.

Hydrogeologic Conditions

The coal-bearing geologic unit in the region is the Tongue River Member of the Fort Union Formation, a sequence of fresh-water sand, silt, clay, and coal beds of early Tertiary (Paleocene) age. Of these, only the coal beds seem continuous over any appreciable distance. The cyclothem form of stratigraphy often ascribed to coal-bearing units is not apparent in the Tongue River Member (Figure 2). Silt and sand beds have little areal continuity and occur unpredictably in the geologic section. Clay beds persist over and beneath most coal beds, and strongly influence ground-water conditions by restricting vertical flow.

The Tongue River Member is the uppermost geologic unit over most of the region, and conditions of structure, stratigraphy, and topography expose two or more surface-mineable coal beds in many areas. The coal and sandstone beds are the only significant aquifers that can be economically utilized for domestic or livestock water supplies. Of these, the coal aquifers are the more preferred because of greater areal continuity and generally superior water quality.

HYDROLOGIC CHANGES CAUSED BY MINING

Mining-related impacts on ground water can be divided into two distinct categories: those related to active mining operations, and those which persist long after mining and reclamation operations have been completed. The first category (mining phase) includes decreases in springflow and well yields caused by hydrostatic-pressure declines, pit-inflow rates that can affect mining operations, and pit effluent rates and qualities that may be environmentally unacceptable. The

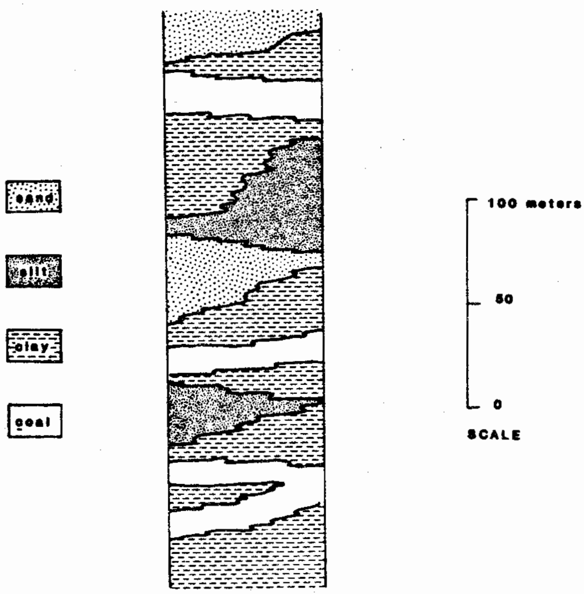

Figure 2. Example of stratigraphic relations in the coal-bearing unit of the Fort Union Formation.

second category (post-mining phase) includes ground-water availability from the mined lands, quality and flow rate of ground water in spoils (cast overburden), and off-site effects of the newly created systems.

Changes During Active Operations

Mine-inflow rates and associated water-level or hydrostatic-pressure declines are influenced greatly by the positions of mines within the ground-water flow system. Mine cuts beginning along aquifer outcrops stress the ground-water systems very slowly. Such pits gradually change aquifer boundaries, and associated hydrostatic-pressure changes are also gradual. Most inflows to those pits consist of intercepted ground water, and the inflow rates are generally negligible. The pits are expanded or repeated too slowly to induce significant flow rates from ground-water storage. Hydrostatic-pressure declines associated with such gradual releases from storage are also very gradual and commonly are not perceptible in wells more than about 500 meters from the mines. Active pits at most Montana mines are examples of this gradual outcrop displacement, and create almost imperceptively gradual hydrogeologic effects (Van Voast and Hedges, 1978). Inflow rates generally are so low that most cuts are dried by evaporation, and water levels in nearby wells are not strongly affected by the extremely slow rates of storage depletion.

In contrast, one mine opened between the outcrops of a coalbed aquifer created relatively rapid and dynamic changes in the ground-water system. The coalbed aquifer there has similar hydraulic conductivity to that of the coal in the rest of the region, but was first penetrated by mining about 1 km upgradient from its nearest outcrop. The first opening intercepted natural ground-water flow estimated to be 250 m^3/d (cubic meters per day) and induced inflow of additional ground water from storage at an estimated maximum rate of about 1250 m^3/d. Water levels in observation wells declined dramatically with this rapid removal of water from storage (Figure 3). During the first year of mining, a drawdown cone developed with declines of 3 m or more as far as 1500 m from the mine. Currently after 13 years of operation, declines exceed 5 m as far as 4000 m from the mine, and the depressed piezometric surface has merged with a similar depression created by a mine 3000 m away. This merging of areas of piezometric depression beneath a reservoir (Figure 3) attests to the low permeability of clay beds overlying the coal. Fortunately, to date, only a few domestic and stock wells penetrate that aquifer close enough to the mine to be seriously affected.

The chemical qualities of effluents pumped from active mines were originally thought to be a potential problem in this region, but have not proven to be of environmental concern. The effluents are mixtures of waters from aquifers penetrated by the mine cuts and are not chemically different from ground water that discharges naturally to the land surface. About the only notable chemical difference between mine effluent and local ground water is the occurrence of occasional abnormally high nitrate concentrations in effluents. The condition has been observed at several mines (Van Voast and Hedges, 1978) where temporary concentrations as great as 25 milligrams per liter (as N) have been detected. The nitrates are probably dissolved residuals from ammonium-nitrate explosives used in blasting coal and overburden.

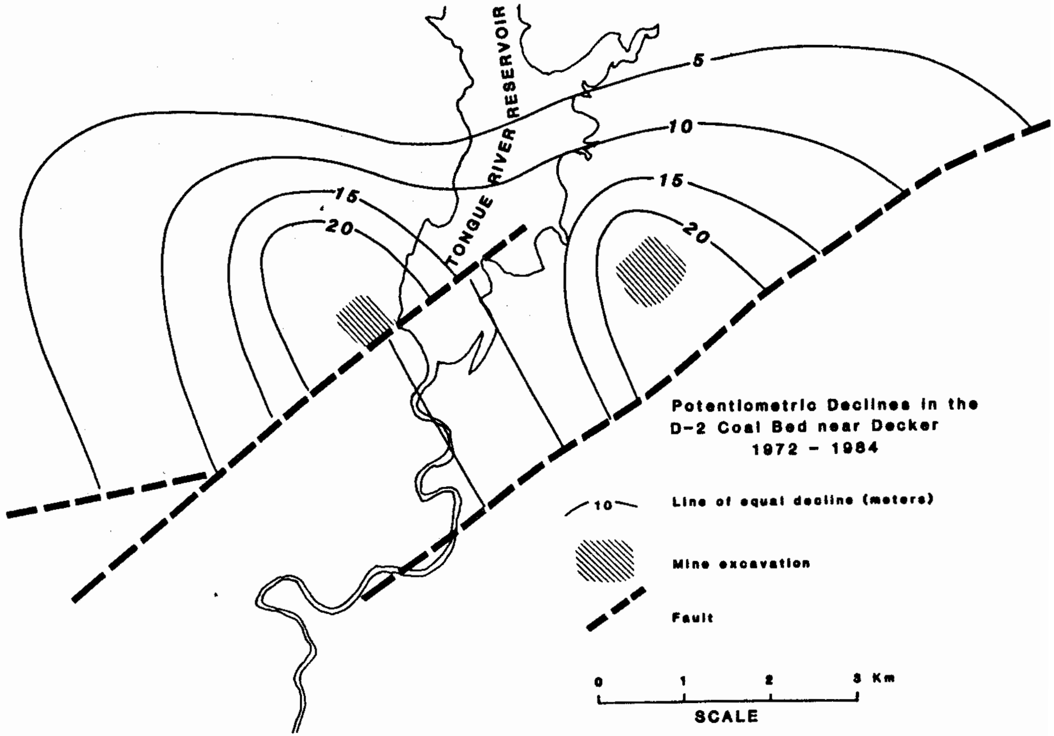

Figure 3. Potentiometric declines after 12 years of mining near Decker, Montana.

Because of short duration and infrequent occurrence, the high nitrate concentrations probably create little increase in average concentrations in the effluents or the receiving streams.

Post-Mining Hydrologic Conditions

Of particular importance in determining post-mining conditions is the relation of hydrologic and geochemical characteristics of mine spoils to those of the pre-existing undisturbed aquifers. Here we are evaluating hydrogeology of abandoned lands before they are actually abandoned. Field tests to determine hydraulic conductivities (water-transmitting capabilities) of spoils and undisturbed aquifers have been conducted by the Montana Bureau of Mines and Geology at five active mine areas. Coal beds in all of the areas have wide ranges of hydraulic conductivity. Statistical comparisons (Figure 4), assuming log-normal distributions of values, suggest that hydraulic conductivities in mined lands are highly variable but not dissimilar to those of the pre-existing systems (Figure 4). The lower mean value for hydraulic conductivity shown for the Decker area on Figure 4 results from the presence of sodic clays in the spoils there, and their expansion upon saturation. Examinations

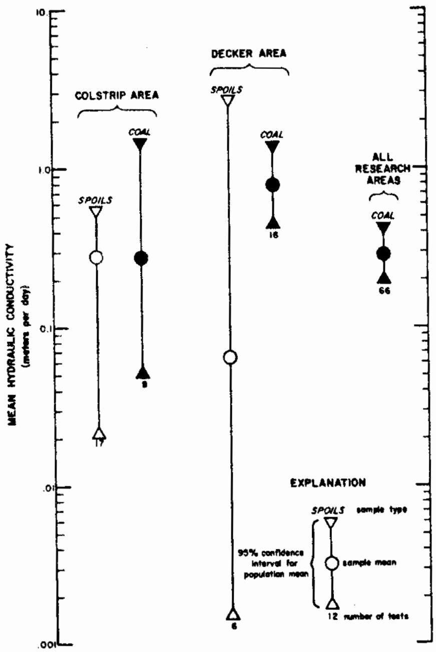

Figure 4. Hydraulic-conductivity ranges and means for coal and mine spoils in southeastern Montana.

of stripping operations and mine floors in all areas indicates that the greatest hydraulic conductivities occur at the bases of spoils, where rubble consisting of rocks and wasted coal has been covered by finer-grained spoils materials (clay, silt and sand). This creation of a "mine-floor" aquifer (Figure 5) is an accidental but highly beneficial result of surface mining.

Chemical quality of ground water in mine spoils is by far the most complex aspect of the post-mining systems. Because of the replacement of organic aquifer material (coal) by clay, silt, and sand, different chemical concentrations are found in post-mining ground waters. Acid production, a condition commonly associated with coal mine waters, does not occur in mine effluents or spoils waters in southeastern Montana because of the geochemical nature of the coal and overburden. Sulfur-oxidizing bacteria, *Thiobacillus ferrooxidans*, have been detected by Olson and McFeters (1978) in these mining environments, but the acid they produce is quickly neutralized by the ample carbonate and bicarbonate in the system.

Post-mining ground water in this region ranges from neutral to alkaline, and in almost all cases contains substantially higher concentrations of dissolved solids than do ground waters in undisturbed aquifers. Dissolved-solids concentrations in coal-bed aquifers average about 1750 mg/L (milligrams per liter); at 3 mines where representative data are available, dissolved-solids concentrations in spoils waters average 2880 mg/L, 3660 mg/L, and 2470 mg/L. At mines in the neighboring state of North Dakota, 2- to 3-fold increases in dissolved solids have been found in spoils waters (Groenewold and others, 1983), supporting the

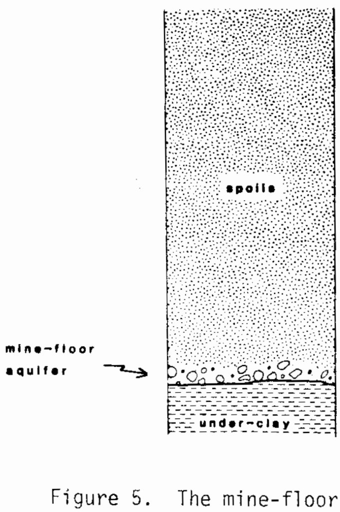

Figure 5. The mine-floor aquifer, formed by rubble and wasted coal.

Montana findings. Specific constituents that comprise most of the increases are sodium, magnesium, and sulfate. In some cases the changes in water quality do not effect the useability of the ground waters; in others the concentrations are so high as to preclude useability for any purpose.

Although the generalities described above are applicable, the evolution and fate of post-mining ground-water quality are poorly understood. The extreme areal diversity of chemical concentrations in any one mined land defies characterization. The temporal variability of spoils-water quality further complicates any description of post-mining conditions, probably for several reasons. Saturated thicknesses of spoils in some of the mine areas have not yet attained equilibrium; the changing water levels vary the availability of salts for solution. Complete circulation of ground water through the mined lands has not yet occurred, so water qualities still reflect the distributions of readily available salts in the spoils aquifers. Because mine-floor aquifers are the most transmissive spoils materials, water-quality samples from many research wells probably reflect aquifer chemistry at the mine floors more than that in the overlying spoils.

SOURCES OF SALTS FOR DISSOLUTION

Leaching tests in the laboratory and observations in the field show that the predominant cause for high dissolved-solids contents in mine spoils waters is the ready availability of highly soluble salts in the coal overburden. The salts are products of weathering and oxidation, and are primarily calcium, magnesium, and sodium sulfates. Sulfate is abundant in the coal overburden as an oxidation product of pyrite and marcasite. Sodium and magnesium appear to be derived from montmorillonitic and chloritic clays, respectively. Additional magnesium may be released from dolomite, and calcium is released from calcite. In this semi-arid region, percolation of recharge water to the ground-water system occurs only occasionally at most locales. At some observation wells, no local recharge has been observed over 14 years of record; at others, recharge has been evident only during occasional periods of unusually high snowmelt or springtime precipitation. Evapotranspirative demands are such that optimum conditions are required to allow percolating water to penetrate below the root zone, and in most locations those conditions rarely occur. Weathering and oxidation products of minerals therefore are not mobilized and flushed from the profile as they would be under conditions of more active recharge.

In the undisturbed (pre-mining) system, soluble salts accumulate at various depths in the overburden profiles. Their depths of accumulation are established by the depths and rates of deep percolation of recharge waters. Figure 6(a) demonstrates an overburden profile where unusually deep percolation occurs. The steady increase in soluble salt content with increasing depth occurs because rates of formation of soluble salts exceed the rates of removal by lateral ground-water flow. Figure 6(b) represents conditions where only shallow percolation occurs. Again, rates of formation of soluble salts at or near land surface far exceed rates of removal. These two examples only demonstrate the great variability of available salt content in overburden profiles. A more detailed discussion of these and other conditions

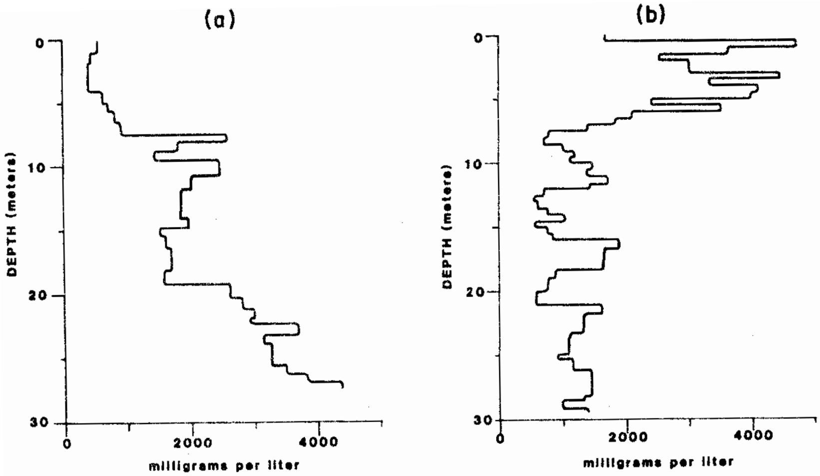

Figure 6. Examples of soluble salt concentrations in coal overburden.

are provided by Moran and others (1978) from their work in North Dakota.

Soluble-salt distribution such as shown on Figure 6 are known for all mine areas in Montana, these data being required for reclamation planning. Unfortunately, the current practice is to bury materials with high salt content as deeply as possible to enhance revegetation. Once buried and resaturated, such materials create the greatest degradation of ground-water quality. Knowledge of their locations in the spoil profiles, and knowledge of the salt species and potential concentrations do, however, enable rough predictions of chemical qualities of post-mining ground waters and their potential off-site effects.

PREDICTIONS OF SPOILS-WATER QUALITY

Before-mining predictions of probable post-mining water quality are required under regulations in the permitting phase of surface-mine development. Leaching experiments conducted on overburden or spoils using columns or batch reaction vessels have been used to provide indications of the availability of salts that might influence post-mining ground-water quality. However, such experiments are expensive and slow.

An alternative approach has been the use of saturated-paste extract chemistry by standard techniques developed by the U.S. Department of Agriculture (U.S. Salinity Laboratory staff, 1954). The analyses are currently required by Montana and other western states during pre-mining planning for revegetation purposes; application of the data to hydrologic studies has been an additional benefit. The paste-extract data is often used for water-quality predictions, but give only the roughest of approximations of average concentrations that might be expected in a given mine area. Chemical concentrations in paste extracts are similar to the average concentrations in first pore volumes of leachates (Van Voast and others, 1978).

To consider conservation of mass as ground water re-enters mined lands (lateral flow only), leach columns have been modified by emplacing specific-conductance probes at incremental distances along the leach paths. Results consistently show distributions of dissolved solids that can be approximated by the type curve and equations shown on Figure 7. The equation, $C/C_0=e^{-kn}$, is a basic first-order dissolution equation (Lerman, 1979, p. 233, for example) in which C is the concentration at any point along the flow path; C_0 is the maximum (and first) concentration measured at the end of a flow path; k is a constant; and n is the number of pore volumes of water that have passed any point (ΔD) along the flow path.

The distribution curve shown in Figure 7 applies best to sodium, magnesium, and sulfate concentrations because they are least limited by solubility constraints. These ions also contribute the bulk of dissolved solids in spoils waters and generally account for abnormally high concentrations that are of greatest concern.

The distribution curve suggests that, under conditions of lateral flow only, highest concentrations in mined-land ground water should be found farthest down gradient, and that some compensation for vertical

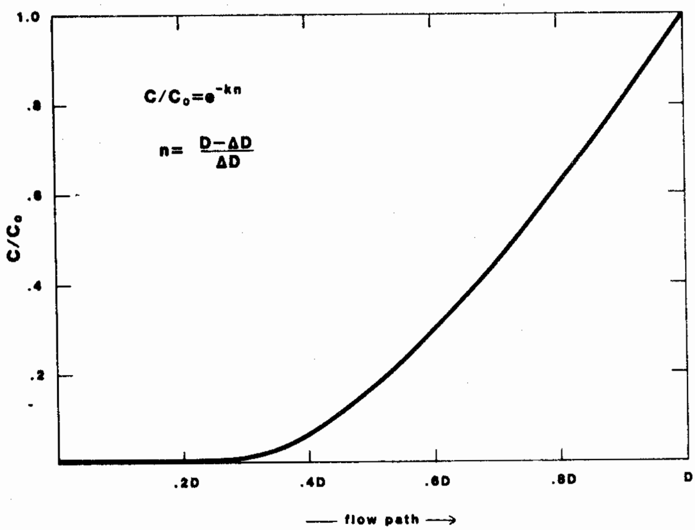

Figure 7. Idealized distribution of soluble ion concentrations behind a wetting front.

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recharge could be made by mass balance along the flow path. Unfortunately, this model developed from leach columns is not supported by field data. There are suggestions of verification at a few selected sites in southeastern Montana mines, but even these are tenuous. Without doubt, Figure 7 is an over-simplification of extremely complex conditions, although it remains to be seen whether better application might be found with older mined lands where hydrologic and geochemical equilibria are better established.

SUMMARY

Mining of subbituminous coal in southeastern Montana has accelerated since 1968 to a current annual production of 30 million tons. Climate of the area is semiarid, so agricultural enterprises there are reliant upon wells and springs for stock and household water supplies. Many of the coal beds destined for mining are also aquifers that supply vital ground-water.

Ground-water levels near mines along aquifer outcrops do not change substantially during mining. In contrast, a mine penetrating a more central part of an aquifer has thus far caused potentiometric declines exceeding 5 meters over a distance of 4 kilometers from the excavations. Chemical quality of effluents is not different from that of ground water native to the region, so they create no environmental problems.

As backfilling follows coal removal, ground water re-enters spoils at the mines. Greatest resaturation has thus far occurred where nearby sources of recharge by lateral flow are available. Hydraulic conductivity has been found to be statistically similar for mine spoils and for coal beds. Much ground-water flow in spoils occurs along "mine-floor" aquifers where a variable thickness of wasted coal and coarse rubble have been covered by finer-grained materials. Evidence is very strong that mine spoils do not act as barriers to ground-water flow, and in some places can provide adequate quantities of water for stock or domestic use.

Quality of mined-land ground water is very diverse. Cations (calcium, magnesium, and sodium) and anions (sulfate and bicarbonate) occur over a wide range of concentrations and ratios; chloride concentrations are minor compared with those of other ions. Extreme variability of water quality within mined areas is probably caused by the following factors: 1) variability of saturated thicknesses; 2) insufficient time for establishment of complete circulation of ground water; and 3) complex distribution of soluble salts in the spoil materials. In all cases, however, mined-land ground waters are substantially more highly mineralized than ground waters from undisturbed aquifers. Two- to three-fold increases in dissolved solids occur as ground waters re-enter the mined lands of this region.

Leaching experiments conducted with spoils produce water of similar quality to that found in the field. Recession curves of specific conductance measured *in situ* along flow paths in leach columns allow idealized modeling of salinity distributions, but they cannot be applied satisfactorily to available field data. Mined-land ground-water conditions, at least in the early years after mining, have not approached a geochemical equilibrium that can be addressed by models.