Mine Drainage Pollution Prevention and Abatement Using Hydrogeological and Geochemical Systems

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Introduction

The potential significance and need for specific research demonstrations are outlined. Appropriate demonstrations should control and abate mine drainage using naturally occurring hydrogeological and geochemical systems that are repetitious and widely distributed in the bituminous coal regions of western Pennsylvania and elsewhere. Some of these same systems also occur in the anthracite region of Pennsylvania and other coal fields throughout the world. These natural systems must be recognized and defined in active and abandoned mining districts so that they may be relied upon and included in engineering design to control and abate mine drainage where conditions are suitable. Failure to use natural systems for treatment and abatement of mine waters inevitably will lead to the adoption of more costly treatment procedures such as the use of treatment plants where construction and annual operating costs can be high. Recent estimates indicate that treatment costs may range from $0.05 to $1.25 per 1,000 gallons depending upon the quality of mine water involved and quality standards set for the watershed. The lower figure is for water with about 2 to 3 ppm of iron and up to 20 ppm of acidity, the upper figure for water with 500 to 700 ppm iron and 2,000 to 5,000 ppm acidity (Parizek, 1971). These figures need not include collection and pumping costs nor the cost of disposing of chemical waste byproducts. An average figure frequently cited today is $.40 per 1,000 gallons for water with 100 ppm iron, 500 ppm acidity and using a hydrated line method of treatment.

Harold Lovell, Head of Mine Drainage Research Section, The Pennsylvania State University (personal citation) considers these figures as conservative. In his opinion reported figures tend to underestimate treatment costs because taxes, depreciation, amortization, and maintenance figures, sludge disposal costs, etc., are not always included, hence the coal industry is actually paying more for treatment than attributed (Parizek, 1971).

According to Pennsylvania Department of Environmental Resources estimates, more than 4.5 billion gallons of coal mine drainage is produced in

Pennsylvania alone each day, and contrary to popular opinion, mining activity is on the increase. The cost of treating these mine waters will be horrendous and must be borne by the coal industry, by direct and indirect users of coal, water users in the watershed, and by taxpayers in cases where mines have long since been abandoned. Treatment costs also will depend upon the strength of existing laws, enforcement, and mine-drainage abatement laws still forthcoming.

The economics involved together with the vast volume of mine water which must be dealt with make it obvious that collection and treatment of mine drainage will not always offer the most practical method of solving the mine drainage pollution problem. Treatment plants are costly to construct and would have to be operated and maintained for often an unknown but very long period (one or more generations) at considerable expense until a more permanent solution is achieved. Treatment plants are a logical solution where (1) the reclaimed water is to be reused directly hence there is an immediate economic return, (2) the treatment is to be short-termed as during mining, (3) there are no suitable alternatives, or (4) there is a premium set on high quality water within the watershed.

It is clear that no one abatement or treatment scheme will suffice. Rather, a variety of techniques will have to be employed which are designed around local circumstances, needs, and know how (Parizek, 1971, p. 1). Natural hydrogeological and geochemical systems may be engineered to help prevent, treat and abate mine drainage. However, for corrective action such as back-filling, deep mine sealing, hydraulic isolation, etc. to be effective in preventing or treating mine drainage, engineering works must be designed with these natural systems in mind and after detailed hydrologic, geologic and geochemical data have been collected and analyzed for each mine or region under study.

Use of Physical Hydrogeologic Principles

Downdip Mining:

It was common practice in Pennsylvania and elsewhere to mine coal updip where possible to facilitate gravity drainage thereby greatly reducing pumping costs during mining. Today these same mines are often the most difficult to hydraulically seal and flood. For this reason, and to insure that flooding will be achieved after deep mines are abandoned, coal is being mined downdip with the realization that pumping costs will be greater during mining but, that in the end, flooding will be automatic after pumps are removed (Fig. 1). Coal operators will adopt this initially more expensive procedure only where it is obvious that they will be responsible for meeting stringent water quality standards both during mining and after mining is completed as is now required in Pennsylvania and where it is assured that mine flooding will be beneficial. Thompson and Emrich (1969) reported that present amendments to the 1965 Clean Streams Law broadens the powers of the Department of Environmental Resources to assure that pollution will neither result from active mines nor after mines

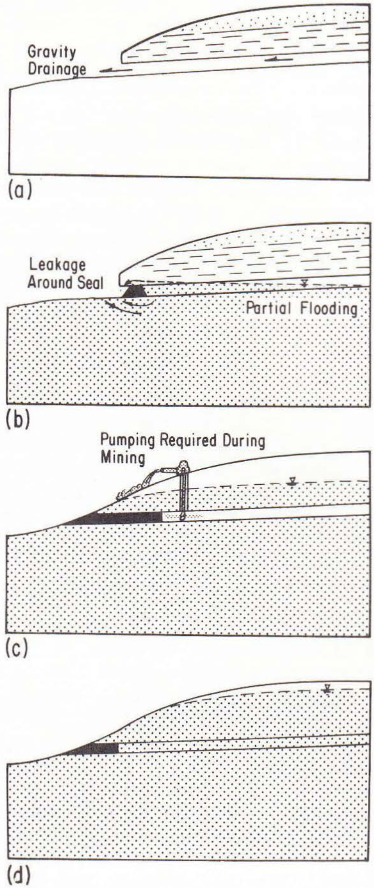

Figure 1. Deep mining of coal to provide free gravity drainage during mining (a) and partial flooding of mine after sealing (b). In (c) coal is mined downdip and requires pumping during mining but in (d) the mine floods completely when abandoned.

are abandoned. Their words of caution still apply. Namely "coal companies would be wise to carefully weigh the possible immediate cost advantage in mining on the rise (updip) against the obligation they will incur under the new law to prevent pollution after mining is completed. This obligation could conceivably mean the treatment of any discharges for an indefinite period of time."

The downdip method of mining example noted is an obvious case where a basic but simple hydrologic principle is exploited. The hydrogeologic data requirements necessary to evaluate the system involved to allow proper engineering design are limited and easy to establish in this case (see Thompson and Emrich, 1969). This need not be true for more complicated hydrogeologic and geochemical systems to be outlined later.

Control of Surface and Ground Water:

Lorenz (1962, pp. 21-26) reviewed the variety of schemes used to prevent surface water from entering the mine environment thereby minimizing the volume of water that will become contaminated. The merits of these practices are obvious because it is often possible to divert water using simple gravity drainage systems. Once interceptor trenches, gravity drains etc., have been constructed they will continue to function for years to come often with little or no maintenance. Diversion structures other than trenches, ditches, earth embankments etc., must be built to last for a number of generations or at least until the quality of mine drainage improves sufficiently to be of no further concern. Liners on stream channels, wooden sluice-boxes, canals and the like have all been used for these purposes during mining but cases might be cited where original structures have been damaged or destroyed by floods, or have deteriorated with time. Most were designed to serve their purpose for the short term and can easily be redesigned and replaced with facilities that will have a prolonged life.

One system which holds great promise, but which has seen little adoption, is the use of water wells to intercept and control ground water in overlying or underlying source beds that supply leakage to deep mines (Dutcher, et al., 1967; Parizek, 1970; Ahmad, 1970; and Parizek, 1971). Significant volumes of water can be prevented from entering the deep mine environment and becoming contaminated using this technique provided that certain hydrogeologic conditions are met.

Wells are drilled into source beds located above the mine (Fig. 2a), or where deep mines are located in ground-water discharge areas, in source beds below the mine (Fig. 2b). The mine serves as a free drain to water moving downward through roof rock for the case illustrated in Figure 2a, and to waters moving both up and down as shown in Figure 2b. A significant percent of the water derived from overlying source beds can be controlled under favorable circumstances by reducing the hydraulic head difference (Δh), that is present between the source bed and the roof of the mine. The significance

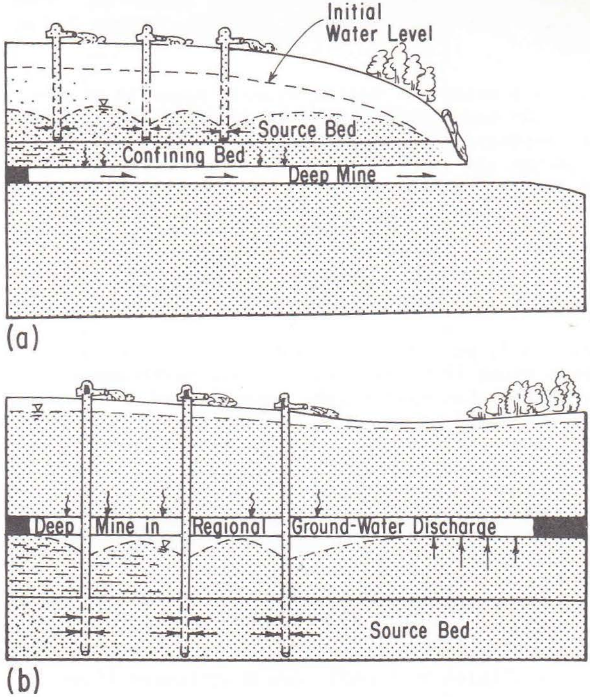

Figure 2. Wells used to control ground water in source beds located above deep mines (a) and in source beds below mines located in ground-water discharge areas.

of changes in Δh will be obvious by studying equation 1 which may be used to compute leakage through confining beds above the mine roof or below the mine floor.

$$Qc = \frac{P'\Delta h A_c}{m'} \tag{1}$$

where P' = coefficient of vertical permeability of the confining bed in gallons per day per square foot of mine roof (gpd/sq.ft.).

Qc = leakage through the confining bed in gallons per day (gpd).

m' = thickness of confining bed through which leakage occurs in feet.

A_c = area of mine roof or confining bed through which leakage occurs in square feet.

Δh = difference between the head in the aquifer or source bed and the mine roof or floor depending upon whether leakage is up or down to the mine.

A reduction in Δh by one-half will result in a reduction in the leakage rate by one-half provided that all other values in equation 1 remain the same. Normally it will not be possible to eliminate roof leakage entirely because it is not possible to dewater the overlying source bed completely. However, even a 50 to 80 percent reduction in vertical leakage would greatly reduce mine drainage treatment costs or might sufficiently reduce the pollution on a receiving body of water to make additional treatment unnecessary.

All upwelling ground water, on the other hand, could be eliminated entirely by controlling heads in the uppermost aquifer or source bed located below the mine. The potentiometric surface for the lower source bed has to be kept just below the level of the mine floor.

Data requirements and analytical techniques used to evaluate the potential of source bed dewatering schemes are more involved than schemes to divert surface water. They require the services of a trained hydrogeologist particularly to analyze complex hydrogeologic settings. However, costs of feasibility studies and dewatering projects can be kept to a minimum by combining where possible hydrogeologic studies with coal exploration programs.

Parizek (1971, pp. 4-25) lists the hydrogeologic data required to determine the feasibility of mine dewatering using wells, describes the methods and equations that can be used to determine aquifer and confining bed hydraulic properties, outlines hydrologic system analysis techniques required to predict drawdowns resulting from dewatering wells placed in complex hydrogeologic systems, and gives a cost estimate that may be required to pump 2.7 million gallons per day from two hypothetical mines.

It will not always be practical or economically feasible to control leakage into deep mines under all field conditions. Favorable hydrogeologic settings are required. Parizek (1971) gives examples of desirable and undesirable conditions.

Under some circumstances ground-water pumping costs can be greatly reduced or eliminated entirely. Wells can be used whereby water will drain from source beds under the influence of gravity (Fig. 3). These waters would be piped from the mine to prevent them from being contaminated within the mine environment. Where downdip mining is practiced, gravity derived waters can be conveyed by pipe to a central location where it can be pumped to surface. This eliminates the need for having a pump in each dewatering well.

It is apparent that a gravity well system might be suitable for some active mines but would not work in abandoned mines where it is dangerous or impossible to enter and lay pipe lines, provide connections with gravity wells etc., or where roof collapse is likely to disrupt collector lines. Under some circumstances the hydrogeologic system again can be exploited to get rid of source bed water using gravity wells. The system to be outlined normally would apply to controlling water in source beds overlying deep mines which are located in regional ground-water recharge areas. The technique was independently conceived by Ahmad (1970) and Parizek (1970).

Brown and Parizek (1971) showed for the Kylertown, Pennsylvania area that three separate water tables are present within rocks associated with deep mines developed in the Lower Kittanning "B" Coal of the Allegheny Series. The first and uppermost water table is within sandstones, siltstones, and shales overlying the Lower Kittanning "B" Coal particularly where mine roof breakage is not extensive. The maximum thickness of this upper system is approximately 100 feet. The second water table is, in part, within the Lower Kittanning "B" Coal mine where water is pooled on the mine floor and, in part, within underclays, siltstones, sandstones, shale or coal comprising the Clarion Formation of the Allegheny Series. The Clarion Formation immediately underlies the Lower Kittanning "B" Coal. The third water table is within the underlying more massive and extensive Connoquenessing Sandstone of the Pottsville Series.

The middle water table has resulted from deep mining and the fact that deep mines have never been flooded. The mines serve as free drains for water derived from mine roofs. The lower water table relates to the high permeability of the Connoquenessing and to the fact that the sandstone is exposed along deeply dissected valleys, and recharge rates to the Connoquenessing are restricted by the low permeability of shales, underclays, and siltstones that overlie the Connoquenessing Sandstone.

Although different rock types and different sequences of beds occur elsewhere in Pennsylvania and adjacent states a similar hydrogeologic setting involving two or more distinct water tables are known to occur in many other mining regions. These areas are ideal for controlling mine drainage using gravity wells. Wells can be drilled through all three water tables, the mine roof rock and mine opening. Casing and grouting of the mine roof rock and mine opening will be required to prevent (1) uncontaminated ground water from

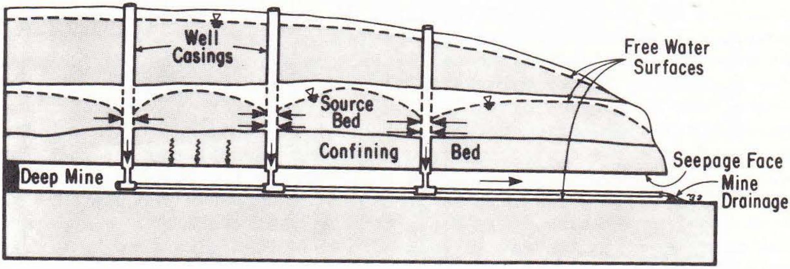

Figure 3. Gravity drainage wells used to dewater source beds above a deep mine. Wells are drilled from land surface and cased above the source beds. Water is piped from the mine to prevent contact with wall rock. (From R. R. Parizek, 1971)

entering the mine environment and (2) contaminated mine water from flowing down the wells and entering the underlying aquifer. By this scheme shallow source bed waters can be diverted past the mine into deeper aquifers without first being contaminated (Fig. 4). Double casings and grout also would be required to prevent corrosion of steel casing within the mine environment.

This system has many desirable aspects. (1) Potable ground water will not be contaminated but will still be available for later use from the deep aquifer system. (2) Gravity wells can be added to the system as required to control source bed waters as mining progresses. (3) Only the lowest source bed need be dewatered when two or more source beds overlie a deep mine. This would tend to protect shallow ground-water supplies which are widely used for domestic and farm purposes in mining districts. (4) Pump costs, maintenance, power, etc. would be eliminated. This would amount to a considerable savings because mine drainage abatement schemes may have to last for generations. (5) Source bed waters normally would not be contaminated by mine drainage, hence, the efficiency of the well system would not drop off in time due to precipitation of iron, etc. on the well bore-aquifer interface. Air would be excluded from the system and iron and other mineral species contained in ground water naturally would tend to remain in the reduced state and would not cause plugging problems as ground water enters and moves through the lower aquifer system. (6) At any time in the future that a consistent need for water developed equal in volume to the yield of one or more gravity wells, selected wells could be plugged below the source bed and used to provide water. If a greater volume of water were required and both the source bed and receiving aquifer contained favorable quality and quantities of water, a pump could be set in the gravity well directly and both aquifers pumped. State and federal regulatory agencies undoubtedly would prefer a gravity well exchange system involving potable ground water as outlined over one in which mine drainage is injected into deep aquifers containing poor quality ground water. However, even mine drainage could be disposed of in this manner provided that mine waters could be maintained in a reduced state and a suitable hydrogeologic system were present. A gravity disposal system has a distinct advantage over others where waters have to be injected into aquifers under artificially induced pressures. However, whether source bed waters or mine waters were to be disposed of in this manner, both a regional recharge area and deep aquifer system would have to be present for the system to work.

Recharge areas are easy to define provided that several bore holes are available and are cased to different depths. The deeper the hole and the longer the well casing the deeper the water level will be for recharge areas. Figure 5 shows an example of a well where a number of potentiometers have been set to different depths and the interval between the potentiometers grouted to prevent vertical leakage. Figure 6 shows the water level variations noted in each potentiometer. Nearly a 230 foot head difference was recorded between potentiometer C and H. Flow is downward at this site and the region is ideally suited for a gravity well system.

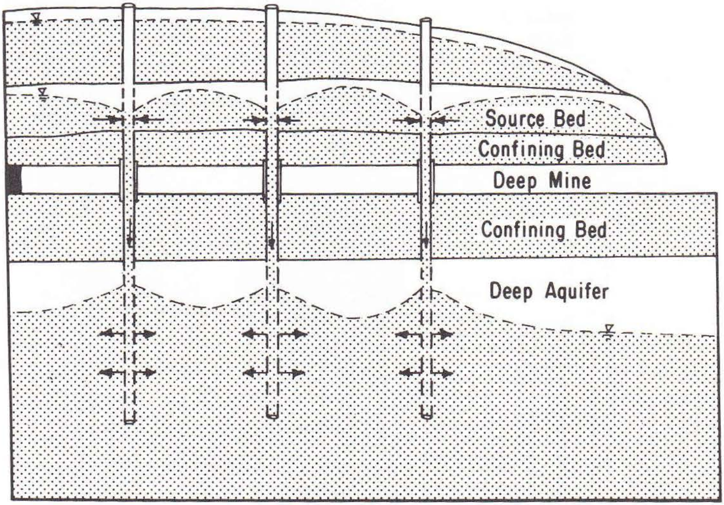

Figure 4. Gravity drainage wells used to dewater source beds above deep mines located in regional ground-water recharge areas. Three distinct water tables are shown which commonly occur in western Pennsylvania where less permeable coal bearing strata overlie more massive and permeable aquifers which serve as regional underdrains. The same system would work if there was but one water table provided that ground-water flow is downward.

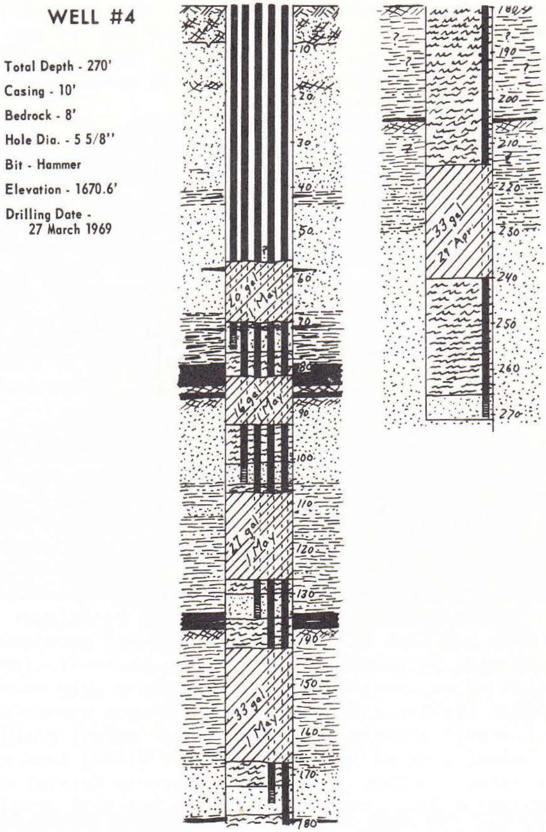

Figure 5. Lithologic log and potentiometer settings for Well 4 near Kylertown, Pennsylvania. (After R. L. Brown and R. R. Parizek, 1971, p. 144)

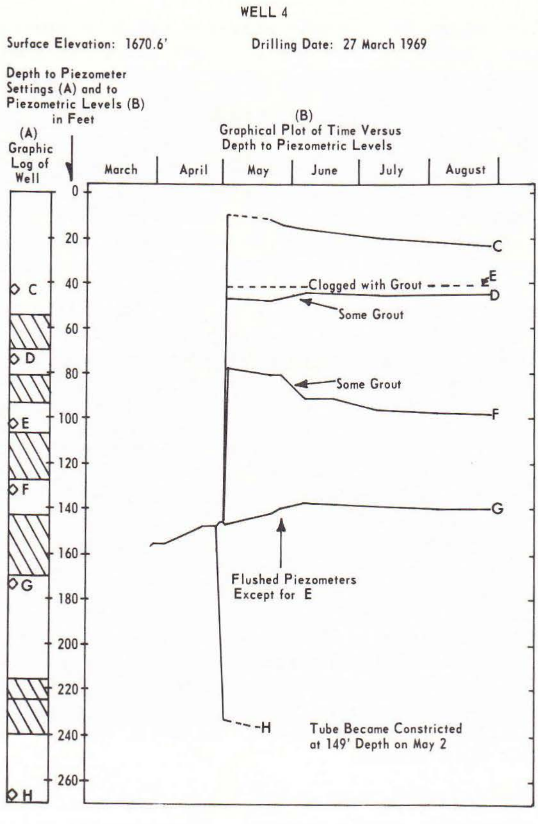

Figure 6. Graphic log showing depth of potentiometers and grout settings (a) and a graphical plot of time versus depth to piezometric levels for Well 4 (b) near Kylertown, Pennsylvania. (After R. L. Brown and R. R. Parizek, 1971, p. 193)

Ignoring Physical Principles

Sealing deep mines is a widely accepted practice for controlling mine drainage formation. However, mine seals do not guarantee that mine drainage will be controlled in all situations.

Cases may be cited, for example, where mine seals have been placed in shafts, ventilation openings etc., for the purpose of flooding deep mines thereby reducing the rate of pyrite oxidation or stopping the oxidation reaction entirely. In some cases mine waters were free to drain away from deep mines along undefined routes and the mines were never flooded. Some deep mines will never be flooded at a reasonable cost using mine seals because strip mines were open in the crop area and stripping continued until deep mine workings were encountered. Frequently these areas cannot be identified easily because strip mines were later backfilled thereby obscuring previously exposed deep mine workings. At other localities mine roofs have settled and collapsed greatly increasing the vertical permeability of mine roof deposits (Fig. 7). Commonly roof breakage extends to land surface where the overburden is thin as along valley bottoms and valley walls. These same areas will later serve as rather open ground-water discharge regions after mine flooding is attempted. Flooding will fail or be incomplete. Roof collapse also increases the permeability of overlying confining beds thereby increasing the infiltration rate to deep mines, and the likelihood of oxygen circulation. Overlying source beds may now be directly connected to the mine environment. Attempts to intercept uncontaminated roof water will meet with failure because roof and mine water are one (Parizek, 1971).

At still other mines, coal was removed close to the crop and mine drainage is free to discharge to surface along the crop even before mines are sealed (Fig. 8). Mine seals only would aggravate these discharges as the hydraulic head is increased. Where the mine roof rock, coal, or underlying deposits are rather permeable, a nearly free drain might be established under the heads imposed after seals are placed. At best, deep mines might only partially flood for this reason.

The circumstances under which deep mine seals will fail to improve the quality of mine waters are poorly defined. Ground-water circulation patterns and the chemical character of strata overlying and underlying deep mines and the quality of water they contain will not always favor neutralization and other improvements in quality after seals have been placed even if mines are flooded successfully. Where this occurs and mines are in regional ground-water recharge areas, (ground-water is moving downward) contaminated mine waters, previously discharged directly to surface will be induced to enter underlying deep ground-water flow systems (Fig. 9). Although still poorly documented, this is already occurring in some areas in the absence of flooding (Emrich and Merritt, 1969).

Monitoring of surface water might show that mine drainage "has been abated" when in fact in the long term, underlying aquifers were being devistated. Ground-water flow rates are slow enough that a number of years might be required before the pollution is detected, but by this time serious

Figure 7. Roof collapse above an abandoned deep mine. Note that pillars of coal are still visible marking the original mine location. Siltstone and shale above the coal are highly brecciated and cease to serve as confining beds. (From R. R. Parizek, 1971)

Figure 8. Mine drainage discharging from a deep mine along a coal outcrop. The vegetation kill and soil erosion are caused by mine drainage. (From R. L. Brown and R. R. Parizek, 1971) Attempts to flood such a mine would aggravate these discharges and would meet with failure if the drainage rate were not curtailed.

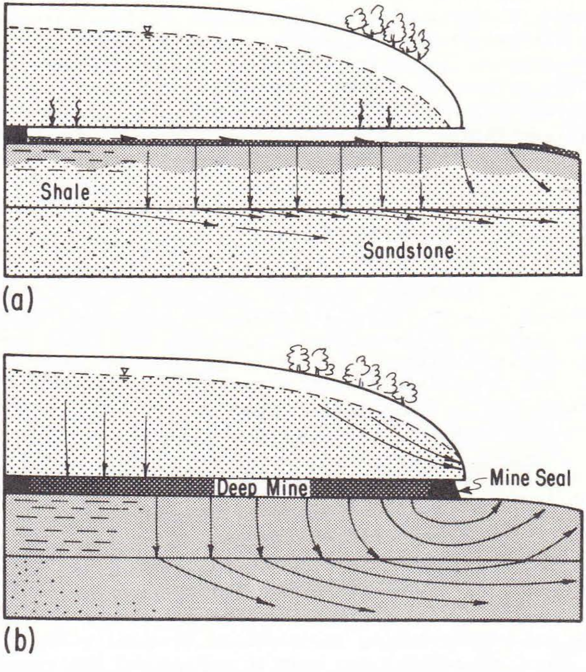

Figure 9. Relationship of deep mines to ground-water flow systems before mine sealing (a) and after sealing and flooding (b). In (b), a greater proportion of mine drainage is diverted to the regional ground-water flow system.

pollution problems may have developed. It is important that we do not unknowingly transfer surface pollution problems to the subsurface. In the long term, contaminated ground water eventually will be discharged to surface having first degraded previously potable ground water supplies.

Fortunately the vertical permeability of most strata associated with coal tends to be very low. As long as deep mines drain freely to surface, ground-water pollution tends to be minimal. Indiscriminate sealing of deep mines could change this situation. This whole question is being studied by Parizek using digital models to define ground-water flow systems under complex field settings.

Use of Geochemical and Hydrogeological Principles

Mine sealing programs involving both air and water seals have met with criticism because in some mining regions seals have substantially reduced the acid drainage problem. Whereas in other areas, mine seals did not effectively change the quality of water in local streams (Thompson and Emrich, 1969, p. 5, and others). The potential value of flooding some deep mines was recognized early. Vanzandt (1933) for example, reported some mines that were flooded produced alkaline discharges; whereas nearby operating mines still had acid discharges. Thompson and Emrich (1969, p. 5) offer an explanation for this unresolved controversy. Namely, there is limited information available regarding the location of mine seals and the quality of water coming out of the mine after being sealed. Also many seals were not maintained to insure they remain in operating condition. Seals have failed because of vandalism, extended contact with acid water, natural conditions, and others where disrupted by more recent mining. Other explanations can be added to the list. The quality of water draining from mines was not determined and recorded in detail before and after sealing to determine if quality improvement did in fact occur. Also, no attempt was made to understand the ground-water flow system and geochemical system involved within and adjacent to the mine.

Alkaline ground waters have been detected near mine openings which have been successfully grouted. However, this need not prove that mine waters ponded behind the seals are alkaline. Rather, alkalinity may be derived from the grout used in the sealing program. Monitoring wells should be provided within the mine to determine quality changes with time that result after seals are placed. These same wells could be used to determine if hydraulic heads have increased within the mine.

Air sealing attempts have been made in addition to water seals. These tend to fail for other reasons. Braley (1962a) reported little success in air sealing of mines located above the water table and concluded (1962b) that mines below the water table are already largely isolated hydrologically and thus air sealing is of no practical value. The oxidation of pyrite may take place if the pressure of oxygen is about 10^{-60} atm or more, and evidence indicates that the rates of oxidation are adequate to reach pH's of 3 or less even at this very low oxygen pressure. Braley (1962b) argued that reducing oxygen pressure below 10^{-60} atm, is a difficult and costly job and air seals have not been effective in even suffocating mine fires. There is little hope that this procedure can be used on a routine basis.

An alternate explanation may be offered to account for the seemingly contradictory results obtained from sealing and flooding some deep mines. Those mines which had rather effective seals and which received alkaline ground water by roof leakage (Fig. 10a) or floor leakage (Fig. 10b) derived from regional ground water flow should have turned alkaline once air circulation was retarded. By contrast those mines which received little or no alkalinity would have showed little or no improvement in quality no matter how effective their seals. This is a potentially critical point to consider when designing mine sealing programs.

Under some circumstances, calcareous deposits are available above or below deep mines. These serve as a source of alkalinity which can help retard acid reactions and buffer mine drainage (Fig. 10a). Calcareous shales, siltstones, sandstones, limestone, and calcareous glacial drift including sand and gravel, till, loess, and lake silts and clay will increase the alkalinity of soil water and ground water (Table 1).

A significant portion of western Pennsylvania is overlain by calcareous deposits which can be relied upon to produce natural alkalinity. Included is the northwestern portion of Pennsylvania where calcareous glacial drift blankets nearly all bedrock. Much of Illinois, Indiana, and Ohio coal mining districts also have this advantage. Glacial drift of Illinoian age exposed to the southeast of the Wisconsinan drift border in Pennsylvania tends to be thin and has been subjected to prolonged chemical weathering. Calcareous materials have been leached from this drift to considerable depths. Hence, these deposits generally will not produce high alkalinity by contrast to younger drifts.

Alkalinity need not be derived from nearby sediments. Rather ground water may have traveled thousands of feet to miles from where they picked up alkalinity until reaching the mine environments (Fig. 10b).

Calcareous shales and limestone are also widespread in western Pennsylvania and elsewhere and serve the same purpose. The realtionship between calcareous material and alkalinity can be appreciated by studying Table 1. Water samples were collected from shallow wells near Clearfield where calcareous material was missing, and from shallow wells drilled and dug below a calcareous zone, and from strip mines where calcareous glacial drift overlies the high acid producing Lower Clarion Coal.

Caruccio (1968, p. 141) indicated that CH-9A was collected from a well located below the Johnstown Limestone or calcareous horizon, in the Clearfield area and CH-9B was located above the calcareous zone which accounts for the differences in alkalinity. Samples CH-12, 14, 16 and 17, show negligible alkalinity which is typical of ground water that has not been in contact with $CaCO_3$ minerals. Water samples GRM-1, HRM-2, SLM-1,2 and 4 by contrast had

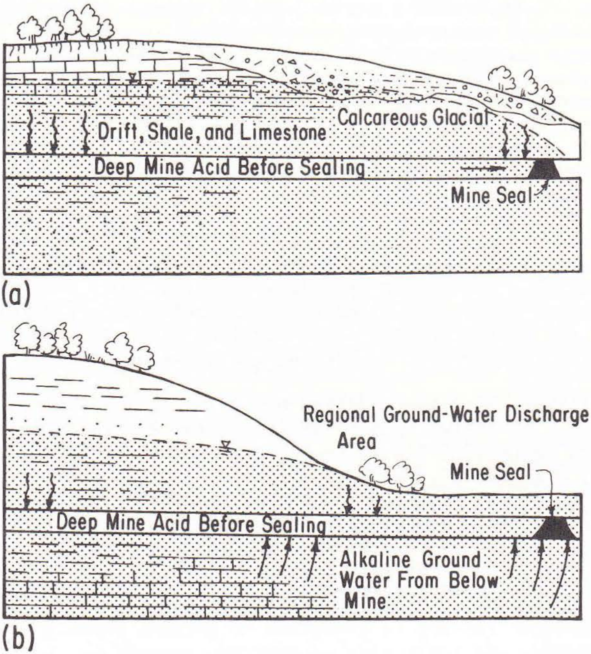

Figure 10. Alkaline ground water derived from overlying source beds that can abate mine drainage pollution after mine seals are placed (a) and from deep alkaline ground water brought to surface in discharge areas (b).

Table 1. Selected analyses of mine drainage, and ground waters of the Clearfield and Mercer areas, Pennsylvania. (Modified from F. T. Caruccio, 1968)

Sample	Source	Temp. °C	pH	Specific Resistance (ohms)	HCO_3^-	H^+	$SO_4^=$	Ca^{++}
					(all expressed in mg/l)			
Clearfield area (calcareous material missing)								
CH-12	Dug well	11	5.3	25,000	5	0	0	0
CH-14	Dug well	10.5	5.44	24,000	6	0	0	0
CH-16	Spring	9	4.85	28,000	6	0	0	0
CH-17	Dug well	10	5.60	27,000	5	0	0	0
CH-9A below calcareous zone; CH-9B above calcareous zone								
CH-9A	Drilled well	--	6.95	3,400	170	0	0	2
CH-9B	Dug well	10	5.20	3,400	4	0	85	12
Mercer area (calcareous material above highly acid producing Lower Clarion Coal								
GRM-1	High wall bleed	10.5	7.65	--	112	0	125	50
HRM-2	Pool in strip mine	10.5	7.1	--	240	0	160	81
SLM-1	Pool in strip mine	12	7.05	--	224	0	140	98
SLM-2	Pool in strip mine	11	6.45	--	152	0	740	117
SLM-4	Pool in talus	10.8	6.6	--	338	0	140	300

contacted calcareous deposits, hence contained 112 to 240 mg/l HCO_3^-, and 50 to 98 mg/l Ca^{++}. Highly alkaline ground and surface water have a favorable buffer or neutralizing capacity. Caruccio (1968, p. 146) points out that the alkalinity contained in SLM-4, for example, is capable of neutralizing about 6 mg/l of acidity assuming a mole to mole reaction and neglecting dilution. Neutralization did take place for the SLM-2 sample as can be seen from the analyses. A $SO_4^=$ content of 740 mg/l for example should be associated with an acidity in excess of 1.5 mg/l. The relatively low alkalinity of this sample coupled with high sulfate establishes that the sulfate was derived from acid mine drainage which was neutralized.

The neutralization and dilution potential of alkaline waters can be exploited more fully than has been done in the past where ground-water flow patterns and geochemistry favor the inflow of alkaline water. Alkalinity provides a buffer capacity against acid production and reduces the rate of acid formation because according to Clark (1966) catalyzing bacteria are not as active metabolically at near-neutral pH's as under acid conditions.

The pH of limestone or dolomite saturated water is slightly above 8, (depending upon grain size, carbon dioxide pressure, and water composition) and the bicarbonate content may approach a maximum of about 500 mg/l (Hem, 1959). Garrels and Christ (1965) show that such water could be capable of neutralizing the acid formed by complete reaction when about 120 mg/l of iron is precipitated from solution. This buffering capacity would be adequate to improve the quality of a significant volume of mine drainage produced in western Pennsylvania.

Barnes and Romberger (1968) discussed the role of carbonate rocks in the neutralization of acid waters where crushed $CaCO_3$ is added to mine drainage. They give the minimum weight of $CaCO_3$ necessary to raise the pH from some given value to neutrality assuming a complete reaction between $CaCO_3$ and acid water. Barnes and Romberger (1968) and others point out the difficulty that arises when carbonate rocks are added to iron-rich acid-mine water. Namely, insoluble ferric hydroxide tends to precipitate on reactive surfaces of carbonate rocks. This armor prevents further reaction of the calcium carbonate with acid, and the neutralization reaction stops after a short while. This difficulty could be eliminated if alkalinity were first added to surface or ground water naturally or artificially and then these waters were allowed to enter the mine environment. Precipitates of iron etc., resulting from an increase in pH might coat reactive surfaces of pyrite and marcasite further retarding acid forming reactions. A secondary benefit would obtain. Namely amorphous ferric oxyhydroxide hydrates would be deposited within the mine hence would not pose a pollution problem in streams or in ground waters and would not have to be disposed of or treated. Barnes and Romberger (1968) indicate that in addition to "yellow boy," gypsum ($CaSO_4 \cdot 2H_2O$), and amorphous aluminum oxide hydrate, also might appear but in smaller amounts.

The pH of acid mine water can be raised both by simple dilution and by buffering when it is mixed with waters containing HCO_3^-. Barnes and Romberger (1968) show the pH changes as a function of dilution when the dilutent is free of bicarbonate and has a pH of 7. Their equation for curves at low initial pH's is:

$$pH_2 = pH_1 + \log(x). \quad (2)$$

For example, if 1,000 volumes of water of pH 3 are diluted to a final volume of 100,000 volumes, the ratio of the final to initial volume is 100 and the final pH would be 5. They point out that water containing bicarbonate is much more efficient in neutralizing acid water than bicarbonate-free water. They present a series of diagrams showing for different concentrations of bicarbonate in the diluent, the initial and final pH relations as a function of dilution. Their equations that describe these relationships are:

$$(M_H+)\ \text{final} = [(M1_H+)\ \text{initial x D})] - [M_{HCO_3}-)\ \text{initial x (1-D)}] \quad (3)$$

$$(M_H+)\ \text{final} = \frac{10^{-11.37}}{[(M_{HCO_3}-)\ \text{initial x (1-D)}] - [(M_H+)\ \text{initial XD}]} \quad (4)$$

$$pH = -\log\ (M_H+) \quad (5)$$

where (M_H+) final and (M_H+) initial are the final and initial concentration of H^+ in moles per 1,000 g of water.

D = the dilution (ratio of initial to final volume)

$(M_{HCO_3}-)$ = initial concentrations of HCO_3^- in the diluent in moles per 1,000 g of water.

They show from their theoretical plots of dilution and buffering with bicarbonate waters for initial pH values, that there are critical levels of dilution for any initial pH and HCO_3^- content of the diluent. Near this critical ratio, very small changes in the degree of dilution have major effects on the effluent pH. They point out that the critical ratio is caused by buffering by HCO_3^- and is important only above bicarbonate concentrations in the diluent of roughly 25 mg/1. This relationship could be exploited by diverting alkaline surface water or ground water to mines (Fig. 11) to help shift them into this critical region where they could be maintained in an alkaline state at little additional cost through geochemical management practices.

Increases in pH should result in more treatment with less diluent, buffering, precipitate formation to coat reactive surfaces thereby reducing acid reactions, and reduction in bacterial activity, hence, reduction in the

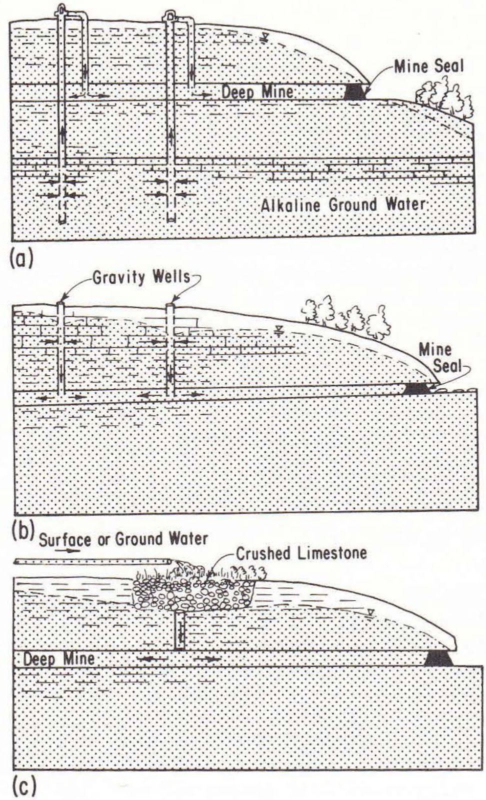

Figure 11. Natural sources of alkalinity that may be added to the mine environment. In (a) water is pumped from underlying aquifers containing alkaline ground water. In (b) natural alkaline water is fed by gravity into the mine environment and in (c) surface water is made alkaline and gravity fed into the mine. Crushed limestone may be used which has a soil cover to increase alkalinity.

rate of acid forming reactions. Thus it may be entirely possible that where alkaline waters can be added to sealed deep mines, more than one process can be relied upon to decrease acid forming reaction. Natural alkaline waters can be pumped from underlying aquifers where conditions permit (Fig. 11a), gravity fed into mines from overlying source beds (Fig. 11b), or artificially produced at land surface above the mine (Fig. 11c).

Where calcareous sediments underlie deep mines, and mine waters can be diverted into ground-water flow systems below the mine after sealing, neutralization can be expected naturally. However, this procedure of bringing acid, iron-rich waters to carbonate rocks where precipitate coatings will form may prove less desirable in the long run than diverting alkaline waters to mines and keeping precipitates within the mine environment.

Parizek in Dutcher et al. (1966 and 1967) pointed out that in areas where alkaline surface and ground waters are present in close proximity, there is hope that mine drainage can be treated and neutralized by other water resources management techniques. This might involve the regulation of flows of either mine waters or impounded alkaline waters to achieve the desired quality. Certainly this technique could be combined with flood control and related projects to improve water quality down watershed until corrective action can be taken within the mining district. He also stressed that mine drainage frequently bypasses strata which might alter its quality under natural conditions given the opportunity to do so. Mining operations greatly alter the surface-water and ground-water recharge and runoff characteristics, thereby diverting mine drainage from the available treatment media.

The availability, amount, and distribution of neutralizing strata and ground and surface water must be considered in hydrogeologic and geochemical studies aimed at abating mine drainage. Alkaline surface water can be brought in contact with the mine environment containing poor quality water after mines are sealed, or acid surface water can be pumped into mines that have a neutralization capacity as was done at a Barnes and Tucker mine near Barnsboro, Pennsylvania.

Conclusion

1. It should be apparent that knowledge of the hydrogeology and geochemistry of strata associated with deep mines must be known when considering the ground-water reservoir's role in transporting and neutralizing mine drainage. The relative position of sources of alkalinity and mine drainage within the ground-water flow regime are important in assessing ground-water pollution of potential deep mines and when evaluating the potential role of the ground-water reservoir as a treatment media or source of alkalinity.

2. The potential benefits of various management schemes outlined here should be obvious as they rely on natural geochemical and hydrogeological systems and involve a minimum of engineering manipulation and management.

They have the advantage of attacking the problem at its source to help curtail acid reactions rather than treating mine waters after they are contaminated. The later practice is destined to require huge sums of money and must be continued for an unknown but long period of time.

3. Likewise to ignore basic geochemical and hydrologic concepts when designing mine restoration projects will prove to be foolhardy in many cases as past experience reveals. These restoration projects must be designed in harmony with the natural systems involved.

4. One or more of the schemes outlined here will apply to most deep mine situations in western Pennsylvania and elsewhere. Mines, associated strata, and the hydrogeologic setting will have to be studied for each region to determine which if any of these schemes might be exploited in restoration projects.

5. In some cases it will be obvious and will require little study to determine which scheme should be adopted. These should be tested immediately on a trial basis. For example, wells can be used to drain source beds located above deep mines particularly where strip mining has extended into deep mine workings and sealing will be impossible. Here, options are limited.

6. Pilot projects should be set up at the earliest possible date to test each of these abatement procedures where appropriate field conditions exist. The job to be done is so extensive and will be so costly that we can no longer afford to attempt to solve mine drainage problems on a trial and error basis. Projects must be carefully designed, monitoring carried out, and data carefully analyzed to establish whether or not the restoration project has had the desired effect. The cost of such pilot projects will be great compared with some studies conducted in the past but the savings will be significant if restoration attempts can be designed to work with rather than against nature. Monitoring may be required for three or more years after restoration is attempted because many natural systems are slow to respond and it may be difficult to isolate natural seasonal changes in water quality and flow from changes brought about by restoration and engineering manipulations.

Acknowledgments

Much of the information presented here is contained in a research proposal entitled "Prevention and Abatement of Mine Drainage Pollution Using Natural Hydrogeologic and Geochemical Systems" submitted to the Department of Environmental Resources and jointly to the Federal Water Quality Administration by R. R. Parizek and E. G. Tarr.

The study was conducted under the auspices of the Department of Environmental Resources of the Commonwealth of Pennsylvania through funds provided by contract number CR-66.

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