

Hydrogeochemical Aspects of Surface Mine Reclamation in the Northern Great Plains

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ABSTRACT

STUDIES of several coal-mining sites in western North Dakota have resulted in the development of a hydrogeochemical model which accounts for the observed chemical characteristics of subsurface water in undisturbed settings. Critical hydrogeochemical processes include sulfide oxidation, gypsum precipitation and dissolution, carbonate mineral dissolution and cation exchange.

In the semi-arid climate of western North Dakota, the near-surface several meters of the landscape is constantly subjected to alternate wetting/drying. This mechanism is the key to hydrogeochemical evolution of both pore water in the rooting zone and subsurface water that eventually reaches the water table.

Recent refinements in the hydrogeochemical model have focused on the sulfur cycle and determination of the applicability of the model to postmining (spoils) landscapes. Field activities have included detailed groundwater instrumentation of undisturbed and spoils areas at two geologically distinctive mine sites in western North Dakota. Refinement of the model included analyses of the texture, bulk mineralogy, clay mineralogy, sulfide abundance, and sulfur concentration in overburden core samples. Laboratory experiments were designed to determine the source and mechanisms of sulfate salt production from overburden samples.

From the study we conclude that the hydrogeochemical model is equally applicable to undisturbed and spoils landscapes and that the major species of concern in this region are sodium and sulfate. This research indicates that the major source of sulfate is sulfides in the overburden and that the solubility of sulfate in groundwater in these settings is largely controlled by the sodium/calcium ratio.

We also conclude that negative hydrogeochemical impacts resulting from surface mining in the Northern Great Plains will include increased mineralization of groundwater and sodic and salt effects on plants. The degree of these impacts will be dependent upon site-specific hydrogeological, geochemical, and mineralogical variables. A consideration of these non-soils aspects of

surface-mined lands thus is essential to proper surface-mine reclamation design in this region.

INTRODUCTION

Surface coal mining in the Northern Great Plains has increased significantly in recent years. The majority of active and proposed mining areas in this region are in agricultural lands. In addition, throughout much of this region, a considerable percentage of the potable groundwater is obtained from shallow wells typically 10 to 100 m in depth. In many of the surface coal mining areas of the Northern Great Plains the coal which is mined is a major groundwater supply.

Surface coal mining activities in this region have generated considerable concern with respect to potential impacts on postmining plant growth success and groundwater quality. In recent years significant research and regulatory efforts have been designed to address these concerns. Typically, these research efforts have been restricted to a specific discipline. A plethora of research activities have focused on restoration of the agricultural productivity of postmining landscapes. Those research activities have largely been restricted to a detailed evaluation of that portion of the disturbed landscape that is within the soil horizons or solum. The vast majority of agricultural research associated with reclamation of mined lands thus has been limited to the expertise of soil science.

Research efforts designed to evaluate the potential impacts of surface coal mining on groundwater quality have, for the most part, been similarly restricted in their disciplinary scope. These research efforts have relied heavily upon geological, hydrogeological, and geochemical expertise.

In actuality, each landscape consists of complexly interrelated components. These components include the morphology of the surface, the physical and chemical characteristics of the surface and subsurface materials, and the hydrologic regime that is operating upon and within the sequence of materials. Prior to mining, in the time scale of normal observations, these landscape components are largely in a steady state with each other and with the forces acting upon them.

The disturbance of a landscape by surface coal mining typically results in severe disequilibrium within that landscape. Disequilibrium in postmining settings may take various forms. The most obvious indications of disequilibrium in postmining settings, when contrasted with premining conditions, are:

1. Significant degradation of plant growth potential.
2. Significant degradation of groundwater quality.

Design of disturbed landscapes based upon reestablishment of the premining equilibrium necessitates an integrated evaluation and redesign of all components of the landscape. In turn, a

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multidisciplinary approach to mined-land reclamation research is essential.

Continuing research in North Dakota focusing on the impacts of surface coal mining on groundwater quality has resulted in the development of a conceptual hydrogeochemical model. This model focuses on the key geochemical processes which control the chemical evolution of subsurface water in undisturbed and reclaimed spoils settings. The hydrogeochemical processes operative in this region are not only critical to groundwater chemical evolution, but also commonly control the quality of pore water in the plant rooting zone. Thus, a detailed knowledge of these geochemical processes is critical to the evaluation and design of reclamation techniques focused on both the reestablishment of plant growth success and groundwater quality in the postmining setting.

It is hoped that this paper will promote a better understanding of the need for integration of site-specific soils, geologic, hydrogeologic, and geochemical data and expertise as input to reclamation design for surface-mined lands. Although the concepts presented here have resulted from research in western North Dakota, we feel that these concepts have wide application throughout the Northern Great Plains and similar regions of western North America.

STUDY SITES

Location and Overview

The concepts presented in this paper are largely the result of research in several active and proposed mining sites in western North Dakota. These sites include the Falkirk, Indian Head, Beulah-Hazen, Dunn Center, and Center areas of west-central North Dakota (Fig. 1). Studies at these sites have been continuing since 1974. These studies have led to considerable insight into the geological, hydrogeological, and geochemical mechanisms which control subsurface water chemical evolution in this region. In many cases the data obtained from these studies represent the only extensive compilations of such data available in western North America. Some results of these studies can be found in Groenewold (1979), Groenewold et al. (1979, 1980, 1981, 1983), Groenewold and Rehm (1982), Moran et al. (1975, 1976, 1978, 1979), Rehm et al. (1980, 1982) and Williams et al. (1978).

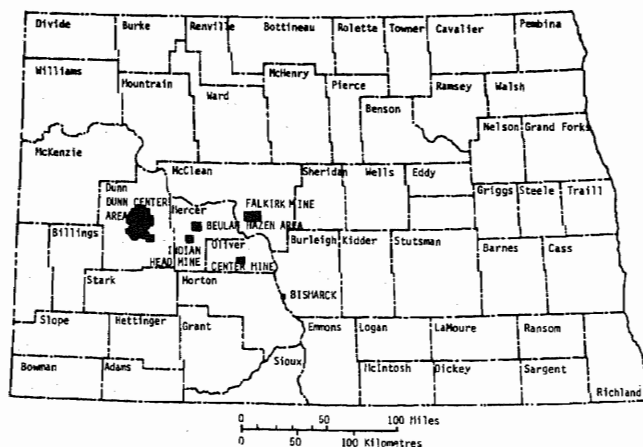


Fig. 1—Location of the study sites in Western North Dakota.

Detailed premining geologic, hydrogeologic, and groundwater chemical data have been generated at all five study sites. In addition, considerable data regarding postmining hydrogeologic and groundwater chemical characteristics as well as mining and reclamation techniques are available for spoils areas at the Center and Indian Head mines. The Center and Indian Head mines thus are key study sites for comparison of premining and postmining hydrogeochemical conditions.

Mining at the Center and Indian Head mines utilizes a walking dragline to remove overburden and dozers and pan scrapers to recontour spoils. The study areas at the Center and Indian mines are characterized by significant and consistent differences in the character of the overburden and groundwater quality in both undisturbed and spoils settings (Groenewold et al., 1979, 1981). Considerable variability in overburden characteristics is present at both mines. However, the overburden in the area of the Indian Head Mine utilized for this research was predominantly silty and clayey sediment; the overburden in the study area at the Center Mine was predominantly silty sand to sandy silt. Since all other significant variables such as mining and reclamation methods and climate are the same at these sites, the Center and Indian Head mines offer an essentially unique opportunity to compare overburden textural and mineralogical characteristics with groundwater quality and chemical evolution in undisturbed and spoils settings.

Climate

The climate in the vicinity of all the North Dakota study sites is classified as semiarid-continental. The summers are generally cool with only a few hot, humid days. The winters are typically quite cold and long. The mean annual temperature for Bismarck, North Dakota, which is located approximately 50 km southeast of the Center Mine is 5.7°C, varying from -12.3°C in January to 22.1°C in July. Precipitation at Beulah, North Dakota, approximately 6 km east of the Indian Head Mine averages 43.7 cm annually.

Geology

The North Dakota study sites are representative of the geological conditions found in most surface coal-mining areas in the plains areas of western North America. Glacial sediments (tills) veneer portions of some of the North Dakota sites are absent at other sites. The potentially mineable coal at all the sites occurs in the Tertiary Sentinel Butte Formation of the Fort Union Group. Although the thickness of the coal beds are less than in some other areas, the coal and associated sediments which underlie the North Dakota sites are typical of the Cretaceous and Tertiary coal deposits found throughout the plains region of western North America.

About 60 to 80% of the sediment making up the coal-bearing Sentinel Butte Formation in North Dakota consists of interbedded silt and clay that occurs in beds ranging from a few millimetres to tens of metres in thickness. From 15 to 35% of the sediment making up these formations consists of silty, fine-grained to medium-grained sand in beds that range in thickness from 0.3 to 35 m. Lignite is a minor constituent occurring in beds that range in thickness from 1 cm to

about 12 m locally. The lignite generally comprises less than 5% of the total thickness of these units in North Dakota.

The sediments of which the rocks are composed were derived from tectonically active areas to the west. The sediments were transported via lowgradient streams which terminated at the shorelines of inland seas. The coal-bearing sediments were deposited in various subenvironments within an alluvial flood-plain environment. Sand and silt were deposited in predominantly oxidizing environments on point bars and natural levees. Clayey sediments were deposited farther from the channels in largely reducing flood-basin settings (Jacob, 1972, 1973; Hemish, 1975; Cherven, 1978).

These differences in the original depositional settings of the sediments are reflected in the mineralogy of the sediments. Carbonate minerals are most abundant in the sand and silts. Clay minerals and pyrite are more abundant in the fine-textured sediments deposited in reducing environments. The predominant clay mineral at all the North Dakota sites is sodium montmorillonite (Groenewold et al., 1983). Thus, the original depositional setting of the near-surface sediments in an area has particular significance with respect to hydrogeochemical evolution in that setting, both prior to and after disturbance by mining. Detailed discussion of the geology of the coal-bearing sediments of western North Dakota and, in particular, the Center, Indian Head, Dunn Center and Falkirk study sites can be found in Moran et al. (1978), Groenewold et al. (1979 and 1981).

Geohydrology

As is common throughout the plains region of North America, the hydrologic regime at any site is primarily a function of the climate and stratigraphy, as well as the configuration of the landscape. Most precipitation at the study sites is scattered both temporally and spatially. Most precipitation is lost through evapotranspiration.

All the study sites are within groundwater recharge areas. Nearly all recharge to the groundwater system occurs during spring runoff and occasionally during periods of relatively heavy precipitation in the fall of the year (Rehm et al., 1982). The upper portion of the landscape is thus constantly subjected to alternating wet and dry cycles (Fig. 2). Recharge occurs, to some degree, over most of the landscape but is concentrated in restricted positions. These include areas of standing surface water (closed depressions) and ephemeral stream bottoms. In most other landscape positions, the majority of the precipitation is lost through either runoff or evapotranspiration.

Subsurface water movement is largely controlled by the lithologic characteristics of the sediments. Movement of water through sand and lignite aquifers is generally lateral, whereas movement through fine-textured Tertiary sediment is generally vertical and downward. The hydraulic conductivity of sediments at the North Dakota sites varies considerably, ranging from 10^{-5} to 10^{-6} m/s in sandy Tertiary sediments, from 10^{-5} to 10^{-7} m/s in the lignite, and from 10^{-8} to 10^{-10} m/s in the fine-textured Tertiary and glacial sediments (Groenewold et al., 1979; Rehm et al., 1980). The hydrogeologic characteristics of the North Dakota study sites have been discussed in detail by Moran et al. (1978), Groenewold et

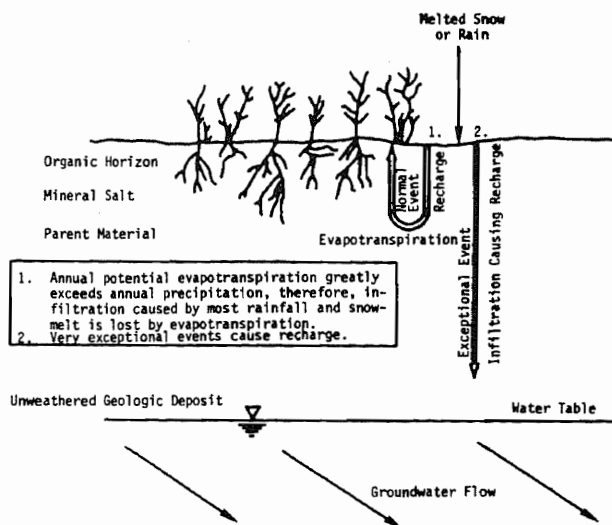


Fig. 2—Schematic diagram of subsurface water movement in much of the plains region (from Moran et al. (1978)).

al. (1979), and Rehm et al. (1980).

HYDROGEOCHEMICAL MODEL

The conceptual model which has been developed to account for the observed chemical characteristics of subsurface water in western North Dakota has been discussed in several recent publications (Moran et al., 1978; Groenewold et al., 1979; Groenewold, Rehm, and Cherry, 1981; Groenewold et al., 1981 and 1983). The following discussion is summarized from those publications.

The ultimate objective in the development of an interpretive hydrogeochemical framework is to provide a basis for prediction of the chemistry of subsurface water that will develop in reclaimed mine land. The most desirable path would be to develop a framework and then test (or verify) it by comparison of predictions based on its use with data from actual field situations. We have proceeded with the reasonable assumption that an interpretive framework that adequately accounts for the observed water chemistry in the natural overburden will have some applicability in the analysis of salt generation and accumulation in reclaimed land. The framework used in this paper follows closely that originally proposed by Moran et al. (1978).

Table 1 is a summary of groundwater chemical characteristics in shallow lignite aquifers at the five North Dakota study sites. Groundwater of similar quality is found throughout the Plains region of North America. For the interpretive hydrogeochemical framework to be valid, it must account for the predominant ions in these subsurface waters and the pH of the water. More specifically, it must account for the fact that most groundwater in the study areas is characterized by dominant concentrations of Na^+ , HCO_3^- and SO_4^{2-} . It must also account for the less widespread but significant number of groundwater zones that have Ca^{2+} or Mg^{2+} as the dominant cations, with HCO_3^- and SO_4^{2-} as the dominant anions. The model also must explain the variation in total dissolved solids of the groundwater, the general lack of detectable H_2S and the generally low concentrations of Cl^- and K^+ . Development of a hydrogeochemical model that will accomplish these tasks requires the use of constraints or

TABLE 1. SUMMARY OF CHEMICAL ANALYSES OF GROUNDWATER FROM SHALLOW (LESS THAN 75 m) LIGNITE AQUIFERS AT THE FIVE NORTH DAKOTA STUDY SITES (FROM GROENEWOLD ET AL., (1981))

	Field temp., C	Field pH	Field cond., $\mu\text{S}/\text{cm}$	TDS	Ca	Mg	Na	K	HCO ₃	Cl	SO ₄
							mg/L				
Falkirk Site-Hagel Lignite Bed											
\bar{x}	7.9	7.3	1603.0	1169.0	122.9	66.4	174.5	8.8	575.5	16.0	447.2
s	0.7	0.5	1332.2	1210.3	104.9	53.1	228.5	5.4	184.5	18.3	680.2
n	10	7	10	10	10	10	10	10	10	10	10
high	9.0	7.75	5000	4310	400	204.8	620	20.2	932.1	46.9	2264
low	7	6.46	630	195	36.2	20.4	9.5	4.4	378	0.5	20.6
Indian Heat Site-Beulah-Zap Lignite Bed											
\bar{x}	—	7.6	3213.4	2617.6	51.7	30.9	742.8	27.6	1099.6	20.0	937.4
s	—	0.2	1803.9	1565.4	25.9	11.7	414.4	7.3	616.0	12.0	516.0
n	—	4	5	5	5	5	5	5	5	5	5
high	—	7.83	5587	4390	75.0	44	1107	35.5	1663	37.7	1608
low	—	7.28	1497	938	19.4	12.8	278	18.5	415	8.2	409
Beulah-Hazen Site-Various Lignite Beds											
\bar{x}	7.5	7.48	2700.0	1480.1	39.1	24.6	415.5	10.3	818.7	14.5	427.8
s	4.2	1.01	1874.3	853.3	37.2	19.9	337.6	7.3	465.6	12.4	321.7
n	9	5	6	12	12	12	12	12	12	12	12
high	12	8.69	6250	3380	87	54.1	1039	31.4	1779	39.8	1211
low	1	6.07	1100	482	3.0	2.4	99	4.5	221	4.3	123
Center Site-Kinneman Creek Lignite Bed											
\bar{x}	10.4	6.7	1655.6	1229.3	84.3	51.9	249.7	18.8	651.1	8.1	372.2
s	2.8	4.6	437.1	33.3	47.0	20.3	122.7	11.3	208.7	8.0	137.5
n	9	9	9	9	9	9	9	9	9	9	9
high	16.0	7.5	2200	1631.0	165.0	94.4	441.0	48.0	1021.1	21.0	642.7
low	6.5	6.0	975	838.0	29.0	29.0	115.0	11.4	334.3	0.5	232.6
Dunn Center Site-Various Lignite Beds											
\bar{x}	9.3	7.06	3000	1602.5	113.0	56.1	388.0	11.1	665.3	16.5	821.1
s	2.2	—	—	831.3	108.8	39.3	226.9	7.3	375.9	18.7	591.5
n	4	1	1	4	7	7	7	7	7	6	7
high	12	—	—	2256	334	103	700	23	1405	38	1760
low	7.0	—	—	413	8.0	1.0	71	2.4	350	2.7	70

boundary conditions that are based on geologic, hydrologic, and geochemical factors. It must also account for the changes in water chemistry that occur as the water moves from the ground surface, where it originates as rain or snowmelt, through the solum and the underlying unsaturated zone into the groundwater zone.

The hydrogeochemical framework must also account for the chemical characteristics of saturated-paste extracts. Saturated-paste extract chemical data are commonly used to evaluate the suitability of the overburden materials as a plant-growth medium. Saturation-paste data from the North Dakota study sites, as well as from other sites in the plains area, show a strong similarity to shallow groundwater chemistry. Both are a function of pore-fluid chemical evolution. Thus, it is reasonable to assume that saturation-paste chemical data can be described in terms of the same geochemical processes that account for the chemical evolution of groundwater.

Important geochemical processes that are active in the soil and subsoil and their relationship to salt accumulation in the plant rooting zone, infiltration events, and groundwater chemical evolution are illustrated in Fig. 3. Normal rainfall and snowmelt events (on the right side of Fig. 3) result in infiltration of water below the ground surface but not beyond the root zone. During these normal infiltration events, acidity results from the production of CO₂, biochemical decay of organic matter and, to a lesser extent, from the oxidation

of pyrite which is finely but widely dispersed throughout the landscape (Groenewold et al., 1983). The pH is buffered by the dissolution of carbonate minerals. Evapotranspiration causes the concentration of salts in soil water and, consequently, the precipitation of those salts, usually within 1 to 3 m of the land surface. By this mechanism soluble salts, particularly gypsum, are generated and occasionally concentrate in horizons above the water table. Areas of low permeability accentuate the salinity by retarding water movement and permitting maximum evaporation.

Exceptional rainfall or snowmelt events (as demonstrated on the left of Fig. 3), are those which cause infiltration below the root zone and thus eventually produce groundwater recharge. CO₂ production, pyrite

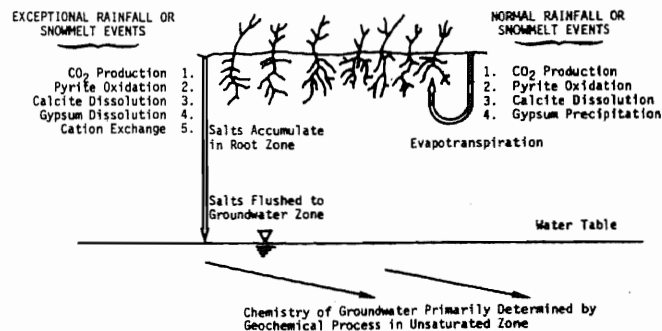


Fig. 3—Schematic diagram of chemical processes and salt movement in coal-bearing strata of the plains region (from Moran et al. (1978)).

oxidation, and calcite dissolution occur as during normal events. The "flushing" action of such an event, however, results in dissolution of the gypsum thereby generating major concentrations of SO_4^{2-} . Dissolution of calcite (and occasionally dolomite) is the main mechanism by which HCO_3^- is generated in the groundwater. Cation exchange in the form of Ca^{2+} for Na^+ on Na-montmorillonitic clays results when excess Ca^{2+} from calcite and gypsum dissolution is available to the infiltrating waters. Exchange of Ca^{2+} and Na^+ on the exchange sites results in an increase in dissolved sodium and further dissolution of calcite. Through the mechanism of cation exchange, high concentrations of Na^+ can be generated in the subsurface.

This framework of geochemical processes accounts for the (Na, Ca- SO_4 , HCO_3^-) type water which is common in the Tertiary deposits of the Northern Great Plains. It also accounts for the chemical characteristics of saturated-paste extracts. More importantly, it demonstrates the significance of geological variability as related to hydrochemical evolution in the near-surface environment. For example, in settings where Na-montmorillonite is essentially absent, (sandy bedrock) Ca^{2+} , HCO_3^- , and SO_4^{2-} will be the dominant ions. If pyrite or secondary gypsum are absent (some glacial and sandy bedrock sediments), Na^+ and HCO_3^- will dominate.

The significant role played by gypsum is worthy of note. Elevated salinities in extract samples, expressed in terms of electrical conductivity, result from the dissolution of gypsum as do the elevated levels of SO_4^{2-} in groundwater. Since gypsum does not appear to be a primary constituent of the sediment but rather an alternative product of pyrite, the sulfate content of the saturated-paste extract is determined by the state of oxidation. Salinity and sodium adsorption ratio (SAR) values will be particularly high in settings which are characterized by a minimum of flushing. The degree of flushing is determined by landscape position and texture of the materials. Knolls and certain side-slope positions are the least likely to allow infiltration below the rooting zone. This will be compounded if the near surface materials in these settings are of very low permeability.

These observations have serious implications from the standpoint of reclamation design. Of particular concern is the potential for salt generation and elevated SO_4^{2-} concentrations in the subsurface waters in post-mining landscapes where unoxidized overburden characterized by relatively high concentrations of sulfides is placed in the near-surface oxidizing environment during mining and contouring operations. In the Plains region overburden materials containing significant concentrations of sulfides also typically contain high concentrations of sodic clays (Groenewold et al., 1982). Thus, such settings are potential sites for elevated SAR values and the generation of highly sodic groundwater.

In summary, it appears that the chemical composition of groundwater and of saturated-paste extracts in much of the plains areas of western North American is a function of three factors: (a) the amount of calcite (and dolomite), sodium-montmorillonite and pyrite in the near-surface sediments; (b) the degree of oxidation of pyrite and the resulting gypsum in the near-surface sediments; and (c) the degree of flushing that occurs in the near-surface sediments.

VALIDITY AND APPLICABILITY OF THE HYDROGEOCHEMICAL MODEL TO SPOILS SETTINGS

Material Redistribution and Increased Availability of Oxygen

The previous discussion summarized the hydrogeochemical model as it relates to chemical evolution of subsurface water in undisturbed settings in western North Dakota. The processes and mechanisms described in the model allow us to account for the observed chemical characteristics of subsurface water in these settings. Evaluation of the applicability of the model to disturbed (spoils) landscapes requires a knowledge of the physical and chemical changes that occur in the landscape during mining operations and their potential impact on the overall hydrogeochemical regime.

As discussed previously, the premining landscape consists of various components that are more or less in equilibrium with one another and the forces acting upon them. Disruption of the landscape by surface mining typically results in two major changes in the landscape. These are: (a) redistribution of the overburden materials, and (b) increased availability of oxygen in the postmining landscape relative to premining conditions.

Redistribution of overburden by a dragline during surface mining operations has been described in detail by Winczewski (1977). That study, which focused on the Indian Head Mine, indicated that spoils handled by dragline consist of non-homogeneous, semi-stratified materials. That study also indicated that during mining operations sediments from the mildly reducing environment below the position of the premining water table are often emplaced in the near-surface oxidizing environment of the postmining landscape. Conversely, it was observed that sediments from the oxidized portion of the premining landscape are often emplaced in the saturated basal portion of the spoils.

Redistribution of overburden sediment suggests the potential for significant changes in the chemical reactivity of the landscape. Emplacement of unoxidized sediments in the oxidizing, near-surface environment increases the potential for sulfide oxidation, sulfate dissolution/precipitation and cation exchange on clays. However, there is no reason to believe that such increased reactivity in the near-surface environment in any way requires changes in the model. Conversely, emplacement in the base of the spoils of sediments from the near-surface portion of the premining landscape, or those which have been oxidized during the mining process, can be expected to cause rapid dissolution of sulfate salts in those sediments. Again, there does not appear to be any reason to believe that redistribution of sediments in this manner requires reevaluation of the hydrogeochemical model.

During mining operation large volumes of air, and thus oxygen, are entrapped within voids in the spoils. At least initially, the entrapped oxygen will promote oxidation of sulfides present in the unsaturated portion of the spoils. The presence of significant volumes of oxygen in the spoils can promote the generation of highly mineralized water. However, as in the case of sediment redistribution, we know of no reason for believing that this condition in spoils requires any changes in the basic hydrogeochemical processes and mechanisms as defined in the model.

Subsurface Water Flow and Occurrence in Spoils

The hydrogeochemical model emphasizes the significance of the near-surface portion of the landscape with respect to chemical evolution of subsurface water. Of particular significance is the wetting/drying mechanism which results from sporadic recharge events. The chemistry of subsurface water in the upper approximately 150 m of the landscape in western North Dakota is determined by geochemical processes that occur during recharge. Thus, for the model to be applicable to postmining settings, it is essential that recharge conditions in the spoils be similar to those which exist in undisturbed settings.

The vast majority of recharge in undisturbed settings in western North Dakota results from sporadic depression-focused infiltration (Rehm et al., 1982). Evaluation of recharge in reclaimed spoils at the Center and Indian Head mines based upon stable isotope data, flooding experiments and sporadic availability of water from pressure-vacuum lysimeters in the unsaturated portion of the spoils at positions well below the rooting zone all suggest recharge conditions similar to those which occur in undisturbed settings in western North Dakota (Groenewold et al., 1983). Thus, it is appropriate to conclude that the critical wetting/drying condition and associated geochemical processes are essentially the same in undisturbed and spoils settings.

The hydrogeologic conditions observed in the saturated basal portion of spoils at the Center and Indian Head mines suggest very similar conditions to those which existed prior to mining. The values for hydraulic conductivity in the spoils fall within the same range as sediments in undisturbed settings (Groenewold et al., 1983). In addition, the postmining position of the water table as observed in spoils at the Center and Indian Head mines is approximately the same as in the premining settings. It is clear, as previously discussed, that the mechanisms and rates of movement of subsurface water are critical to the hydrogeochemical processes operating in western North Dakota. The observed similarities in hydrogeologic conditions in spoils and undisturbed settings at the study sites indicate no reason to suspect that our model is not equally applicable to spoils as to undisturbed settings.

Subsurface Water Chemical Characteristics in Spoils Versus Undisturbed Settings

A detailed comparison of groundwater chemical characteristics in undisturbed settings and spoils at the Center and Indian Head mines is discussed by

Groenewold et al., (1983). Comparison of premining groundwater chemical characteristics at the Center and Indian Head mines indicates the presence of typically a (Na, Ca-SO₄, HCO₃)- to (HCO₃, SO₄)-type groundwater at both mines (Table 2). The major difference in premining groundwater chemical characteristics at the two mines is the degree of mineralization. The mean TDS concentrations in groundwater from near-surface lignite aquifers at the Center and Indian Head mines are 1,257 and 2,427 mg/L, respectively (Table 2).

These differences are a reflection of the mineralogy of the overburden at the two sites. The overburden sediments at Indian Head are commonly enriched in fine-textured, sodium montmorillonitic materials. The average clay content from 13 analyses of overburden from the Indian Head Mine was 57%. Overburden sediments at the Center Mine are commonly coarser-textured material that is relatively deficient in sodic clays. At Center, 26 analyses of overburden averaged only 39% clay (Groenewold et al., 1983). The hydrogeochemical model suggests that the Na⁺/Ca²⁺ ratio is the major factor controlling sulfate concentrations in shallow groundwater in this region. Thus, the relatively sodic overburden at the Indian Head Mine produces more highly mineralized groundwater than at Center. Predominant species in solution at both mines are typically sodium and sulfate.

Data generated by analyses of saturated-paste extracts of near-surface spoils materials from various locations at the Center and Indian Head mines also indicate significant differences in the chemistry of spoils at the two mines. The mean EC for spoils at the Center Mine is 2.9 with a standard deviation of 1.6. The mean EC for spoils at the Indian Head Mine is 5.2 with a standard deviation of 2.0. The mean SAR for spoils at the Center Mine is 3.6 with a standard deviation of 2.9. SAR values for spoils at the Indian Head site have a mean of 13.9 with a standard deviation of 5.6 (Groenewold et al., 1983). These data indicate that the near-surface spoils at the Indian Head site have the capacity to generate much more highly mineralized pore water than spoils at the Center Mine.

Groundwater in spoils at the Center and Indian Head mines is generically the same as in the undisturbed settings. The predominant ions in solution in groundwater in spoils at both mines are Na⁺, Ca²⁺, SO₄²⁻ and HCO₃⁻ (Table 2). However, comparison of data in Tables 1 and 2 indicates that groundwater in spoils at the two mines is typically two to three times as mineralized as in undisturbed settings. These conditions suggest that

TABLE 2. SUMMARY OF GROUNDWATER CHEMICAL DATA FROM RECLAIMED SPOILS AT THE CENTER AND INDIAN HEAD MINES (FROM GROENEWOLD ET AL., 1983)

Mine	Field temp., °C	Field pH	Field cond., µS/cm	TDS	Ca	Mg	Na	K mg/L	HCO ₃	CO ₃	SO ₄	Cl
Center												
x	10.5	7.1	4,969	3,282	281	145	497	20	958	304	1,516	7
s	2.8	0.6	2,181	1,326	180	103	289	11	294	2	789	15
n	98	98	98	97	98	98	98	98	98	42	98	57
Indian Head												
x	12.6	7.0	8,446	5,479	256	164	1,321	35	1,087	3	2,762	10
s	2.4	0.6	5,339	3,460	212	177	853	36	482	3	1,901	9
n	40	38	40	40	39	39	39	39	40	33	40	39

x = mean; s = standard deviation; n = number of samples

the same hydrogeologic and hydrogeochemical mechanisms and processes are operating in spoils settings as in undisturbed settings. These conditions further suggest that the significant difference between premining and postmining settings, with respect to subsurface water chemical evolution, is the chemical reactivity of the near-surface materials. Particularly problematic are sulfate/sulfide-rich and sodic sediments if emplaced in the near-surface portion of the spoils.

DISCUSSION AND CONCLUSIONS

Impacts on Groundwater

The redistribution of overburden sediments during mining operations commonly generates a more chemically reactive landscape than was present in the premining setting. All the mining operations at the North Dakota study sites utilize a dragline for overburden removal. Dragline removal of overburden promotes the "overturning" of the overburden materials. If such mining techniques are utilized, a two-fold to three-fold increase in the potential mineralization of groundwater in spoils relative to premining conditions can be anticipated.

The major chemical species of concern in groundwater in the Plains region are sodium and sulfate. Sufficient extractable sulfur is available in most overburden sediments in this region to potentially generate very high concentrations of sulfate in solution. The sulfate concentration is controlled by the solubility of gypsum. Thus, the concentrations of sulfate in groundwater in spoils will be controlled by the $\text{Na}^+/\text{Ca}^{2+}$ ratio.

The short-term impact of surface mining on groundwater quality has been clearly documented at the Center and Indian Head mines. These data indicate that TDS concentration within the average of 3,000 to 5,500 mg/L can be anticipated in surface-mined areas where dragline was used for removal of overburden. In areas of highly sodic spoils, the concentrations of sodium and sulfate can be anticipated to be in excess of 1,000 and 2,500 mg/L, respectively.

Long-term trends are more difficult to evaluate. The key variable will be the degree of vertical infiltration (recharge) through the spoils. If recharge is minimal, an initial flush of soluble salts emplaced in the base of the spoils during mining can be anticipated. This will result in a short-term peak in the generation of highly mineralized groundwater. Because of the large salt load of typical spoils in this region, more extensive recharge may, but need not necessarily, be a problem. If recharge is confined to small areas of the spoils or occurs primarily through fissures, only a small portion of the potential mineralization would actually be transferred to the groundwater. In contrast, recharge which is equal to or exceeds premining conditions and results from infiltration over a wide area of the spoils would lead to serious groundwater degradation and must be avoided.

Reclamation design should take into account that the mining process has increased the overburden material salt load and allows for the possible placement of reactive reduced materials near the surface which would increase the salt load even further. Each reclamation plan should provide assurance that area-wide infiltration leading to groundwater recharge will be avoided and thus minimize negative impacts on groundwater quality.

Impacts on Pore Water and the Near-Surface Environment

The complexly interrelated components of landscapes in this region were discussed above. The focus of this research has been on the chemical evolution of subsurface water. As discussed, the most significant portion of the landscape from the perspective of subsurface water chemical evolution is the near-surface (upper few meters). The quality of groundwater in both undisturbed and disturbed settings is almost totally dependent upon geochemical processes which occur in this zone. Thus, these processes determine not only the quality of water which reached the water table, but also the quality of pore water in the rooting zone.

Present reclamation techniques require the selective recovery and replacement of a maximum of 160 centimeters of soil material. At most mines in this region, the amount of available soil material is considerably less than 160 centimeters. Plant roots commonly penetrate deeper than the thickness of replaced soil material. In addition, recent research at the Indian Head Mine had demonstrated the upward migration of sodium from sodic spoils into the overlying solum (Power et al., 1979). Thus, if highly reactive materials such as sodic and sulfide-rich sediments are emplaced immediately below the solum, it is very probable that highly mineralized pore water will be generated in the zone immediately below the replaced solum. As in the case of potential impacts on groundwater, the infiltration characteristics of the reclaimed landscape will be critical to plant growth success in such settings. If infiltration is minimized, impacts on plant growth may be severe. If infiltration is similar to premining conditions, impacts on plant growth will be decreased. If infiltration is maximized, impacts on plant growth in such settings will be minimal.

It is clear that the key to long-term biological productivity and groundwater quality in postmining settings in western North Dakota is the restriction of fine-textured sodic and sulfide-rich sediments, particularly if unoxidized, from the near surface portion of the postmining landscape. The simple replacement of topsoil and subsoil materials without regard for the physical and chemical characteristics of materials below the soil zone will only, by chance, result in long-term reclamation success.

The previous discussion also clearly demonstrates that if an integrated multidisciplinary approach to these topics is not followed, then an inherent conflict exists between concerns associated with groundwater quality impacts and plant growth success on reclaimed lands. If sodic and sulfide-rich sediments are not restricted from the near-surface portion of the postmining landscape, then the infiltration/recharge characteristics of that landscape will determine impacts on plant growth and groundwater. In such a setting, minimizing recharge would be beneficial to groundwater quality but would maximize sodic and salt effects on plant growth. Conversely, maximizing infiltration in such a setting would minimize sodic and salt effects on plants but would maximize groundwater degradation if such infiltration led to recharge. Fortunately, these do not appear to be mutually exclusive requirements. Gentle precipitation events can lead to significant infiltration to the root zone, but without significant penetration to

deeper levels (Schroeder and Bauer, in press). More severe events, thunderstorms and Spring snowmelt, can run off to localized recharge areas (depressions, potholes, etc.) if they are available.

In conclusion, it is essential that reclamation research and design involve expertise from a wide range of disciplines capable of evaluating the entire disturbed landscape. Any other approach will lead to misconceptions and often, short-term reclamation success. In turn, it is very important that regulations governing reclamation practices allow for the highly site specific variability typical of mining areas in the Plains region and that those regulations allow for innovative practices and nonuniform treatment of mined lands to maximize reclamation success.

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