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Wayne A. Van Voast
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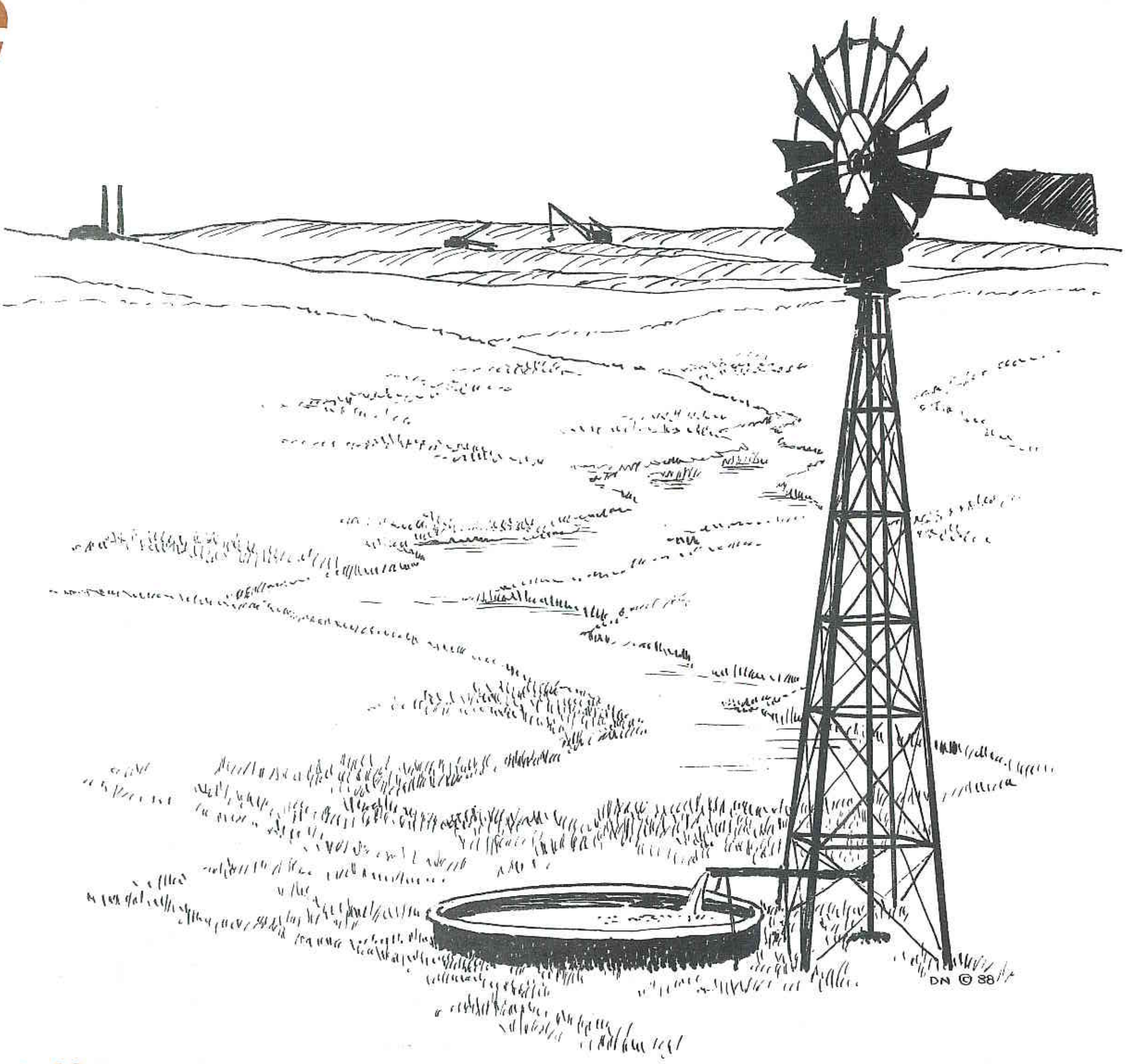

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Front cover sketch
by
Diane Nugent

Preface

Ground water is the lifeblood of agriculture in southeastern Montana. Much of it is obtained from coal-bed aquifers that comprise tremendous energy reserves. This dual role of the coal resource prompts immediate concerns for the hydrologic effects of mining that may create long-term changes in agricultural water supply.

This report contains an overview of current knowledge and theory on hydrologic aspects of surface coal mining, and presents selected examples and interpretations of monitoring results at and near the Rosebud, Big Sky, and Decker mines in southeastern Montana. Additional information can be obtained from the Montana Bureau of Mines and Geology (Billings office).

Appreciation is extended to the Bureau of Land Management and the Montana Coal Board for funding and for cooperation on technical aspects of mining hydrology, and to the Rosebud Conservation District for administrative support in recent years. Thanks are also extended to Western Energy Company, Peabody Coal Company, Kiewit Mining and Engineering Company and the Decker Coal Company for long-standing access to their properties and for sharing of data.

Special gratitude is owed to Joe Lalley and Teresa Donato of the Montana Bureau of Mines and Geology, Billings office, for their labors in the collection of data and in the preparation of this report. Assistance by Joseph Donovan in computer management and manipulation of data is also appreciated.

Wayne Van Voast
Senior Hydrogeologist
Jon C. Reiten
Hydrogeologist
Montana Bureau of Mines and Geology

February 26, 1988
Billings

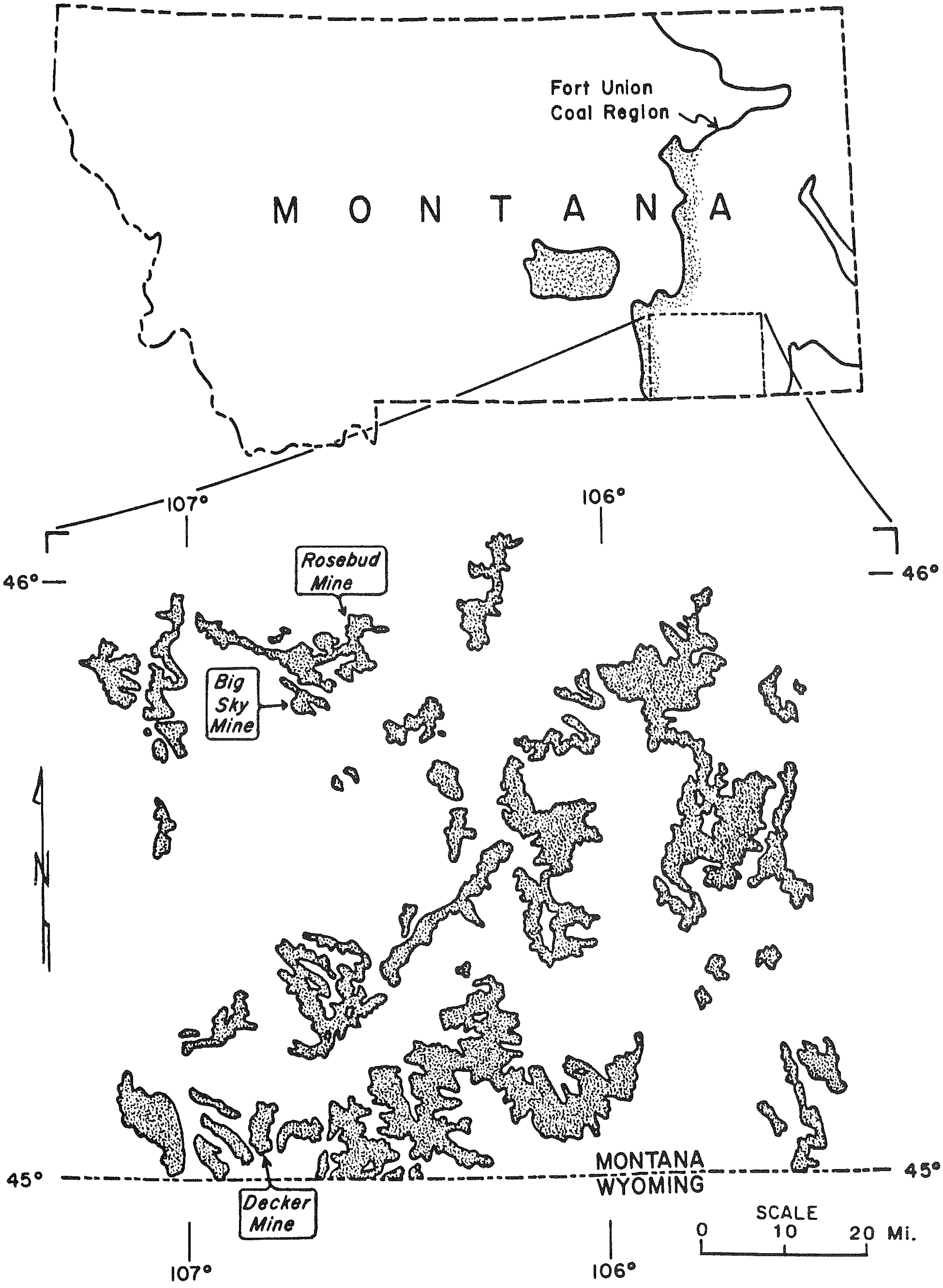

Figure 1—The Rosebud, Big Sky, and Decker mine areas are in the subbituminous portion (stippled pattern) of the Fort Union coal region.

Abstract

Hydrologic conditions near surface coal mines in southeastern Montana are being monitored because coal beds are the most accessible and widely used aquifers of the region. Mining has thus far affected water levels in alluvium only locally, if at all. Water levels in coal-bed aquifers are being lowered within about 2 miles of active mines near Colstrip. As mine pits are backfilled with spoil, hydrostatic pressures in both the spoil and adjacent aquifers are recovering toward pre-mining levels. At Decker, a potentiometric depression has formed over an area more than 5 miles wide and 15 miles long, caused by converging of drawdowns created by three mines. At all mines, water-level declines clearly illustrate the influences of directional permeabilities and hydrologic boundaries.

As pits are being backfilled, spoils are rapidly becoming resaturated by inflow from undisturbed aquifers, laterally at all mines, and vertically where conditions are appropriate. It is hypothesized that pre-mining, non-plugged drill holes allow vertical flow. In the resaturation process, strongly increased concentrations of dissolved solids (primarily calcium, magnesium, sodium and sulfate) are evolving. The initial chemical quality of spoils water is highly diverse because of the variable distribution of soluble salts in the spoils. As ground-water flow in the spoils continues, water-quality trends are becoming apparent. Some sites are currently showing increasing concentrations where surface recharge introduces dissolved solids faster than they are flushed from the system. Other sites show decreasing concentration trends where new salts are not introduced by recharge. In these cases, chemical quality of spoils water may approach pre-mining quality within the predictable future.

Introduction

Energy is not the only resource that southeastern Montana coal can provide. The coal beds, because of their generally fractured characteristics and broad areal continuities, are commonly the most accessible and widely used aquifers of the region. In this semi-arid climate, many inhabitants are almost totally dependent upon ground water for stock and domestic supplies, and in many places it is obtained from coal beds that will be removed by mining. Impacts of mining upon water supplies that are vital for agriculture are causing concern on both State and federal levels.

More than 32 billion tons of lignite and subbituminous coal are present within Montana's portion of the Fort Union coal region (Matson and Blumer, 1973). Twenty-six coal beds have been identified, having thicknesses between 3 feet and 75 feet, and underlying almost 800 thousand acres. 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. Although coal has been mined in the region by individuals and small operations for many years, most of the production was from underground mines that had little noticeable effect on the land or water. Large-scale surface mining has now become prevelant in the subbituminous fields; since 1968, six surface mines have been opened and numerous others are in the planning stage.

The need for ground-water information became important with the advent of these large-scale surface mining operations, whereby the Montana Bureau of Mines and Geology began programs of hydrologic study near the Rosebud, Big Sky and Decker mines (**Figure 1**). Information on many important hydrologic aspects of surface mining has been developed from these studies and has been applied extensively by State and federal regulators on decisions regarding leasing, data standards, mine permits, methods, and reclamation. Also, a network of strategic observation wells evolved and a sophisticated, coal-field-specific, computerized data system was generated. The data file contains water-level and -quality data, in many cases covering 15 or more years of record.

This reporting of data and interpretations is not made in disregard of monitoring efforts by mining companies of the area. Each company painstakenly monitors hydrologic aspects of its own activities and reports appropriate data to the Montana Department of State Lands. Exchange and comparison of data between the agencies and the companies is a long-standing tradition that adds credibility and cohesiveness to the program.

Ground-water terminology

The uppermost surface below which geologic materials are saturated under hydrostatic pressure is termed the *water table*. Water is stored within spaces between grains or in fractures in the geologic material; the ratio of volume of pore space to total volume of material, expressed as a percentage, is known as *porosity*. All geologic materials are porous to some degree. Their ability to transmit water under field conditions is termed *hydraulic conductivity* and depends upon the size of the pore spaces and the degree of their interconnection. Hydraulic conductivity as used in this report is defined as the flow of water in cubic feet per day through a cross-sectional area of geologic material 1 foot thick and 1 foot wide under a hydraulic gradient of 1 foot per foot. *Transmissivity* is used to indicate the ability of an aquifer to transmit water and is equivalent to the hydraulic conductivity multiplied by the aquifer thickness in feet. Transmissivity is defined as the flow of water in cubic feet per day through a section of aquifer 1 foot wide under a hydraulic gradient of 1 foot per foot. The volume of water that an aquifer can release from or take into storage per unit surface area of the aquifer per unit change in head is known as *storage coefficient*. Storage coefficient and transmissivity are the main characteristics that determine the worth of an aquifer as a source of water.

Water-quality evolution

Commonly considered, the major chemical constituents in water are the cations calcium (Ca), magnesium (Mg), and sodium (Na), and the anions sulfate (SO_4), bicarbonate (HCO_3), and chloride (Cl). Concentrations and relative abundances of these ions in ground water reflect geochemical processes that are active in ground-water flow systems (**Figure 2**). The relative abundance of any cation or anion is expressed by its concentration (milliequivalents per liter) as a percentage of the total concentration of cations or anions. Other ions identified on **Figure 2**, carbonate (CO_3) and potassium (K), are also common, but usually in relatively very low concentrations. In the coal-bearing and associated sediments of southeastern Montana, chloride also occurs in very low concentrations, probably because of the non-marine origin of the sediments. The remaining five constituents comprise more than 97 percent of the dissolved contents in almost all ground water in the Fort Union Formation and other shallow aquifers of the region.

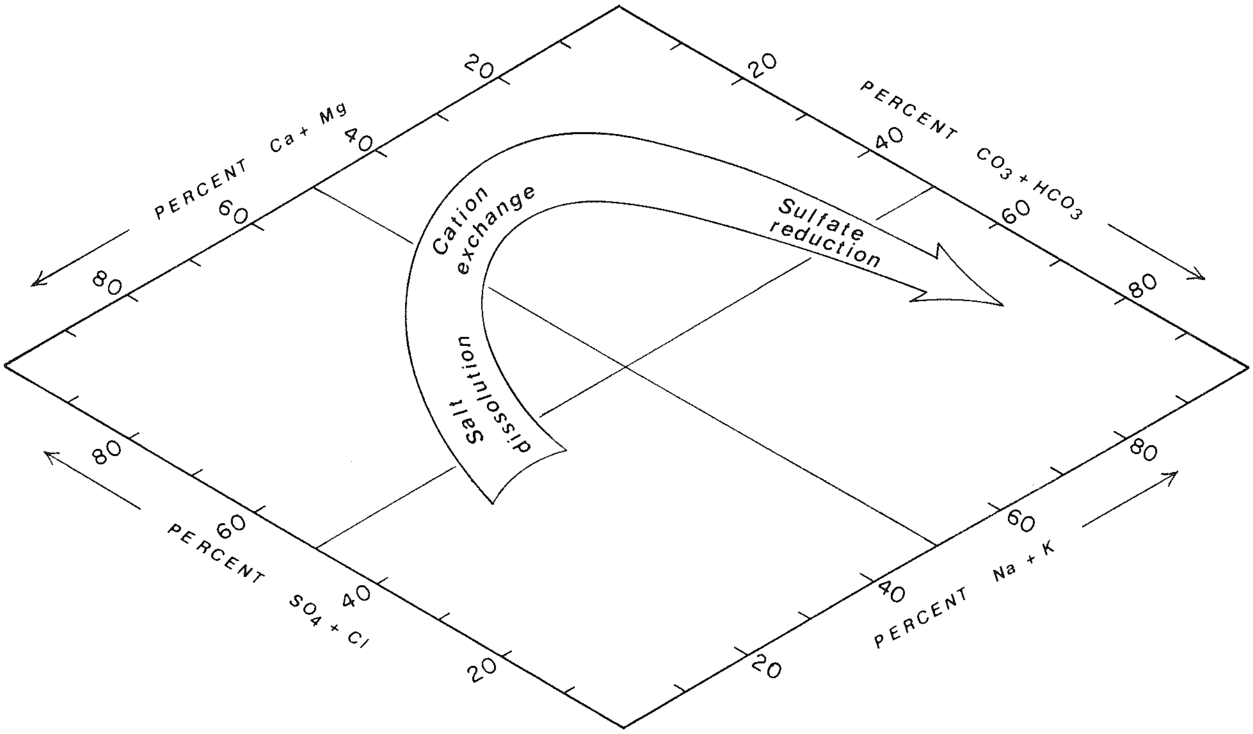

Figure 2—Chemical characteristics of ground water are altered by natural processes along the path of flow.

Recharge areas are characterized by oxidizing conditions, which, when enhanced by mechanical weathering of geologic materials, generate large amounts of salts that are readily available for dissolution by percolating ground water. Percent ion concentrations for ground water in recharge areas would plot in either the left-hand or the lower quadrilateral of **Figure 2**, depending upon the chemical species of the salts. Where products of sulfide weathering (sulfates) are present, relative ion percentages in ground water would favor the left-hand quadrilateral and dissolved-solids concentrations could be very high. With a paucity of sulfates, relative percentages would favor the bottom quadrilateral and dissolved-solids contents would be much lower.

As ground water moves away from sources of soluble salts, cation-exchange processes modify the relative proportions of dissolved ions. Sodic clays, abundant in the Fort Union Formation, selectively adsorb the divalent calcium and magnesium ions onto their surfaces and release monovalent sodium ions to the water through ion exchange mechanisms grouped as "natural softening" reactions. Sodium then becomes the strongly predominant cation, and the dissolved-solids concentrations remain high.

Simultaneously with cation exchange, sulfate-reduction reactions decrease the proportion of sulfate relative to bicarbonate. Dockins and others (1980) found significant numbers of sulfate-reducing bacteria in 25 of 26 water samples collected from aquifers in southeastern Montana. These anaerobic bacteria obtain their energy by oxidizing certain simple organic compounds, and also produce sulfide from reduction of sulfate by the following reaction:

$$2\,CH_2O + SO_4^{-2} = H_2O + CO_2 + HCO_{-3} + HS^-$$

Carbon dioxide and hydrogen sulfide gases in many aquifers of the area are products of this reaction.

The combined effect of the exchange and reduction processes is a modification of ground-water quality so that sodium and bicarbonate are ultimately the predominant constituents, and the dissolved-solids concentrations are commonly less than 2,000 milligrams per liter (mg/L). Where exchange and reduction processes are highly active, such as the Decker area, the sodium-bicarbonate character of water evolves within a few miles downgradient from the recharge sites. Thereafter, the water quality remains relatively uniform. The reduction process does not seem active in the Colstrip area, so the quality of most ground water is a product of salt dissolution and, to a lesser degree, cation exchange.

Mining effects: Current knowledge and theory

Mining-related impacts on ground water can be divided into two distinct categories: (1) those related to active mining operations, and (2) those which persist long after mining and reclamation operations have been completed. The first category (mining phase) includes springflow and well-yield decreases that can affect water use, pit-inflow volumes that can affect mining operations, and pit effluent volumes and qualities that may be environmentally unacceptable. The 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 newly created hydrogeologic conditions.

Changes during active operations

Water levels

Mine-inflow rates and associated water-level or hydrostatic-pressure declines are influenced greatly by the positions of mines within the ground-water flow systems. Mine cuts that begin along aquifer outcrops stress the flow systems very slowly. Such pits gradually change aquifer boundaries, and hydrostatic-pressure changes are similarly gradual. Inflow to the pits consists mostly of intercepted ground water, and the inflow rates are generally negligible. As mining proceeds, pits are expanded or moved too slowly to induce significant inflow from ground-water storage. Hydrostatic-pressure declines associated with such gradual releases from storage are also very gradual and commonly are not detectable more than about 2 miles away. Mines near Colstrip are examples of gradual outcrop displacement that creates gradual hydrogeologic effects.

In contrast, mines that operate between the outcrops of coal-bed aquifers (such as near Decker) create relatively rapid and dynamic changes in the ground-water system. Coal beds in this area have hydraulic conductivities similar to others in the region, but lie in a somewhat unique geological setting where parallel faults, uplifted recharge areas, and a regional discharge area control ground-water flow. Effects of mining near Decker have been dramatic and widespread. Drawdowns such as those described for the area would be unlikely over much of the region, but should be expected along its western edge where faulting and uplift have occurred. They may be particularly important where cumulative effects of multiple mines are a concern.

Mine effluents

The chemical qualities of effluents pumped from active mines were originally thought to be an environmental concern, but this is erroneous. The effluents are mixtures of waters from aquifers penetrated by mine cuts and are not chemically different from ground water that discharges naturally to the land surface. The only notable chemical difference between mine effluent and local ground water is the occurrence of occasional abnormally high nitrate concentrations in the effluents. The condition has been observed at several mines (Van Voast and Hedges, 1975) where temporary concentrations as great as 25 mg/L (as N) have been detected. The nitrates are probably dissolved residuals from ammonium-nitrate explosives used in blasting coal and overburden. 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

Aquifer characteristics

Many field tests to determine hydraulic conductivities (water-transmitting capabilities) of spoils in the mine areas and undisturbed aquifers throughout southeastern Montana have been conducted by the Montana Bureau of Mines and Geology. Statistical comparisons (**Figure 3**), 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. Examinations of stripping operations and mine floors indicates that the greatest hydraulic conductivities occur at the bases of spoils where rubble (sandstone, shale, siltstone, limestone) and wasted coal have been covered by finer-grained materials (**Figure 4**). Storage coefficients for these basal materials in Montana (Van Voast and others, 1978a) and in North Dakota (Houghton and others, 1984) have been estimated to be about 10_{-5}. Basal spoils, therefore in most cases, are confined aquifers that allow rapid resaturation in mined lands. Where water quality is acceptible, these "mine-floor" aquifers may become useful ground-water sources.

Spoils resaturation

The rapidity with which mine spoils become resaturated cannot be explained only by recharge from infiltration of rainfall and snowmelt. Lateral flow from adjacent undisturbed aquifers is an obvious and predictable mode of recharge, given reasonable understanding of the geology and ground-water flow in a mine area. Upward flow from deeper aquifers has traditionally been accepted as leakage through poorly permeable underlying mine floors, and has been given little significance. Evaluations of data presented elsewhere in this report show that hydraulic continuity exists between mined lands and deeper aquifers, and that vertical flow to spoils occurs in at least one location. An explanation is proposed that such flow occurs through unplugged exploration holes drilled in search of additional coal.

Spoils-water quality

Chemical quality of ground water in mine spoils is the most complex aspect of post-mining hydrology. Because of the geochemical nature of coal and overburden, acid production does not occur in mine effluent or spoils water in southeastern Montana. Sulfur-oxidizing bacteria, *Thiobacillus ferrooxidans*, have been detected by Olson and McFeters (1978) at one mine, but the produced acid was quickly neutralized by ample carbonate and bicarbonate in the system.

Post-mining ground water in the region ranges from neutral to alkaline, and in almost all cases contains substantially higher concentrations of dissolved solids than does ground water in undisturbed aquifers. In southeastern Montana mines, average dissolved-solids concentrations in mine spoils are 50 to 200 percent higher than average concentrations in undisturbed aquifers. At mines in North Dakota, two- and three-fold increases in dissolved solids have been found in spoils water (Groenewold and others, 1983). Constituents that comprise most of the increases are sodium, calcium, magnesium and sulfate.

At all mines where spoils-water quality is monitored, temporal changes in quality are evident. At some locations, increases in chemical concentrations can be ascribed to increased water levels because the effectiveness of confined mine-floor aquifers is less pronounced. In numerous other cases there seems little or no direct relation between water-level changes and water-quality changes, and the concentrations seemingly vary randomly or decrease progressively with time. The random changes probably represent original salt distributions in unleached spoils. Trends of decreasing dissolved-solids concentrations are optimistic indications that soluble salts are being leached from the system and that long-term ground-water quality in mined and off-site lands will not be compromised. These trends can be simulated in the laboratory with column-leach tests and can be fitted to

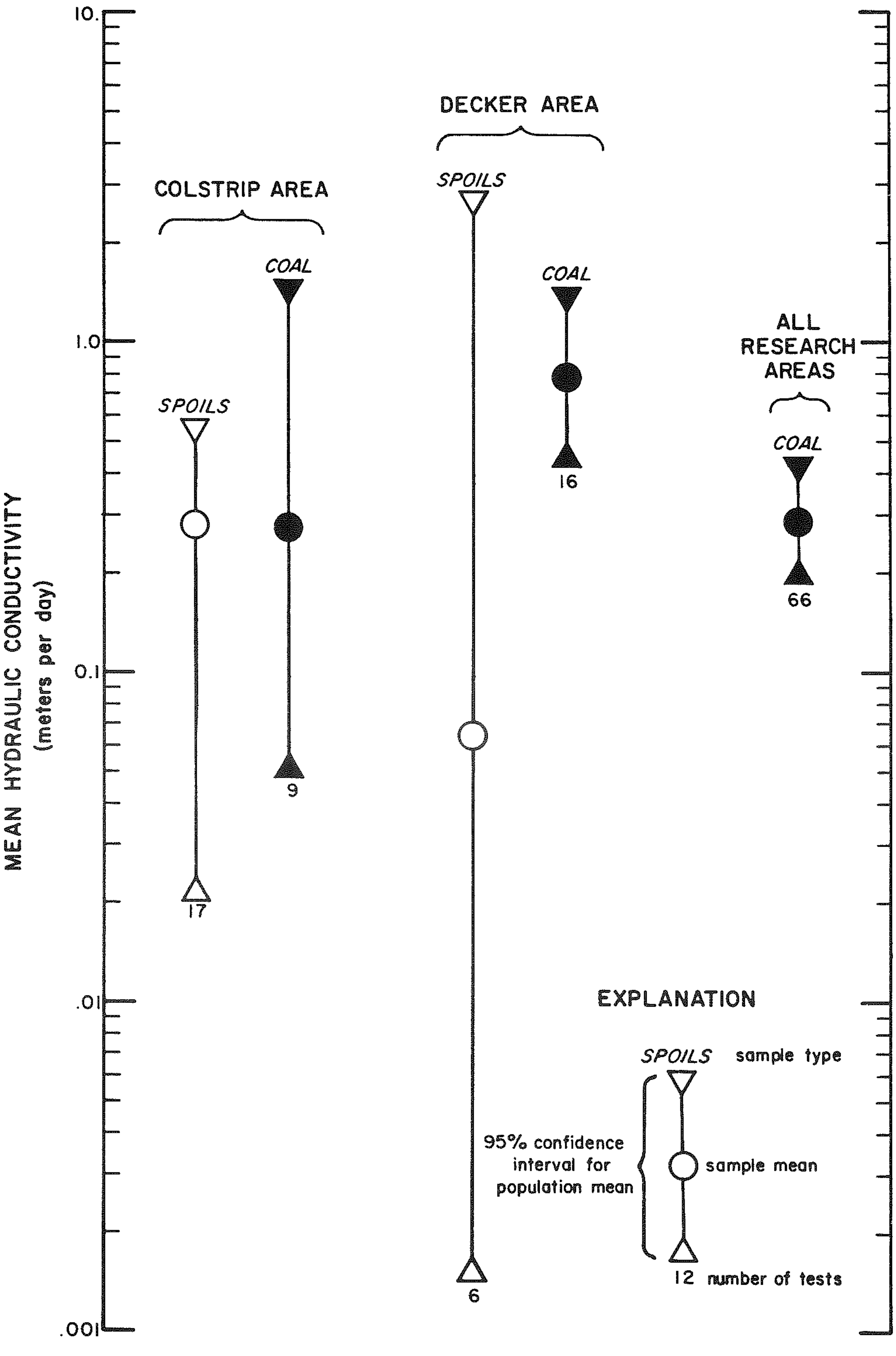

Figure 3—Hydraulic conductivities of coal-bed aquifers and mine spoils have wide ranges, but do not differ greatly in mean values.

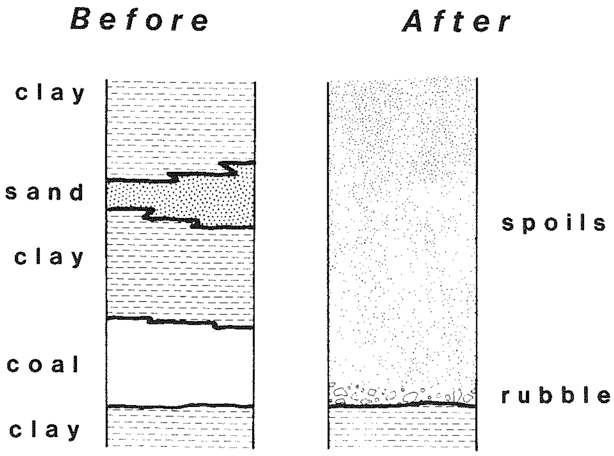

Figure 4—Mining operations inadvertantly create mine-floor aquifers consisting of boulders and rubble covered by finer-grained spoils materials.

mathematical equations. Trends seen in the field resemble those found in the laboratory, but unfortunately at only a small percentage of sampling points. A longer time period is clearly necessary to establish geochemical equilibrium between ground water and mine 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 spoils water 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 may be derived from montmorillonitic and chloritic clays, respectively. Additional magnesium may be released from dolomite, and calcium is released from calcite. The salts thus created accumulate or mobilize, depending upon the availability of water to transport them. 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 15 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 abnormally high and deeply continuous vertical permeability is required to allow percolating water to penetrate below the root zone. Unfortunately, these conditions do not occur widely, therefore the salts are not mobilized sufficiently to be flushed from the overburden profile.

In the undisturbed (pre-mining) system, soluble salts accumulate at various depths, established by the depths and rates of deep percolation of recharge waters. **Figure 5A** shows an overburden profile where unusually deep percolation occurs, probably in sandstone. 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 5B** represents conditions where only shallow percolation occurs.

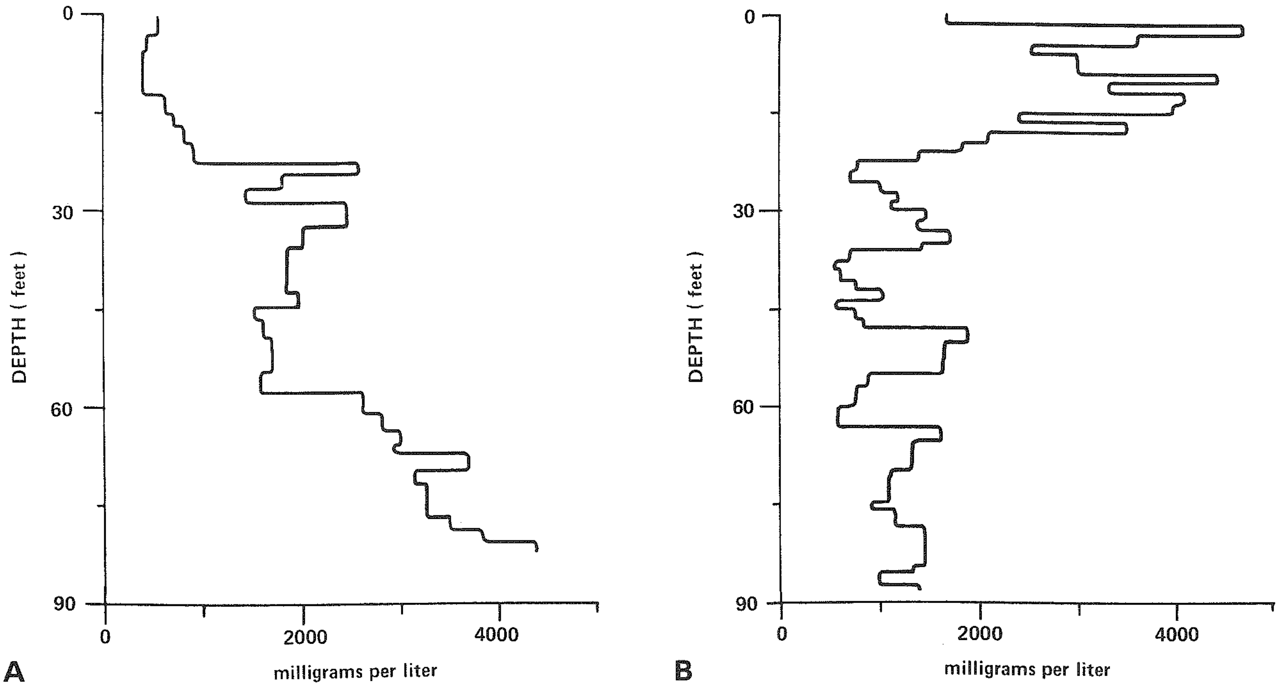

Figure 5—Soluble salts accumulate at various depths depending upon efficiency of percolating water. In 5A, deep percolation occurs in contrast to that at 5B.

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 are provided by Moran and others (1978).

Soluble-salt distributions (**Figure 5**) are known in overburden in all mine areas in southeastern Montana as data are required for reclamation planning. The most common is the condition illustrated in **Figure 5B**, where extremely large amounts of salts are concentrated within 50 feet below land surface. Unfortunately, under most mine plans, overburden stratigraphy is inverted during mining, with shallower overburden being placed closer to the mine floor where it will subsequently become saturated by ground water. Also, a current practice is to bury materials with high salt content as deeply as possible to enhance the viability of 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 can help enable rough predictions of chemical qualities of post-mining ground waters and their potential offsite effects.

Predictions of spoils-water quality

Pre-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 availabiity 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 currently are required by western states during pre-mining planning for revegetation purposes; application of the data to hydrologic studies has been an additional benefit. Though often used for water-quality predictions, the paste-extract data give only approximations of average concentrations that might be expected in a given mine area. Concentrations in the paste extracts are similar to average concentrations in first pore volumes of leachates (Van Voast and others, 1978b).

Pore volume is a term used to represent the volume of water that would occupy a given volume of spoils. It is applied to very small amounts of materials as in paste-extract analyses (about 250 grams), as well as to large acreages of mined lands. In common practice, paste-extract (or batch-leach) data for coal overburden are averaged to predict an approximate chemical quality for future mine spoils, and can be interpreted incorrectly to imply uniform concentrations along a flow path in the field. In field situations however, actual concentrations vary by orders of magnitude, depending upon factors including source of recharge, availability of salts, partical grain size, and distance behind the newly established wetting front.

To examine the relationship between dissolved-solids content and distance behind a wetting front, leach columns were modified by emplacing specific-conductance probes at incremental distances along the flow paths; a program of spoils leaching in eastern Montana was subsequently conducted. Results showed consistent distributions of dissolved solids approximated by an empirical curve (**Figure 6**) that fits the the equation $C/C_0 = e^{-kn}$. This is a basic first-order dissolution equation (Lerman, 1979, p. 233) in which C_0 is the maximum (and first) concentration measured in the column effluent; C is any subsequent concentration measured after n pore volumes of effluent; and K is a rate constant (for this set of tests between 0.9 and 1.8). From measurements along the column flow paths, the above relationship was found to apply to incremental pore volumes as well as to that of the entire column. The factor n, therefore, can be normalized by $n = (1-d)/d$, where d is the fractional distance along a flow path (**Figure 6**). For example, along a 100-foot flow path, four pore volumes have leached the first 20-foot increment, one pore volume has leached the first 50-foot increment, and so forth.

The distribution curve was developed from specific-conductance values; of the ion species, it probably best applies to sodium, magnesium, and sulfate

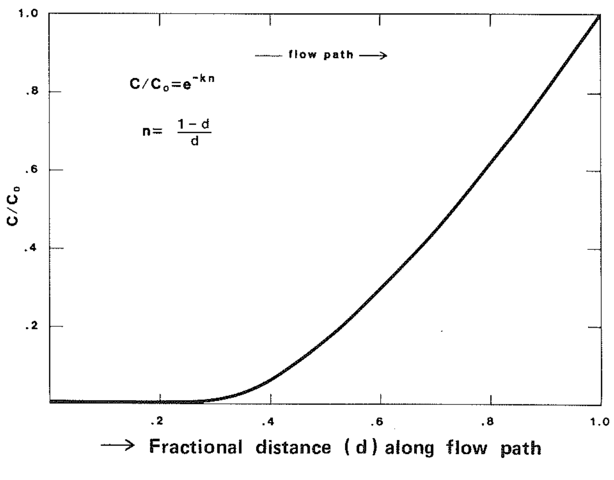

Figure 6—Under conditions of lateral flow, chemical concentrations (primarily sodium, magnesium and sulfate) in spoils water should increase in the downgradient direction.

concentrations as they are least limited by solubility constraints. These ions also contribute the bulk of dissolved solids in spoils waters, accounting for abnormally high concentrations relative to those in the pre-mining system. The distribution curve (**Figure 6**) clearly shows that, under ideal conditions of lateral inflow of uniform quality, highest concentrations in mined-land ground water should be found farthest downgradient in the spoils. Recurring influxes of dissolved solids such as by periodic events of recharge from the spoils surface, are not accounted for by the idealized distribution, and would cause deviations in the field data from the theoretical curve (**Figure 6**).

A common estimate in studies of proposed surface mines is that approximately one pore volume of water must circulate through mine spoils before a pre-mining salt balance is restored. Applying **Figure 6** to a flow path from 0 to 0.5 simulates the concentrations that would remain after one pore volume had passed that distance. The remaining concentrations should all be less than 20 percent of the maximum that had occurred. The one-pore-volume conclusion, therefore, seems to be a reasonable estimate for approaching a pre-mining salt balance, but only in the absence of recharge from the spoils surface.

Long-term data collection

Program description

More than 200 wells are monitored by the Montana Bureau of Mines and Geology in and near the surface coal mines of southeastern Montana. The wells fall into three general categories; in each there is a particular, but not exclusive, value to maintaining a long-term period of record.

(1) *Observation wells where ground-water is judged nonsusceptible to changes created by mining.* Data from these wells are necessary for defining natural conditions. They are irreplaceable in addressing unsuitability petitions and in preparing environmental statements. They show base-line trends and cycles not discernable near areas of active exploration or mining.

(2) *Observation wells where ground water is judged potentially susceptible to changes created by mining.* Monitoring reveals the degree and extent of water-level declines, and provides indications of probable cumulative drawdowns that can be expected with future mines. Records have shown continuous changes in ground-water systems caused by natural and mining-induced conditions. The observation wells that are peripheral to and in proximity to the mines show real effects, and will remain important so long as mine pits are active.

(3) *Observation wells in mine spoils.* Data from these wells help to differentiate reality from conjecture where predictions of post-mining water levels and qualities are necessary. The most important knowledge of mining hydrology thus far has come from observation wells in mine spoils; continued monitoring will yield important additional information.

Methodology

Water-level measurements are recorded monthly at most wells to an accuracy within 0.01 foot. Continuous water-level recorders are utilized on key wells where cyclic fluctuations or other relatively rapid changes are anticipated. Water-sampling is conducted as funding permits; samples are obtained primarily by use of a hand-operated PVC bailer. Water-quality parameters analyzed in the laboratory include major constituents and a wide range of trace elements. All analyses are conducted by the Montana Bureau of Mines and Geology Analytical Division laboratory in Butte.

Colstrip area

Hydrogeologic overview

Two general hydrogeologic studies of the Colstrip area (Renick, 1929; Van Voast and others, 1977) provide data on the geology and hydrology. Numerous other geochemical reports by mining companies, consultants, and federal and State agencies also discuss the area, particularly addressing environmental concerns over future mining. A full collection of those documents can be found at the Montana Department of State Lands in Helena.

The area can be characterized as semiarid, having little perennial streamflow, and being highly dependent on ground water for stock and domestic supplies. Average annual precipitation for the period 1927 through 1985 was 15.52 inches (U.S. Department of Commerce, 1985), of which approximately 60 percent fell during the growing season (May through September). Average annual temperatures for those years was 46.2° F.

Most streams flow only during periods of snowmelt and after infrequent events of high-intensity rainfall. East Fork Armells Creek, downstream from Colstrip, has a perennial flow generated by continuous ground-water discharge. An estimate of average annual runoff, made by applying precipitation and evaporation data to water budgets for stock reservoirs having year-round storage, is about 0.09 inch per year.

Most ground water is obtained from alluvium (unconsolidated deposits of silts, sand and gravel) and consolidated beds of coal, silt and sand of the Tongue River and Tullock members of the Fort Union Formation **(Figure 7)**. Alluvium and the Rosebud and McKay coal beds are the only significant aquifers that are being (or will become) disturbed by mining. Aquifers stratigraphically lower than the Rosebud and McKay beds generally are hydrologically isolated from them by beds of poorly permeable clay. The monitoring program examines hydrologic changes in the alluvium, the Rosebud and McKay beds, and a deeper lying sand bed (here called the "sub-McKay").

Ground-water flow in the aquifers of concern is primarily eastward across the area **(Figure 8)**. The flow patterns are controlled by the structural gradient, variations in transmissivities, and outcrop geometries. Most recharge occurs in uplands west of the active mines. Discharge from the consolidated aquifers drains to alluvium along watercourses of the area.

History of mining

Mining began near Colstrip in 1924 when Northwestern Improvement Company, then a subsidiary of Northern Pacific Railway Company, opened the Rosebud mine **(Figure 8)** which operated until 1958; Western Energy Company, a subsidiary of Montana Power Company, reopened the mine in 1968 and completed its southern portion in 1974. During the cumulative period of its operation, about 2,000 acres of land had been disturbed. Mine cuts have since been opened in area E (1972), area A (1974), area B (1975), area C (1983), and area D (1986). Total pit disturbance of the Rosebud mine is now more than 5,000 acres.

In 1969, Peabody Coal Company opened the Big Sky mine, located about 5 miles south of Colstrip. This operation (Peabody's development area A) has affected about 1,250 acres of land surface. Upon completion of operations in area A, mining activity will concentrate in Peabody's area B **(Figure 8)**. The Rosebud coal bed is the target of mining at the Rosebud mine; both the Rosebud and McKay coal beds are extracted at the Big Sky mine.

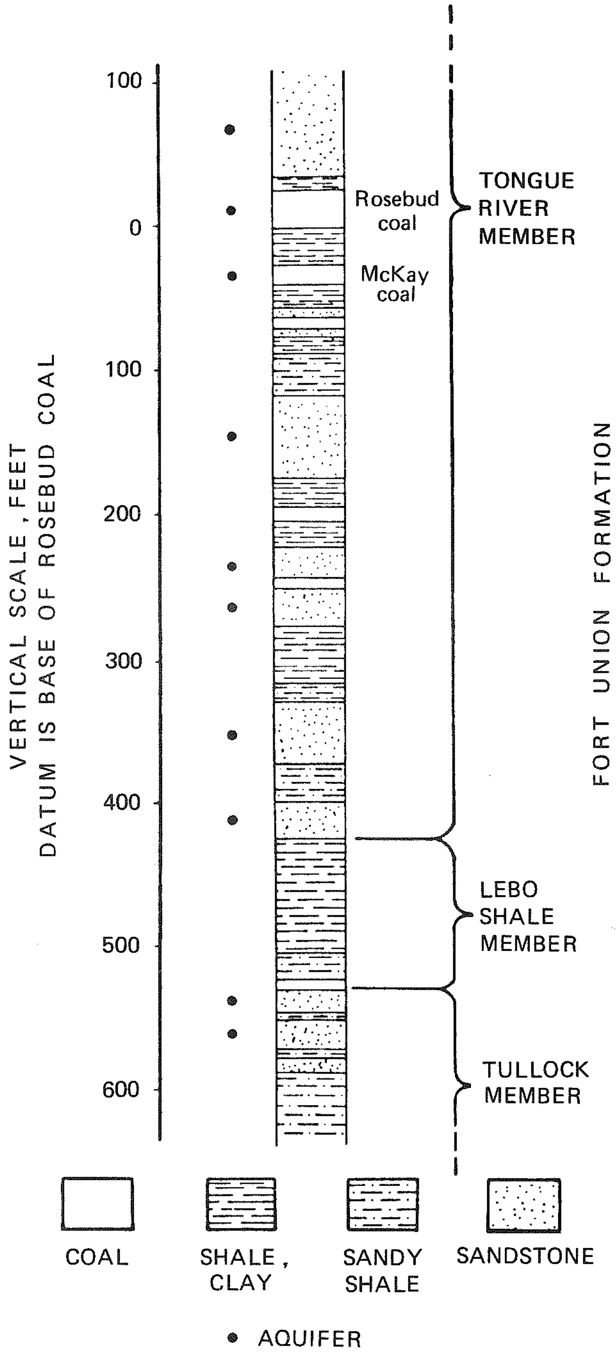

Figure 7—Near Colstrip, the Rosebud coal is being mined at the Rosebud mine, and the Rosebud and McKay coals are being mined at the Big Sky mine. Both beds are important aquifers.

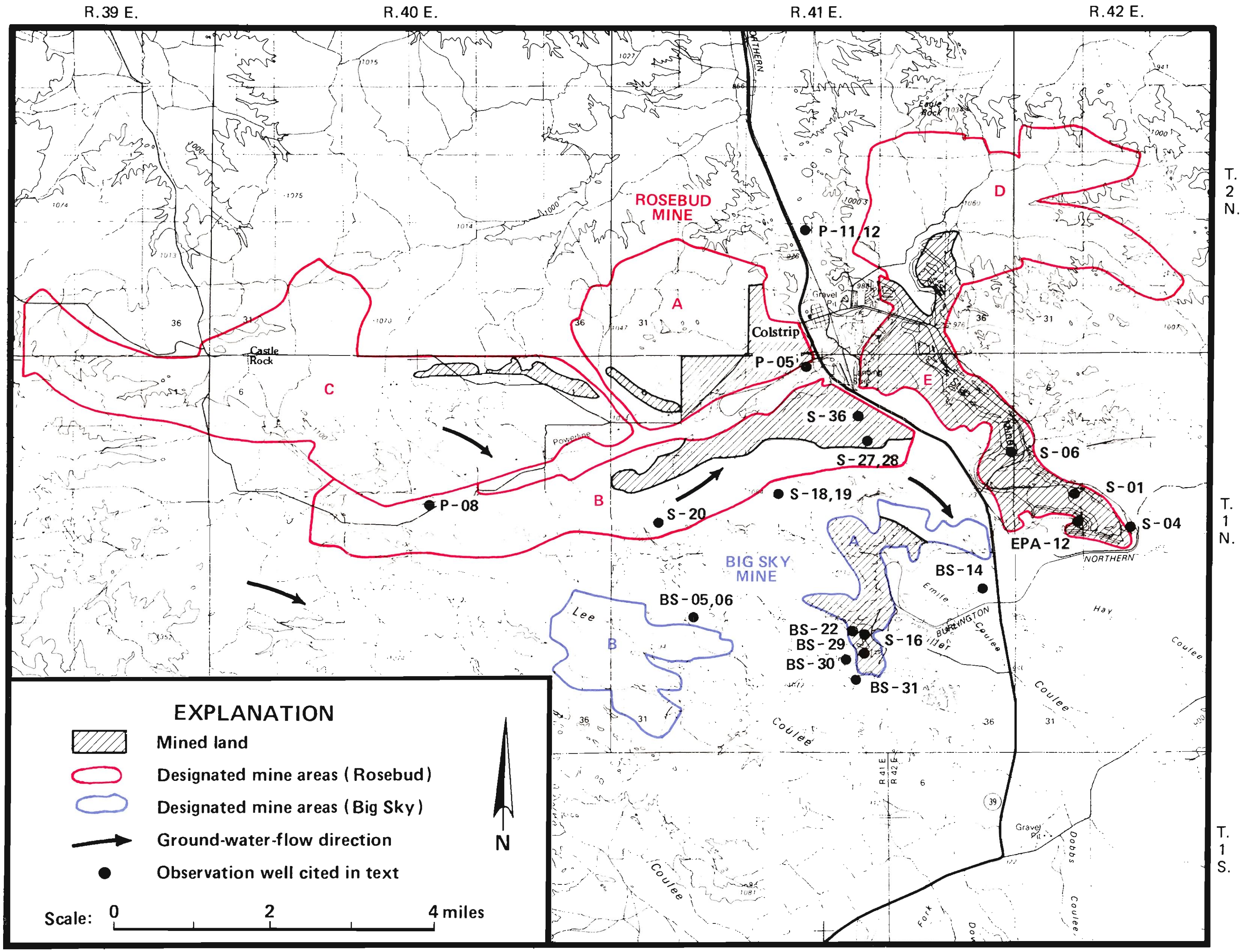

Figure 8—Many wells are monitored in and near the Rosebud and Big Sky mines. Those mentioned in this report are shown here.

Water levels

Nonsusceptible to mining

Water levels in alluvium have been a particular concern since large-scale mining began because of dependency of streamflow and subirrigation on shallow aquifers. Along East Fork Armells Creek, downstream from the Rosebud mine, water levels at well P-11 *(Hydrograph 1)** show occasional recharge peaks from precipitation or snowmelt and also show a very slight rising trend since 1980. Upstream from the Rosebud mine, well P-08 is completed in coal directly beneath the alluvium and shows almost identical conditions to those at the downstream site. Similarly, water levels in alluvium downgradient from the Big Sky mine have been unaffected by mining. Well BS-14, one of several wells installed because of State and local concerns for a nearby area of subirrigated alfalfa, shows that no significant changes have occurred there.

In general, the hydrologic budget in alluvium in the Colstrip area does not appear to have been changed by mining. Local changes, however, probably do and will occur depending on hydraulic connections between pits and aquifers. One such example is described below.

Potentially susceptible to mining

Water levels in alluvium along the East Fork Armells Creek near area B of the Rosebud mine have declined somewhat because of mining. In that vicinity, local ground-water flow is normally northward from area B toward the alluvium (**Figure 8**). Since 1974, water levels in the alluvium (well P-05) have responded cyclically to periodic recharge events, as they have at other locations, but also have declined about 3 feet as the active pit in area B intercepted normal ground-water flow toward the watercourse. This is only a local diversion of ground water, given the absence of effects further downstream at well P-11.

Water levels in coal-bed aquifers, both mined and unmined, are also responding to drainage by active pits. Pits creating the greatest declines are those at area B of the Rosebud mine and area A of the Big Sky mine. The greatest water-level declines have resulted from losses in hydrostatic pressure in the McKay coal bed, even where the bed is not disturbed by mining. Potentiometric drawdown of the McKay aquifer was not expected during pre-mining studies because clay beds above it were considered poorly permeable enough to isolate it from mining effects. Non-plugged drill holes and/or fractures created by explosives during mining may have created the unanticipated vertical hydraulic connection. The large numbers of exploration and core holes drilled before mining are suggested as the likely cause. Wells S-27, S-18, and S-20 (*Hydrograph 2*) demonstrate the hydraulic connection and also suggest a strong formational heterogeneity. These wells are aligned roughly east-west across area B of the Rosebud mine, and are completed in the McKay coal bed about 15 feet stratigraphically below the Rosebud coal bed. The pit in area B was opened in 1975, near well S-27, and has since moved progressively westward past well S-18 and toward well S-20. Water levels at each well reacted suddenly to the approaching pit, probably because of fracture patterns and faults that trend northwestward, transverse to the direction of mining. Formation heterogeneity, giving relatively high transmissivity parallel to the fracture trend, may be responsible for these sudden reactions.

Water-level declines for the Rosebud coal bed have been considerably less than those for the unmined McKay coal bed. For example, at wells S-19 (Rosebud coal) and S-18 (McKay coal), which are at the same location, declines were about 5 feet and about 25 feet respectively. The difference suggests, given equal storage coefficients, a five-fold greater transmissivity for the McKay coal bed, or, given comparable transmissivities, a multi-fold, greater storage coefficient for the Rosebud coal bed. The presence of thick sand beds in the Rosebud overburden supports the possibility of a greater storage coefficient for a combined coal and sand-bed aquifer in that locale.

Mining of the Rosebud and McKay coal beds at area A of the Big Sky mine is also causing declines of water levels, but to a lesser extent from those described above. *Hydrograph 3* for wells BS-05 (McKay coal bed) and BS-06 (Rosebud coal bed), which are at the same location, demonstrate the relative magnitudes of drawdown. Here, also, the water-level declines have been greater in the McKay coal bed.

As mine pits are progressively extended and spoils are backfilled into mined-out segments, water levels in nearby aquifers gradually recover. The degree of recovery in the Colstrip area is not yet known because the periods of monitoring and mining have not been great enough. Examples of post-mining recovery for the Rosebud coal bed are given by hydrographs of wells BS-30 and BS-31, which are near the backfilled part of area A at the Big Sky mine.

In mine spoils

Along with recovery of water levels at undis-

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*Hydrographs 1-5, Colstrip area, are shown on **Sheet 1, back pocket.**

turbed locations, resaturation of the backfilled mine spoils occurs by lateral and vertical inflow from undisturbed aquifers, and by recharge from rainfall and snowmelt. Resaturation occurs over periods ranging from a few months to a few years and, given the semiarid climate, is initially caused by lateral and vertical inflow from other aquifers.

Resaturation of spoils in area B of the Rosebud mine is now occurring and, in some cases, pre-mining water levels are being approached. For example, at well S-28 *(Hydrograph 4)*, the Rosebud coal bed has lost about 10 feet of hydrostatic pressure before the well was mined out in early 1982. Well S-36, in spoils near that location, has since recorded about 6 feet of resaturation. The present water-table altitude is now close to the pre-mining level for the McKay coal bed, and is approaching that of the Rosebud coal bed.

Area E of the Rosebud mine has been partially dewatered by pre-1958 mine cuts. More recent mining and backfilling have created little or no change in water levels. Reportedly, area E will soon have additional reclamation and backfilling; future monitoring should show substantial rises in water levels.

Mine spoils southeast of area E were reclaimed prior to 1974, and water levels there have reached dynamic equilibrium with available recharge. Spoils well S-01 shows cyclic periods of recharge, but only during periods of ideal conditions, such as the extremely wet spring of 1975 and the high snowmelt springs of 1978 and 1979. Well EPA-12 *(Hydrograph 5)* records strong recharge near an impoundment in the spoils. Here, runoff is concentrated at the center of the surface depression (in some years a pond), and a recharge mound about 20-feet high has developed. Unquestionably, closed basins created during reclamation can contribute substantial recharge to mined lands, particularly where spoils contain substantial percentages of sand.

Equally dramatic resaturation of spoils is being recorded in reclaimed parts of area A at the Big Sky mine. At well BS-29, a saturated zone more than 20-feet thick became established approximately 3 years after backfilling and reclamation. Here, recharge is thought to have occurred laterally from undisturbed aquifers. Comparisons of this hydrograph with those presented earlier for Rosebud coal wells (BS-30 and BS-31) clearly demonstrate post-mining recoveries of water levels in spoils and in adjacent aquifers.

From all indications it appears that mine spoils are becoming new hydrogeologic units, enhancing rather than impeding ground-water flow, and in the future may provide adequate quantities of ground water to wells. Questions of water quality are not so clearly answered, however, because of the broad range of conditions being observed.

Water quality

Nonsusceptible to mining

Water quality is being monitored at a few selected locations upgradient from any present mining operations in order to characterize uniformity or variability of natural conditions. Only a few of these wells are monitored because uniformity is the expected state, and has been the case at most locations. Water quality at well P-08 **(Figure 9)**, far removed from any mining disturbance, is an unexplainable exception, however. Dissolved-solids content at this site has more than doubled since 1975; ion percentages **(Figure 2)** suggest approximate equivalent increases in calcium-plus-magnesium and in sodium, with a disproportionate increase in sulfate.

Such increases in concentrations dominated by sulfate are commonly caused by climatic changes that increase recharge, or by land-use changes including farming practices, drainage modifications, or mining. Mining is an unlikely cause at this site because of distance and an unfavorable gradient from pits or spoils. This assumption will be relevant to judgments on causes of water-quality changes at locations farther downgradient.

Potentially susceptible to mining

Ground water in this category is downgradient (vertically or laterally) from mine spoils, the premise being that mining cause changes in water quality and that affected waters might enter undisturbed aquifers. The possibility of vertical migration is problematical, given the generally high clay content in the non-coal beds. Vertical hydraulic continuity exists, however, because drawdowns are being observed for aquifers stratigraphically lower than the pit floors *(Hydrograph 2)*.

Regardless of the demonstrated potential for migration of mined-land waters, they have thus far affected stratigraphically lower or off-site, groundwater quality in only isolated locations. The flow in East Fork Armells Creek is maintained by groundwater discharge, so shallow aquifers nearby would be likely places where increased concentrations have occurred (well P-05). They are similar, however, to those upstream (well P-08), so they are not likely mining related. The ion-content percentages at both locations have changed almost identically, suggesting a common cause.

Downstream of the Rosebud mine and the town of Colstrip (well P-12), concentrations (since 1985)

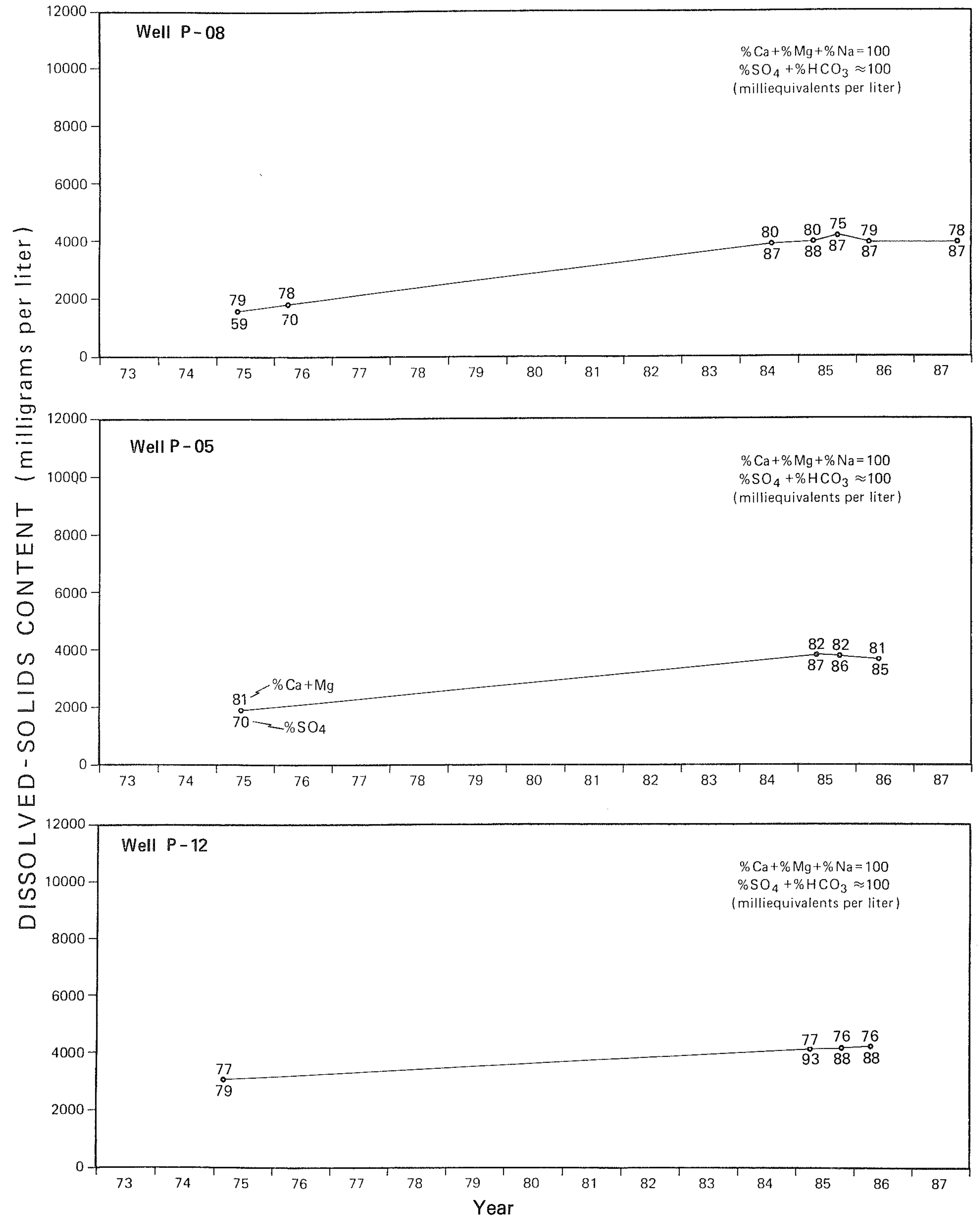

Figure 9—Dissolved-solids contents and sulfate percentages have increased in shallow ground water along East Fork Armells Creek upstream from mining (well P-08), near mining (well P-05), and downstream from mining (well P-12).

are also markedly higher than 1975 levels, and the increase in sulfate-ion percentage has also been disproportionately high. Data thus far indicate that, with respect to major chemical constituents, shallow ground-water quality along East Fork Armells Creek has changed substantially since 1975, but the changes downstream of all activities of mining, urbanization, and operations ancillary to power plants do not differ significantly from those upstream from those activities.

Pre-1958 operation of the Rosebud mine likely has caused off-site changes in water quality, but without pre-mining data the areas affected and degrees of change are conjectural. It is relatively certain, however, that water-quality deterioration through downward leakage to the McKay coal bed and other stratigraphically lower aquifers has not occurred. Water in the McKay coal bed, 5 to 20 feet below the mined-out Rosebud coal bed (e.g. **Figure 10**, well S-06), has far superior quality to waters from other sources. The low percentage of sulfate at well S-06 relative to that at other sites is evidence that water quality in the McKay coal bed is not greatly influenced by products of chemical weathering. With probably few exceptions, water quality for the McKay coal bed, lying 15 feet below the mined-out strata, does not seem altered.

One recorded exception is the history of McKay water at well S-04 (**Figure 10**), where dissolved-solids content has fluctuated over a wide range, at times approaching a ten-fold increase over that considered normal for the aquifer. Influxes of dissolved solids were particularly high during periods of recharge from rainfall and snowmelt, such as those in 1976, 1977 and 1978. Since 1979, a dissolved-solids recession is apparent, reflecting a progressive flushing of salts. Future periods of above normal recharge may interupt the trend, repeating the cycle currently being observed. The influence of sulfide-oxidation products is particularly evident by the high sulfate percentages occurring with the high dissolved-solids peaks. The erratic nature of water quality at this site is probably a local condition. A well installed by Western Energy Company about 100 yards upgradient from well S-04 found water quality more typical of the McKay coal bed and similar to that shown for well S-06.

At the Big Sky mine, one instance of off-site water-quality change is attributable to mining. Dissolved-solids concentrations at well S-16 (**Figure 10**) increased strongly between 1980 and 1984. Ground water sampled at that site occurs in a shallow sandstone bed closely downgradient from the mine. The sandstone bed subcrops beneath alluvium and colluvium disturbed by mining upstream, and undoubtedly receives flow from the spoils. Percentages of calcium-plus-magnesium and sulfate increased with the dissolved solids, suggesting an influx of water rich in those ions.

In mine spoils

Post-mining ground water near Colstrip ranges from neutral to alkaline and generally contains substantially higher concentrations of dissolved solids than does ground water in undisturbed aquifers. Average dissolved-solids concentrations in coal beds are about 1,750 mg/L; average concentration in spoils water at the Rosebud and Big Sky mines are about 2,880 and 3,660 mg/L, respectively. Constituents that comprise most of the increases are sodium, calcium, magnesium and sulfate.

Statistical comparisons of qualities of spoils water and other ground water should be reassessed periodically. Temporal changes in spoils-water quality are evident at most observation wells, attesting to the newness of the spoils and their poor chemical equilibrium with recharge water.

At some locations, changes in chemical concentrations are related to changes in water levels; at others, trends of decrease or increase are apparent. The random changes represent variable salt distributions in unleached spoils. With longer periods of ground-water flow, trends should become established, depending upon salt balances. Where trends of decreasing concentrations have become established, salts are leached by ground-water flow more rapidly than they are replenished by recharge.

An example where flushing of salts has dramatically improved spoils-water quality is evident at well EPA-12 (**Figure 11**). The location is a small closed drainage basin in spoils at the Rosebud mine. Active recharge since 1974 *(Hydrograph 5)* has flushed most of the salts from the spoils. The increasing calcium-plus-magnesium percentage and decreasing sulfate percentage demonstrate a decreasing availability of sulfide weathering products. In places where recharge and ground-water flow occur at slower rates, such as at well S-01 (**Figure 11**; *Hydrograph 4*), dissolved-solids concentrations can vary directly with water levels or can increase with time. Ground-water flow at well S-01 is slow enough that soluble weathering products are introduced to the ground water more rapidly than they can be flushed from the system. The uniformity of ion percentages suggest that the weathering products are primarily calcium, magnesium and sodium sulfates.

A possible "worst case" situation for spoils-water quality is illustrated at well BS-22 at the Big Sky mine. Since 1979, dissolved-solids contents have more than doubled from earlier values that were already unusually high. At the same time, percen-

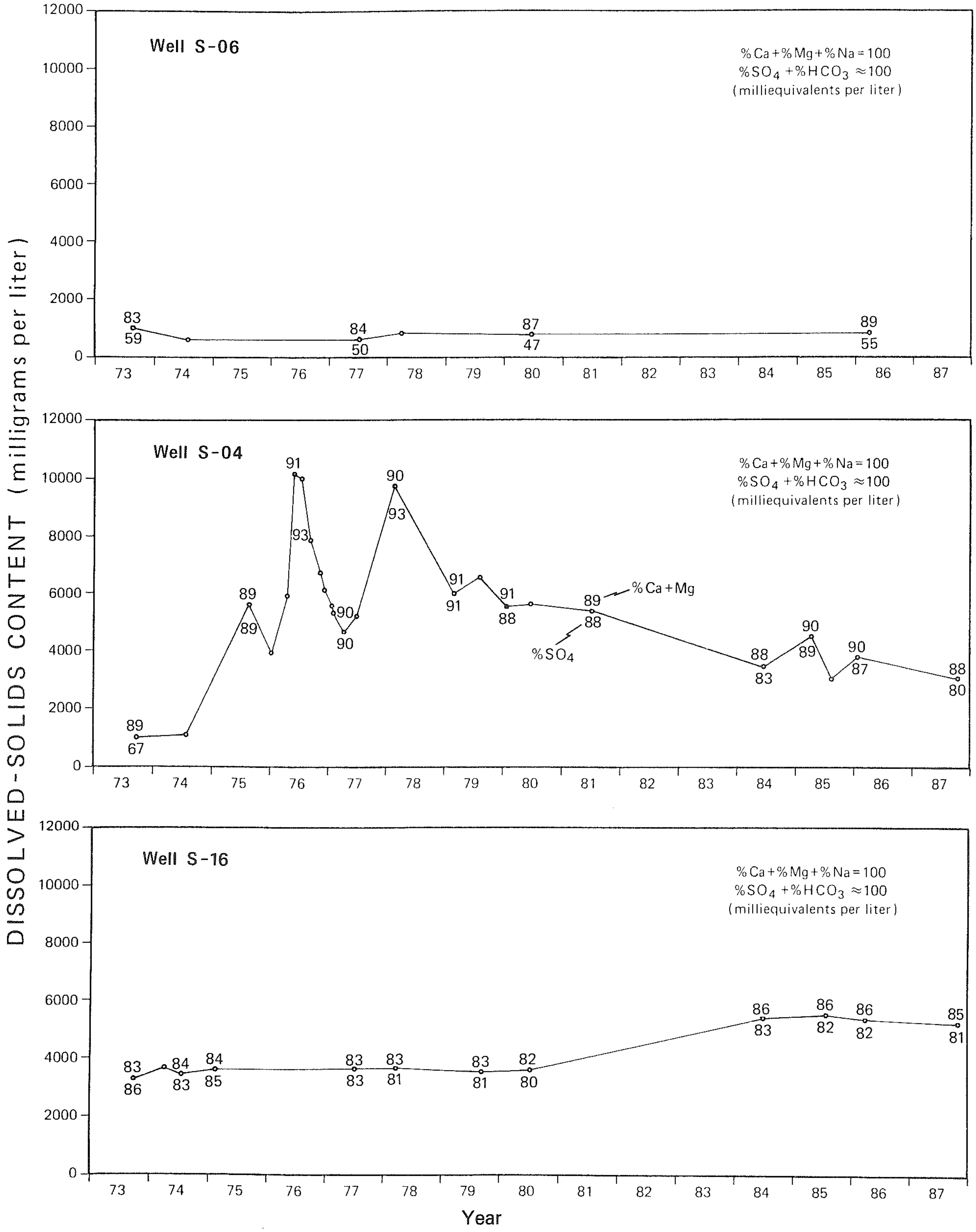

Figure 10—Off-site water quality in most places (well S-06) has been uniform since 1973. Local exceptions (S-04, S-16) may be mining related.

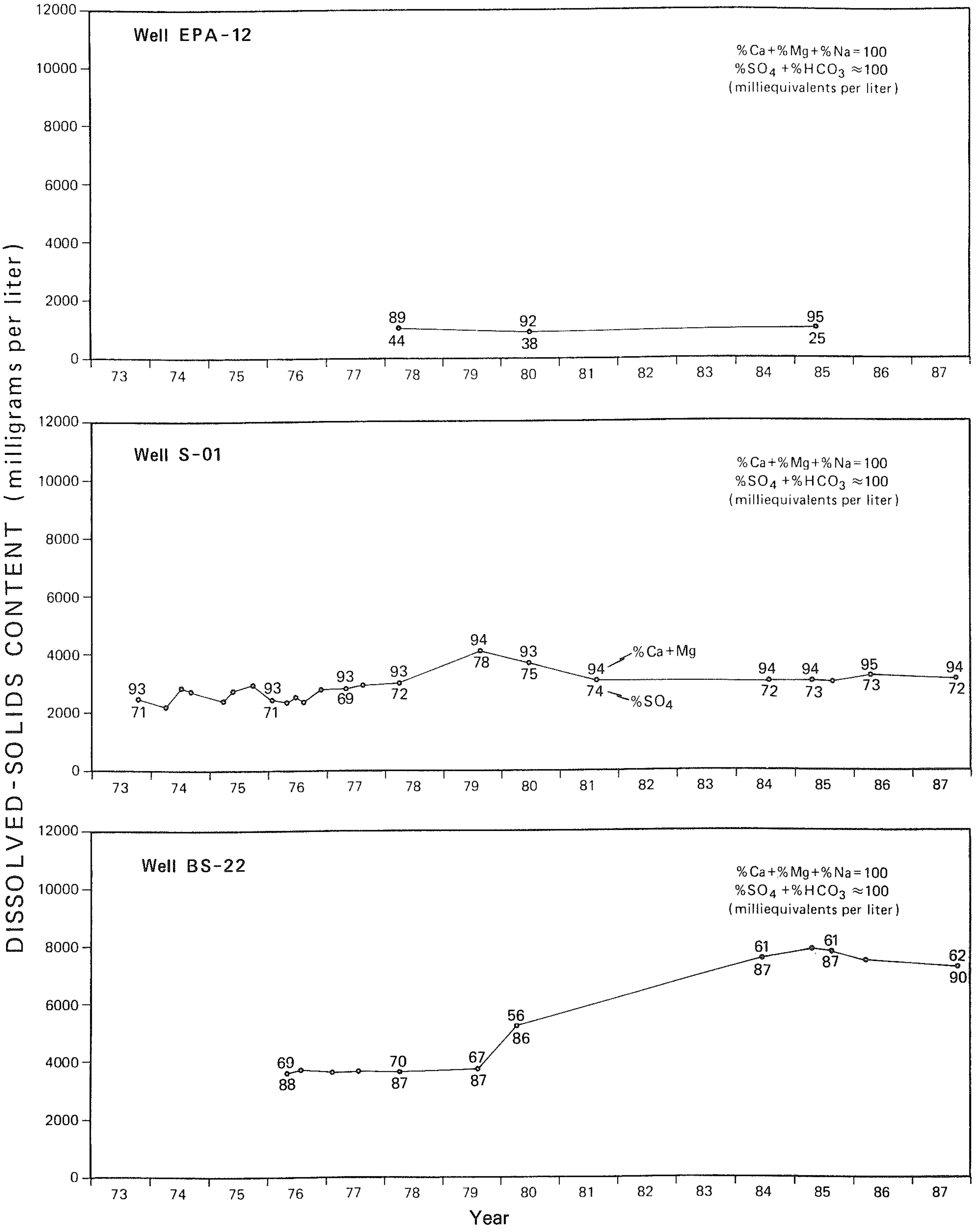

Figure 11—Soluble salts have been flushed from the spoils aquifer at well EPA-12; at well S-01 they are increasing, and at well BS-22 a local plume of highly mineralized spoils water has developed.

tages of calcium-plus-magnesium declined, indicating an influx of dissolved sodium at that site. Conditions were abnormal enough that the Peabody Coal Company installed several wells nearby, some within 10 feet of BS-22, to assess the extent of water-quality deterioration. None of the wells yielded concentrations that existed in BS-22. Likely, a very small plume of highly mineralized ground water is present at the site, and its importance in the overall water-quality regime is correspondingly small.

Decker area

Hydrogeologic overview

Several hydrogeologic studies of the Decker area **(Figure 12)** have been conducted (Van Voast and Hedges, 1975; Hedges and others, 1980; Thompson and Van Voast, 1981). Additionally, other volumnous works of federal environmental statements, consultant's reports, and company documents on the area also exist, and can be examined at offices of the Montana Department of State Lands in Helena.

The Decker area is semiarid, is transversed by several perennial streams, and is highly dependent on ground water for stock and domestic supplies. Average annual precipitation is about 12 inches, of which about 7 inches fall during the growing season (May through September). Perennial watercourses are the Tongue River and its tributaries, Squirrel Creek, Youngs Creek, and Little Youngs Creek. Flow occurs in other watercourses only during periods of relatively heavy precipitation or snowmelt.

Ground water is obtained from alluvium beneath the Tongue River flood plain and other watercourses, from clinker derived from burned coal beds, and from beds of coal, silt, and very fine-grained sand in the Tongue River Member of the Fort Union Formation. The most significant aquifers disturbed by mining are the D-1 and D-2 coal beds (Decker Coal Company nomenclature). In the eastern part of the area, the D-1 coal bed is split by beds of silt and clay **(Figure 13)**. The D-1 upper, D-1 lower, and D-2 coal beds have approximate thicknesses of 25 feet, 15 feet, and 15 feet, respectively. West of the Tongue River Reservoir the two uppermost beds are combined into a single unit that is approximately 50 feet thick. In the vicinity of Ash Creek, the D-1 upper coal bed is split from the other units by variable thicknesses of interburden. The most significant hydrologic effects from mining occur in the D-2 coal bed, as it represents the greatest areal continuity and contains water under the highest hydrostatic pressures.

The Decker mines are near the axis of a gently dipping S-plunging syncline. The synclinal structure is interrupted in the southern part of the area by NE-trending normal faults, on each of which the southeastern side is downthrown. Stratigraphic displacements across these faults are not uniform; where they bound the Decker and East Decker mine areas, their displacements are roughly 200 feet. Continuity of the coal beds northward from the proposed mine areas is interrupted where the beds have burned overlying strata into masses of reddish-colored, brittle, fractured rock, commonly referred to as clinker. Because of extreme fracturing created by collapse into voids left by the burned coal beds, the clinker is highly permeable and is hydrologically significant, primarily through its capacity to accept recharge.

Ground-water flow in the coal-bed aquifers is principally toward the Tongue River **(Figure 12)** from recharge areas in structurally high uplands outside of the mining areas. Before mining, discharge from the beds occurred mostly along subcrops beneath the Tongue River Reservoir; now, mining has temporarily altered the nature of the ground-water discharge.

History of mining

The West Decker mine was opened in early 1972 and was the first major mine in the area. A relatively small test mine, the Ash Creek mine, was opened in early 1976 and the East Decker mine was opened in 1977. Since commencement of operations, the Decker mines have remained in continuous production; the Ash Creek mine remains open, but production has been discontinued. Dewatering of the pit continues, however, creating hydrologic effects similar to those of an active mine.

Water levels

Nonsusceptible to mining

Special mention of water levels in alluvium near Decker is noteworthy because of subirrigation dependence and changes that are occurring in deeper-lying aquifers. In alluvium along Squirrel Creek about 2 miles southwest of the West Decker mine, water levels have not been affected *(Hydrograph 6)*.* Annual cycles of recharge/discharge have occurred causing as much as 2 feet of fluctuation in water-

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*Hydrographs 6-11, Decker area, are shown on **Sheet 2, back pocket.**

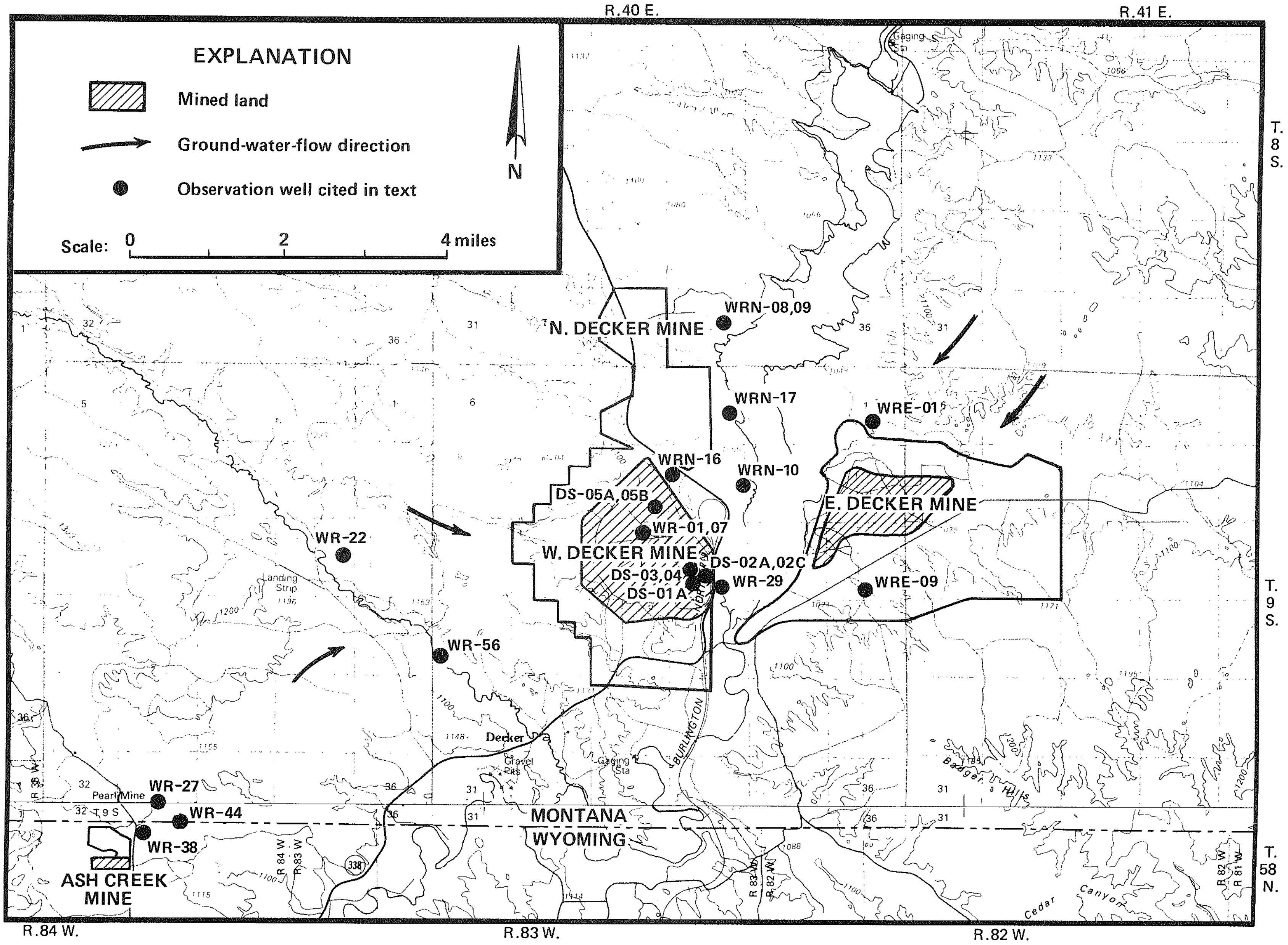

Figure 12—Ground water is monitored at several mines in the Decker area. Observation wells shown here are those mentioned in this report.

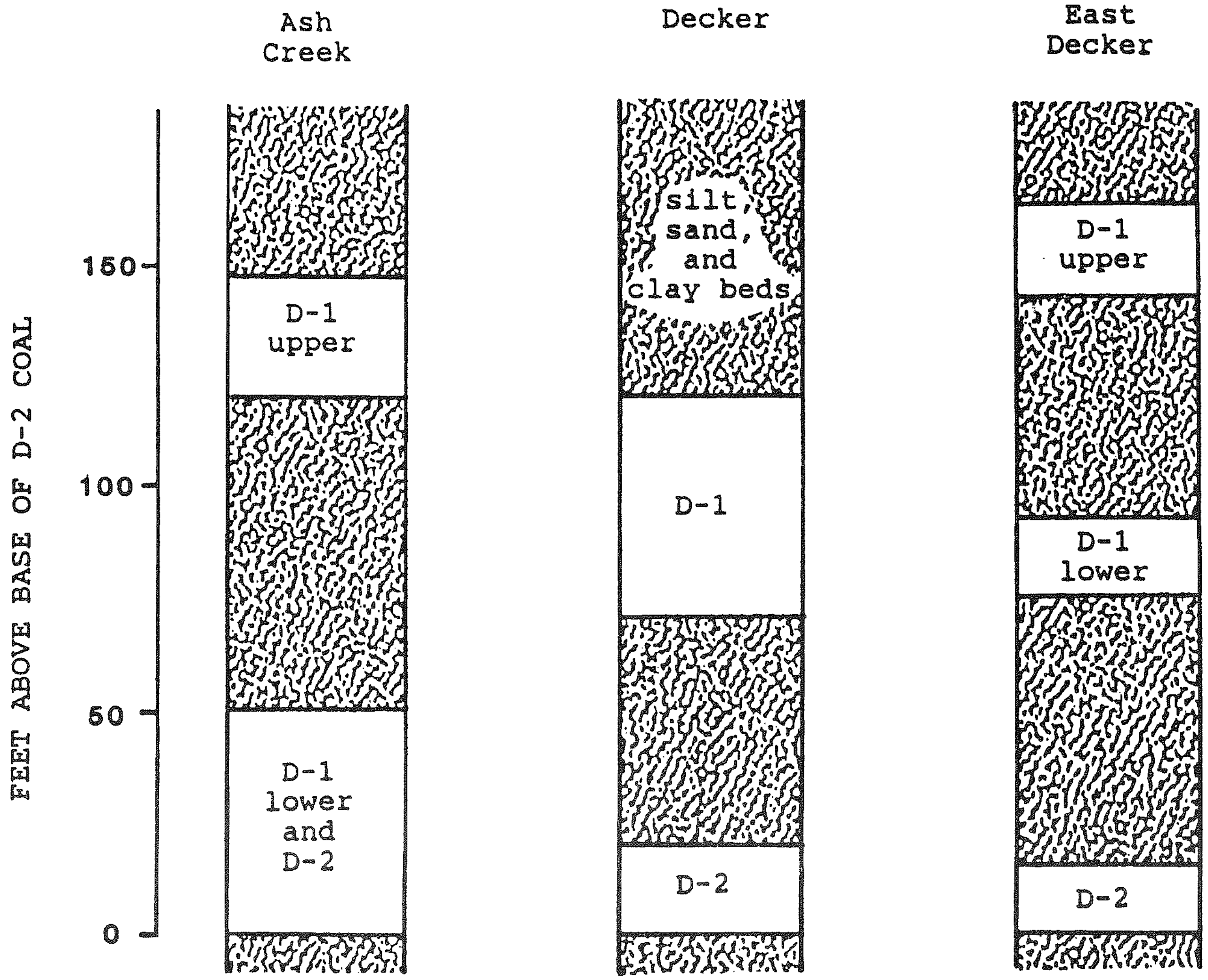

Figure 13—Coal beds being mined in the Decker vicinity are stratigraphically combined at one location or another. Coal-bed designations shown here are those used by the Decker Coal Company.

table elevation, but no long-term trends are evident. Similarly, water levels in alluvium along Youngs Creek at the Montana-Wyoming border reflect no influence of dewatering at the nearby Ash Creek mine in Wyoming, nor of mining at Decker. Alluvium along Deer Creek near the East Decker mine also has not been hydrologically affected *(Hydrograph 7)*. Water levels at this location reflect precipitation from the Deer Creek drainage basin and stage levels of the Tongue River Reservoir. [The declining water-table elevation after 1978 results primarily from lowered reservoir levels.]

Similar effects of reservoir stage on hydrostatic pressures in the D-2 and D-3 coal beds are also clearly shown by *Hydrograph 7*. Both beds subcrop beneath the reservoir north of the mining area, whereby the reservoir stage establishes a base level for hydraulic gradients. These interactions are evident only in wells within about a half mile of the reservoir.

Potentially susceptible to mining

Opening of the West Decker mine in 1972 created immediate changes in water levels for the D-1 coal bed (object of mining), as well as for the D-2 coal bed. Water levels in the D-1 coal bed *(Hydrograph 8)*, showed typical pre-mining conditions until the mine became operative. Following two years of mining, water levels were reestablished at an apparent equilibrium about 40 feet below their pre-mining elevations. As parts of the pit were backfilled with spoil, gradients from the Tongue River Reservoir lessened, and water levels partially recovered (1977-1980). During the years 1972-1981, water levels in the D-2 coal bed also declined, even though that aquifer was not disturbed by mining. The declines likely resulted from (1) upward flow to the mine pit through numerous pre-mining drill holes of the area, (2) upward leakage through confining beds, and/or (3) the latter enhanced by fractures created by blasting. In late 1981, the West Decker pit was deepened for extraction of D-2 coal, and water levels in that aquifer quickly declined to a total drawdown of almost 70 feet. Relatively constant levels during the last couple of years reflect recharge along the D-2 subcrop beneath the Tongue River Reservoir. Ground-water flow is currently reversed from its pre-mining direction, now being from the direction of the reservoir toward the mine.

Water-level declines in the coal-bed aquifers are being detected south and west of the West Decker mine. Three and one-half miles to the west, the potentiometric surface has declined 10 feet since 1981 when the pit was deepened to the D-2 coal bed. The trend continued through 1987 with no indication of induced recharge from a constant-head boundary. At the beginning of the record (September, 1975) at this location, mining had already been in progress for about 3½ years. During that time, water levels in other wells had dropped several tens of feet, so it is likely that the total decline at the location of well WR-22 is substantially greater than that shown.

About 4 miles farther to the southwest, drawdowns near the Ash Creek mine in Wyoming are clearly evident. This mine also penetrates the D-1 and D-2 coal beds that are being mined at Decker. Water levels near the mine dropped rapidly when the pit was opened in 1976, and by 1978 the declines exceeded 40 feet *(Hydrograph 9).* Within a mile to the northeast, at well WR-27, water levels in the coal-bed aquifers have dropped 10+ feet. The rapid transition from falling water levels to apparent new equilibria in this area is caused by recharge from a constant head boundary. The coal beds subcrop beneath alluvial aquifers along Little Youngs Creek within about a mile of the mine, and along Ash Creek within about 3 miles of the mine; either could be the source of recharge.

Opening of the East Decker mine created hydrologic changes similar to those described above when the D-2 coal bed was penetrated in late 1978. Water levels in that aquifer began a steady decline *(Hydrograph 10)*, and by January 1987, the level had dropped about 80 feet.

North of the Decker mines, water levels have been substantially less affected, primarily because of the influence of the Tongue River Reservoir. Technically important changes might be occurring, however, at wells WRN-10 and WRN-17, which are completed in the D-2 coal bed. Cyclic levels related to reservoir stage are clearly evident, demonstrating reservoir influence on water levels in coal subcrops beneath it. Water levels at both wells dropped abruptly in late 1978, corresponding to the same time that the East Decker pit was deepened to include the D-2 coal bed. The abrupt change to a lower base level may have been caused by hydrostatic-pressure reductions in the coal-bed aquifer passing beneath the reservoir. Changes in reservoir-management practices during the same period caused far less severe changes in ground-water levels *(Hydrograph 7).*

Drawdowns created by the West Decker, Ash Creek, and East Decker mines have created a potentiometric depression more than 15 miles long and 5 miles wide extending in a northeast-southwest direction, and contained between faults having the same trend **(Figures 14, 15)**. The faults are hydrologic barriers that restrict or prohibit transverse ground-water flow in the aquifers being affected. The potentiometric depression extends seemingly unaffected beneath perennial streams and alluvial aquifers that are hydrologically isolated from deeper-lying bedrock aquifers. This vertical hydrologic isolation caused by poorly permeable strata of the Fort Union Formation is a critical protection for shallow water supplies of high agricultural value, but acts to project mining effects over larger areas.

In mine spoils*

As active pits are being progressively moved and spoils are backfilled into mined-out segments, ground water is rapidly reentering the disturbed ground (well DS-03, *Hydrograph 9*). Lateral flow from adjacent aquifers and upward flow from deeper aquifers probably account for the greatest percentage of inflow, and it also appears that upward flow, at least for a few years, provided a substantial contribution. During exploration and planning for mine development, large numbers of test holes were drilled to obtain geologic information, and many were drilled to depths far below the beds targeted for extraction. In the earliest days of mining, test holes producing flowing water were observed on the West Decker mine floor; as long as gradients remained favorable, they undoubtedly enhanced recharge to spoils that covered them. Upward leakage through confining beds, perhaps through fractures created by blasting of the coal, is an often-suggested mode of recharge to the spoils, but has not been supported by direct observation and/or data.

Water levels in West Decker spoils reflect recharge both from upward and from lateral flow. Prior to 1981 at the northeast end of the pit *(Hydrograph 11)*, upward flow from the D-2 coal bed (well DS-05A) maintained hydrostatic pressures in the spoils (well DS-05B) at levels several feet higher than those in the adjacent clinker aquifer (well WRN-16). As the mine pit penetrated the D-2 coal bed in 1981,

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*Funding limitations prevented water monitoring in East Decker spoils. Hydrogeologic conditions at the two mines are similar, however, and data from West Decker spoils is probably representative of both areas.

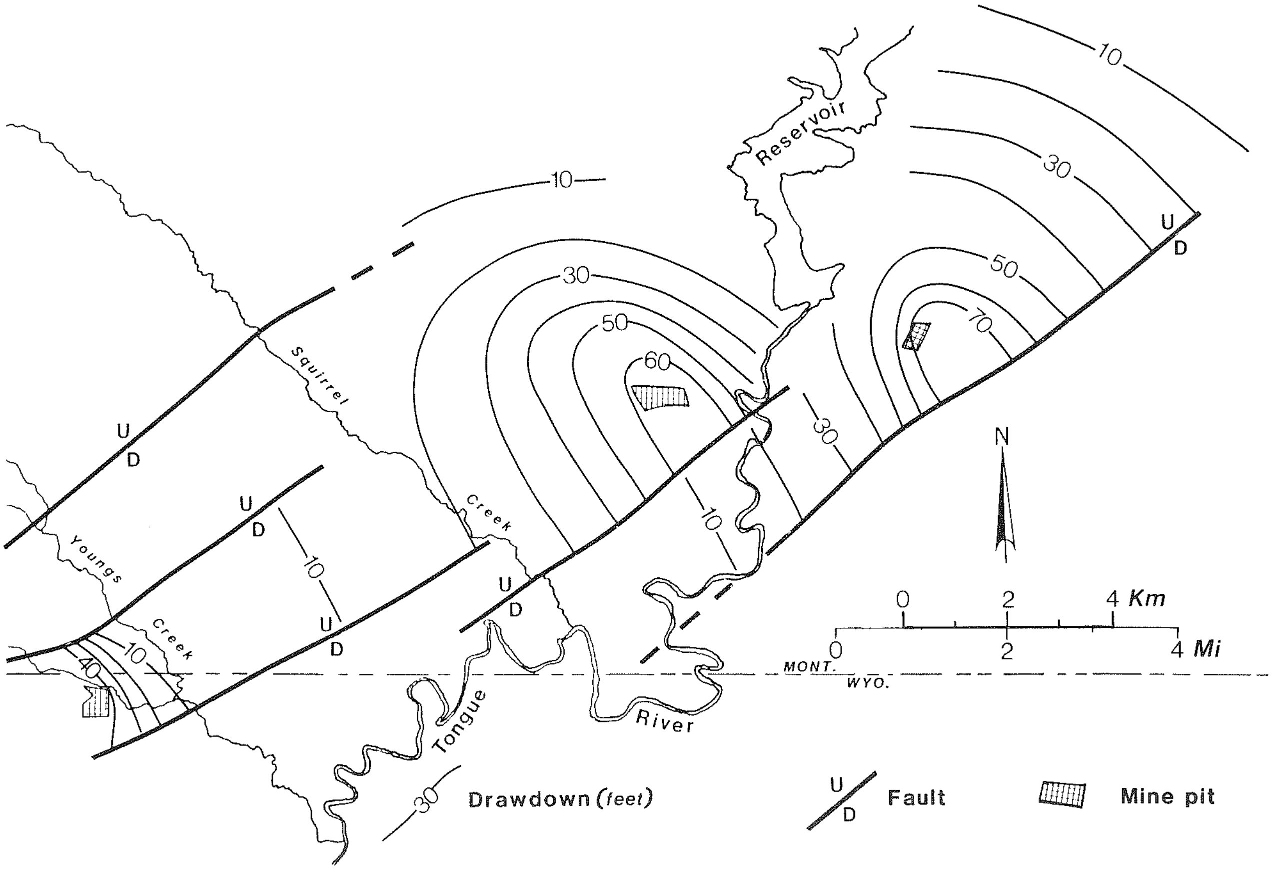

Figure 14—An area of potentiometric decline more than 15 miles long and 5 miles wide has developed for the D-2 coal bed.

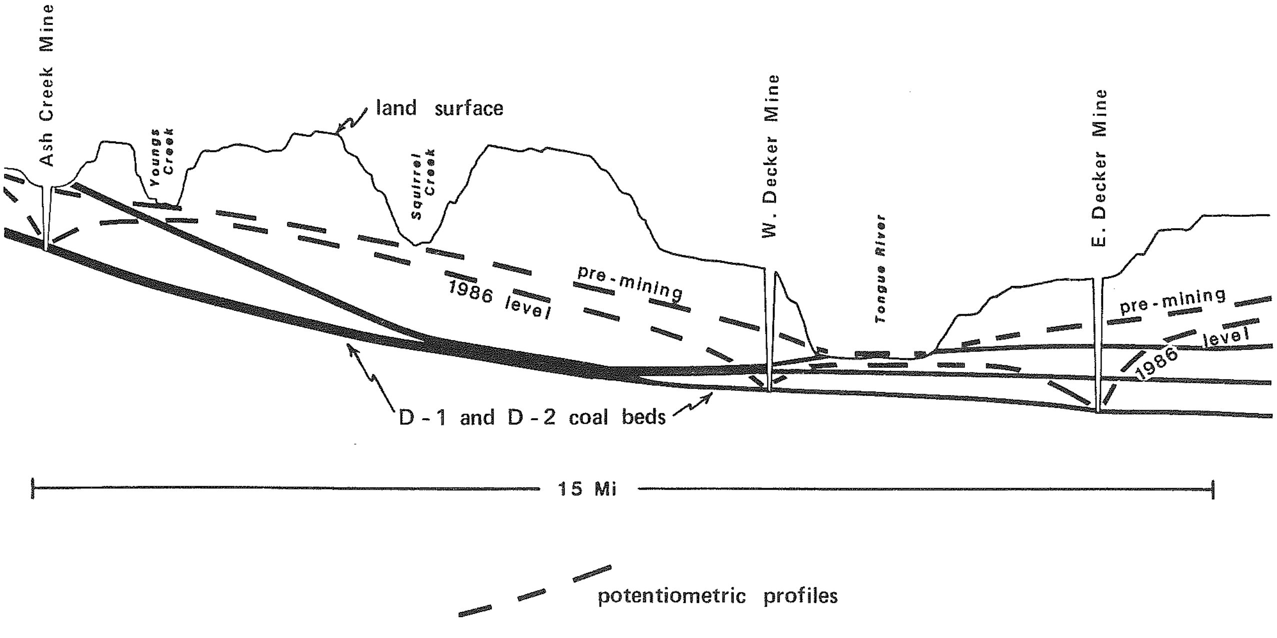

Figure 15—Lowered potentiometric levels pass unaffected beneath valley bottoms and perennial streams.

pressures dropped rapidly in the coal and more slowly in the spoils. A reversal of the vertical hydraulic gradient developed by mid-1982, and some downward leakage from the spoils to the coal may now be occurring. Little correlation between water levels in the spoils and in the nearby clinker is evident.

At the southeast end of the pit, recharge to spoils (well DS- 02C) appears to occur primarily laterally from alluvium along the Tongue River (well WR-29). Penetration of the D-2 coal bed in 1981 caused 50 or more feet of drawdown in the coal (well DS-02A), but no discernable change in water levels in spoils or in the nearby alluvium was observed. Unquestionably, the relative influences of vertical and lateral recharge vary greatly throughout the mined area.

Water quality

Nonsusceptible to mining

Ground water in this category occurs in undisturbed aquifers laterally upgradient from the mines, and in stratigraphically lower aquifers having higher hydrostatic pressures than those in the mine spoils. Under these conditions, hydraulic gradients disallow influence of water quality by migrating mine waters. These are "benchmark" data with which mining-related changes can be compared. Uniformity of concentrations over time has been clearly evident, demonstrating the equilibrium of ground-water quality with long-established patterns of flow.

Potentially susceptible to mining

Near the West Decker mine, consideration of wells where water quality may be susceptible to mining is somewhat problematical because of the dramatic changes in gradients that have occurred. Some of these wells can be affected only after the cessation of operations when ground-water flow resumes the approximate pre-mining patterns. Others are currently susceptible, but only while the mine is operating.

Those of the first type include WR-29 (**Figure 16**, *Hydrograph 11*), completed in alluvium that is currently recharging the spoils. When mining is completed at the West Decker mine, reversed flow patterns will drive spoils water toward the alluvium along the Tongue River; this well (with a long period of "benchmark" data for alluvium) will then provide essential information for appraising post-mining, off-site effects.

Currently susceptible, but probably not in the post-mining period, is water in the D-2 coal bed beneath the D-1 spoils (**Figure 16**, DS-05A on *Hydrograph 11*). The reversed vertical hydraulic gradient since 1982 is currently favorable for spoils water to recharge the coal. A cessation of mining will again reverse the gradient and flow direction, causing water-quality conditions, which at this time are unpredictable. Any water-quality effects of the 1982 gradient reversal are not yet evident at well DS-05A. Dissolved-solids content and ion percentages (**Figure 2**) in the coal remain the same as those under non-mining conditions.

In mine spoils

Water quality in Decker mine spoils is highly variable, both in location and in time. Recharge (laterally and vertically), a highly variable water table along the Tongue River, and the continuously-moving mine pits have created a very complex flow system. Changes in flow direction, including periodic reversals, have been common. Early monitoring data established average dissolved-solids concentrations of spoils-water and pre-mining ground water at about 2,500 and 1,750 mg/L, respectively, but average concentrations in the spoils water are constantly changing. In some cases the changes seem erratic over time; in others there is a suggested long-term trend toward improvement.

Figure 16 and *Hydrograph 11* for well DS-05B demonstrate erratic spoils-water quality. Early analyses found dissolved-solids contents and ion percentages very similar to those in the D-2 aquifer, possibly because of upward leakage from the coal to the spoils. Later dissolved-solids contents increased irregularly as soluble salts in the spoils were mobilized. Strong increases in milliequivalent percentages of calcium-plus-magnesium and sulfate account for much of the higher concentrations. Given the known paucity of surface recharge to Decker spoils, the increases are undoubtedly caused by dissolution of weathering products from the original overburden profile that was subsequently overturned and saturated near the mine floor.

Spoils-water quality at well DS-04 (**Figure 17**) demonstrates a somewhat more consistent dissolved-solids content with increasing percentages of calcium-plus-magnesium and sulfate; translocation of overburden weathering products to a position of saturation may explain the increases.

More encouraging results are being seen at spoils wells DS-01A and DS-03 (**Figure 17**). In both cases, high initial concentrations have been followed by trends of progressive decrease. Flushing of salts at these locations is clearly evident, an optimistic indication of post-mining conditions. Ideally, flushing of salts from spoils should proceed more rapidly in

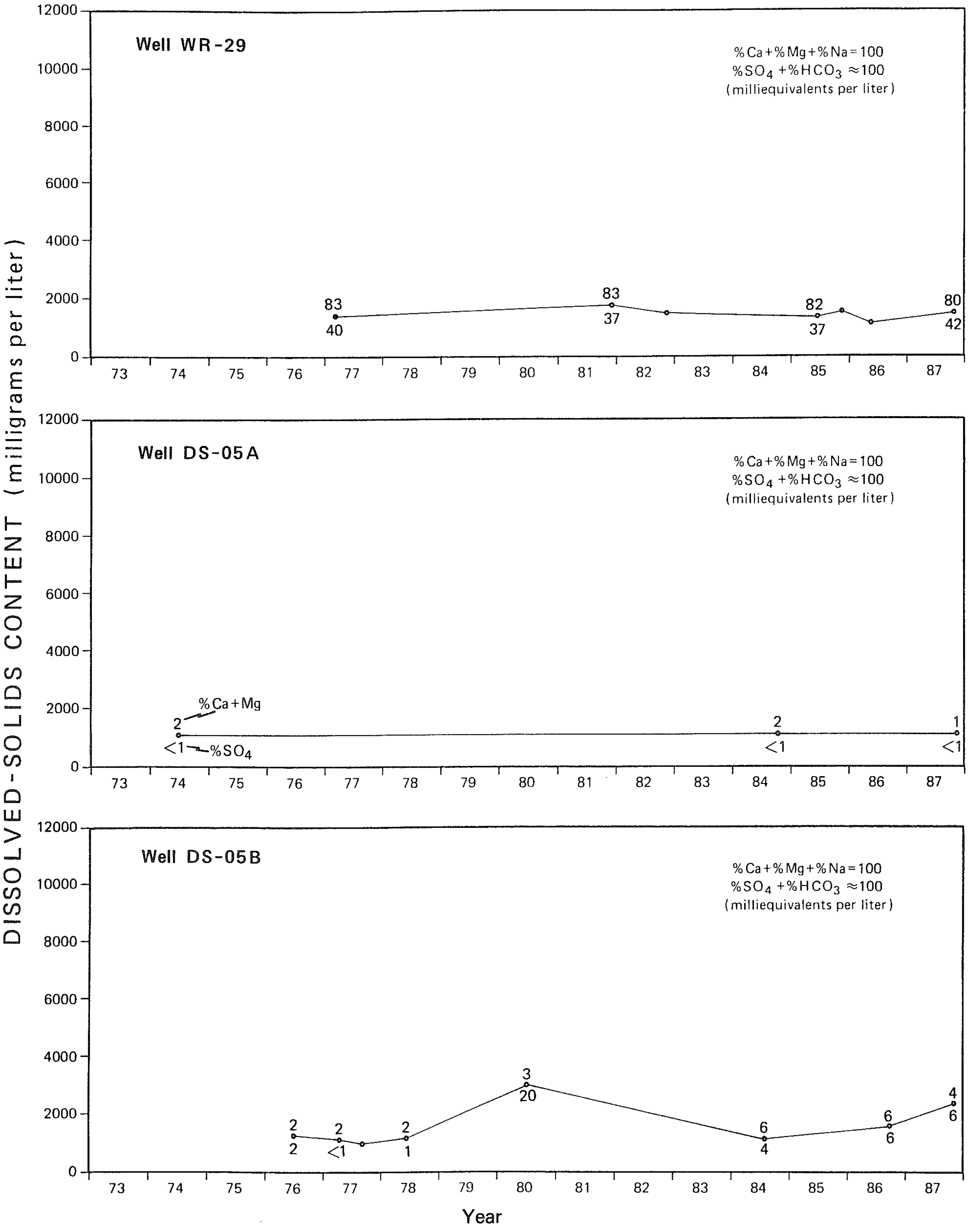

Figure 16—Water quality in Tongue River alluvium (well WR-29) and in the D-2 coal bed at the West Decker mine (well DS-05A) has been uniform. Quality of spoils water at well DS-05B has been erratic.

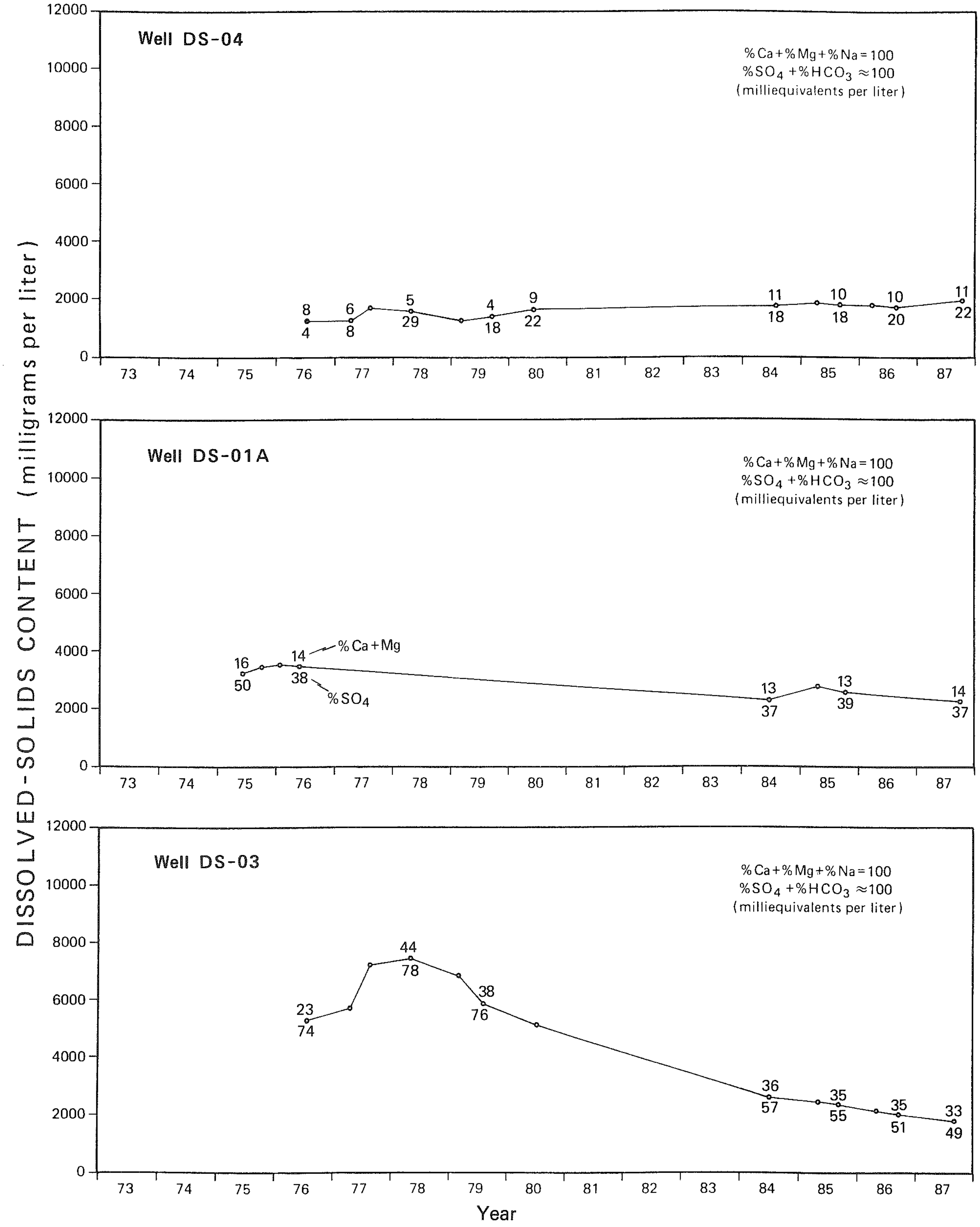

Figure 17—Increases in dissolved solids are occurring in spoils water at well DS-04; trends of decrease are evident in other spoils water.

the Decker area than at most other mines because replenishment of salts from surface recharge probably does not occur. From data collected to date by the Montana Bureau of Mines and Geology, these are the only wells where this trend is being observed. Similar dissolved-solids recessions are apparently evident in spoils at the East Decker mine (Jim Bowlby, Kiewitt Mining and Engineering, written communication, 1987), where two wells in spoils recharged by Tongue River alluvium show trends of water quality approaching that of the alluvium.

The importance of observing trends toward flushing of salts cannot be overstated. Estimates of time for spoils-water quality to approach pre-mining quality have ranged from hundreds to thousands of years, and represent highly negative evidence in environmental approaches toward mining development. The possibility of far more rapid improvement of water quality, as seen at some locales, allows for a more optomistic view of the problem. Continuation of the monitoring done thus far can best characterize post-mining conditions, and the results can be projected to other proposed mines for better-founded predictions.

Summary

Mining of subbituminous coal in southeastern Montana has accelerated since 1968 to a current annual production exceeding 30 million tons. Climate of the area is semiarid, so agricultural enterprises 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, such as near Colstrip, do not change substantially during mining. In contrast, mines that have penetrated a more central part of a flow system near Decker have caused potentiometric declines over an area more than 15 miles long and 5 miles wide. Although the large area of drawdown passes beneath valleys containing perennial streams and alluvial aquifers, alluvial water-table changes have not occurred. Confining beds of clay above the coal-bed aquifers effectively isolate the decreased hydrostatic pressures from shallower ground water.

As backfilling follows coal removal, ground water reenters spoils at the mines. Greatest resaturation thus far has occurred through recharge by lateral flow from undisturbed aquifers. Where vertical gradients are favorable, upward flow (possibly through pre-mining test holes) can be significant. Whether by test holes or other means, hydraulic connection between the mines and deeper aquifers is documented by hydrostatic-pressure changes that occur during mining. Substantial 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 the 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.

Water quality in new mine spoils is highly diverse because of the variable distributions of soluble salts after backfilling. With resaturation and the establishment of new flow patterns, water quality seems to become dependent on a balance between introduction of new salts through recharge and the flushing of salts by ground-water flow. At some wells at the Rosebud mine, recharge from the surface is introducing new salts as fast (or faster) than they can be flushed out. At others wells, such as near a local surface basin, very active recharge and ground-water flow appear to have already flushed most available salts. At some wells in West Decker spoils, trends toward decreasing concentrations of dissolved solids are being established; recharge from adjacent undisturbed aquifers is beginning to flush salts from the mine-floor aquifers.

If trends for progressively decreasing dissolved-solids contents should become apparent at several additional monitoring sites, better projections of the time needed to approach pre-mining water-quality conditions can be made.

The area of hydrostatic-pressure declines near West Decker continues to broaden, providing important new information on cumulative mining impacts. Important information for predictions of post-mining water-quality trends seems to be developing as well, and should be reassessed as new data become available.

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Appendix A

MAJOR CHEMICAL CONSTITUENTS FOR SELECTED WELLS
GROUND-WATER MONITORING, COLSTRIP AREA
All constituents dissolved and in milligrams per liter except SAR, pH. Negative values indicate below detection limit.
Abbreviations: CDS (calculated dissolved solids), SAR (sodium adsorption ratio)

Well	Aquifer	Sampling date	CDS	SAR	Ca	Mg	Na	K	HCO3	CO3	Cl	SO4	NO3 (N)	B	Lab pH
BS-22	Spoils	04/05/76	7172	5.56	430.0	725.0	813.0	12.0	639	0.0	75.6	4787.0	-0.10	1.0	7.55
"	Spoils	06/04/76	7222	5.46	454.0	688.0	790.0	12.5	636	0.0	68.3	4882.8	-0.10	0.9	6.83
"	Spoils	02/19/77	6912	5.55	388.0	675.0	780.0	12.4	519	0.0	71.0	4714.0	1.60		8.05
"	Spoils	07/21/77	7020	5.17	440.0	690.0	746.0	11.9	673	0.0	222.0	4562.0	0.30		7.09
"	Spoils	03/28/78	7053	5.01	440.0	711.0	730.0	11.6	723	0.0	73.0	4712.0	1.20		7.00
"	Spoils	08/15/79	7506	5.80	420.0	729.0	848.0	13.1	730	0.0	92.5	5025.0	6.39	0.6	7.81
"	Spoils	05/29/80	10619	10.35	377.0	939.0	1648.0	16.6	1044	0.0	177.0	6927.0	0.45		5.71
"	Spoils	08/15/84	15679	11.36	441.0	1720.0	2360.0	19.1	1380	0.0	338.0	10100.0	0.02	0.9	7.35
"	Spoils	05/15/85	16168	11.12	415.0	1650.0	2260.0	18.3	1400	0.0	329.0	10800.0	0.77	0.9	7.17
"	Spoils	10/28/85	16040	11.03	425.0	1640.0	2240.0	18.4	1215	0.0	322.0	10790.0	0.43	1.0	7.14
"	Spoils	05/15/86	15417	10.94	413.0	1576.0	2179.0	18.6	1324	0.0	292.0	10280.0	0.35	1.1	7.18
"	Spoils	10/08/87	15334	10.50	414.0	1574.0	2093.0	18.3	1008	0.0	287.0	10430.0	0.57	0.7	7.45
EPA-12	Spoils	03/30/78	1097	0.58	160.0	123.0	40.4	4.9	640	0.0	11.0	417.0	2.20		7.42
"	Spoils	06/05/80	807	0.32	71.9	138.0	20.2	6.9	556	0.0	2.0	272.0	0.15	0.2	8.11
"	Spoils	05/29/85	977	0.26	150.0	135.0	18.4	6.2	869	0.0	1.0	232.0	4.81	0.2	7.31
P-05	Alluvium	05/16/75	2001	1.69	234.0	184.0	142.5	8.5	576	0.0	13.2	1109.0	0.30		7.47
"	Alluvium	05/15/85	4193	2.21	432.0	402.0	265.0	13.2	473	0.0	42.2	2800.0	4.13	0.5	7.58
"	Alluvium	10/24/85	4119	2.16	427.0	397.0	258.0	12.9	471	0.0	57.5	2730.0	3.50	0.5	7.16
"	Alluvium	05/14/86	4098	2.32	423.0	397.0	276.0	12.9	487	0.0	56.7	2690.0	1.53	0.3	7.42
P-08	Rosebud Coal	05/16/75	1593	1.77	137.0	182.0	134.5	11.2	645	0.0	28.0	782.0	0.30		7.48
"	Rosebud Coal	04/14/76	1891	1.88	160.0	205.0	152.0	10.7	546	0.0	13.6	1057.5	3.70	0.3	7.85
"	Rosebud Coal	08/13/84	3994	2.45	326.0	425.0	285.0	13.1	483	0.0	25.5	2680.0	0.05	0.3	7.70
"	Rosebud Coal	05/16/85	4069	2.42	330.0	432.0	284.0	12.8	451	0.0	23.8	2740.0	0.09	0.3	7.26
"	Rosebud Coal	10/23/85	4259	3.30	321.0	420.0	381.0	12.7	477	0.0	24.8	2850.0	0.17	0.3	6.79
"	Rosebud Coal	05/14/86	4024	2.61	324.0	428.0	304.0	12.8	488	0.0	24.0	2690.0	0.18	0.2	7.31
"	Rosebud Coal	10/07/87	4045	2.67	318.0	419.0	308.0	12.8	465	0.0	24.2	2710.0	0.02	0.2	8.13
P-12	Alluvium	05/16/75	2967	2.52	253.0	304.0	251.0	11.0	571	0.0	18.9	1846.0	1.10		7.33
"	Alluvium	05/15/85	4252	3.07	334.0	451.0	366.0	15.0	233	0.0	20.0	2950.0	0.02	0.7	7.28
"	Alluvium	10/25/85	4302	3.14	328.0	436.0	369.0	15.0	473	0.0	19.6	2900.0	0.20	0.8	7.22
"	Alluvium	05/13/86	4481	3.15	338.0	456.0	378.0	14.5	511	0.0	21.5	3020.0	0.10	0.6	7.32
S-01	Spoils	09/25/73	2466	0.60	317.0	269.0	60.4	8.8	724	0.0	9.2	1440.0	0.30	1.2	7.67
"	Spoils	02/04/74	2270	0.59	250.0	281.0	57.3	7.8	530	0.0	8.2	1404.0	0.10		7.67
"	Spoils	05/23/74	2799	0.54	373.0	319.0	58.5	7.9	778	0.0	10.9	1630.0	-0.10		7.17
"	Spoils	06/06/74	2641	0.54	366.0	283.0	57.0	8.1	741	0.0	13.3	1532.0	0.20		7.46
"	Spoils	02/04/75	2430	0.58	283.0	288.0	58.0	8.1	461	0.0	9.7	1544.0	0.10		7.71
"	Spoils	04/10/75	2658	0.50	360.0	289.0	52.0	8.6	615	0.0	9.6	1621.0	0.50	1.0	7.67
"	Spoils	09/30/75	2954	0.53	400.0	324.0	59.0	8.4	849	0.0	12.3	1730.2		0.8	7.54
"	Spoils	01/12/76	2485	0.55	351.2	282.4	57.0	7.7	826	0.0	9.5	1354.9	-0.10		7.15
"	Spoils	03/17/76	2369	0.58	320.0	270.0	58.5	7.8	808	0.0	10.4	1289.2	-0.10		7.75
"	Spoils	04/04/76	2517	0.60	347.0	268.0	61.5	7.6	805	0.0	10.7	1410.0	-0.10	0.8	7.49
"	Spoils	06/03/76	2392	0.56	360.0	248.0	56.4	7.8	829	0.0	8.1	1289.7	-0.10	0.8	7.01
"	Spoils	11/18/76	2719	0.57	376.0	292.0	60.5	8.1	796	0.0	46.0	1529.0	-0.10	0.6	7.38
"	Spoils	04/07/77	2768	0.57	380.0	294.0	61.0	8.3	750	0.0	65.0	1574.0	0.30		7.26
"	Spoils	07/20/77	2840	0.57	400.0	308.0	62.4	8.4	783	0.0	28.0	1631.0	-0.10		6.86
"	Spoils	03/30/78	2941	0.57	410.0	312.0	63.0	7.5	795	0.0	18.0	1721.0	-0.10		7.04
"	Spoils	08/14/79	4259	0.54	521.0	499.0	71.4	10.4	920	0.0	12.3	2675.0	1.02	0.8	7.12
"	Spoils	06/05/80	3597	0.58	480.0	388.0	70.0	8.5	885	0.0	6.6	2189.0	-0.05	0.9	6.90
"	Spoils	08/18/81	3130	0.57	450.0	326.0	64.8	7.4	813	0.0	18.9	1860.0	0.16	0.7	7.12
"	Spoils	08/14/84	3101	0.55	441.0	331.0	62.9	7.3	861	0.0	12.8	1820.0	0.07	0.8	8.17
"	Spoils	05/28/85	3090	0.55	437.0	328.0	62.2	7.2	856	0.0	12.8	1820.0	0.01	0.8	7.09

Appendix A, *continued*

MAJOR CHEMICAL CONSTITUENTS FOR SELECTED WELLS

GROUND-WATER MONITORING, COLSTRIP AREA

All constituents dissolved and in milligrams per liter except SAR, pH. Negative values indicate below detection limit.

Abbreviations: CDS (calculated dissolved solids), SAR (sodium adsorption ratio)

Well	Aquifer	Sampling date	CDS	SAR	Ca	Mg	Na	K	HCO3	CO3	Cl	SO4	NO3 (N)	B	Lab pH
"	Spoils	10/24/85	3062	0.56	436.0	329.0	63.8	7.1	856	0.0	12.2	1790.0	0.11	0.7	6.85
"	Spoils	05/12/86	3266	0.54	465.0	351.0	63.7	7.4	891	0.0	12.6	1925.0	0.04	0.7	6.78
"	Spoils	10/05/87	3273	0.56	468.0	349.0	658.0	7.1	910	0.0	13.9	1900.0	-0.02	0.8	7.41
S-04	McKay Coal	09/25/73	1148	0.66	142.0	123.0	44.4	5.5	383	0.0	8.7	634.0	-0.10	2.0	7.94
"	McKay Coal	06/06/74	1330	1.55	149.0	121.0	105.0	0.6	450	0.0	10.7	698.0	0.20		8.09
"	McKay Coal	09/30/75	5607	1.38	351.2	778.0	203.0	9.1	448	0.0	80.8	3950.5	0.50	1.5	8.20
"	McKay Coal	01/14/76	3869	1.22	285.9	532.1	151.0	7.9	533	0.0	43.4	2571.5	0.50		7.44
"	McKay Coal	04/14/76	6034	1.28	440.0	852.0	200.0	8.6	485	0.0	71.0	4210.5	2.40	1.6	7.53
"	McKay Coal	06/03/76	10401	1.62	525.0	1585.0	330.0	9.7	443	0.0	112.2	7609.3	2.90	1.4	7.49
"	McKay Coal	06/23/76	10207	1.65	535.0	1530.0	332.0	10.0	451	0.0	4.8	7561.1	2.10		7.84
"	McKay Coal	10/07/76	6876	1.28	530.0	945.0	212.5	7.0	602	0.0	169.0	4702.3	0.20		7.20
"	McKay Coal	08/17/76	7911	1.32	540.0	1125.0	234.0	9.3	612	0.0	85.0	5604.7	0.80		7.57
"	McKay Coal	11/18/76	5970	1.37	445.0	800.0	209.0	9.2	539	0.0	92.0	4139.0	-0.10	2.0	7.54
"	McKay Coal	02/19/77	4832	1.24	340.0	665.0	170.0	7.9	382	0.0	44.0	3405.0	-0.10		8.22
"	McKay Coal	02/14/77	5654	1.24	400.0	775.0	185.0	8.4	448	0.0	52.0	4002.0	-0.10		7.57
"	McKay Coal	04/07/77	4586	1.32	356.0	590.0	174.0	7.8	489	0.0	56.0	3149.0	0.20		7.60
"	McKay Coal	07/20/77	5356	1.19	405.0	730.0	173.0	8.0	529	0.0	189.0	3578.0	-0.10		7.16
"	McKay Coal	03/30/78	9843	1.65	445.0	1515.0	325.0	7.5	431	0.0	97.0	7224.0	5.40		7.30
"	McKay Coal	02/13/79	5599	1.08	442.0	766.0	162.0	6.8	395	0.0	44.1	3974.0	0.83		7.37
"	McKay Coal	08/14/79	6544	1.21	478.0	901.0	195.0	8.7	548	0.0	57.5	4625.0	0.56	1.2	7.59
"	McKay Coal	02/19/80	5255	1.02	443.0	691.0	147.0	8.8	499	0.0	59.0	3650.0	0.26	1.2	7.94
"	McKay Coal	06/06/80	5667	1.34	333.0	800.0	197.0	9.8	166	0.0	73.9	4160.0	-0.11	1.9	7.31
"	McKay Coal	08/18/81	5019	1.43	377.0	660.0	198.0	8.3	489	0.0	50.9	3472.0	0.17	1.3	7.64
"	McKay Coal	08/16/84	3471	1.30	302.0	433.0	150.0	6.3	529	0.0	28.1	2290.0	0.06	1.4	7.86
"	McKay Coal	05/28/85	4637	1.23	340.0	628.0	166.0	7.2	458	0.0	29.2	3240.0	0.13	1.6	7.36
"	McKay Coal	10/24/85	2975	1.28	234.0	381.0	136.0	6.2	481	0.0	20.0	1960.0	0.16	1.6	6.90
"	McKay Coal	05/12/86	3891	1.17	302.0	520.0	144.0	6.6	482	0.0	19.7	2660.0	0.18	1.7	7.18
"	McKay Coal	10/05/87	2972	1.24	242.1	381.0	133.0	5.9	569	0.0	18.4	1895.0	0.03	1.5	8.15
S-06	McKay Coal	09/25/73	905	1.00	109.0	92.0	58.8	5.1	383	0.0	6.6	444.0	0.10	0.6	7.91
"	McKay Coal	06/06/74	538	0.48	77.0	58.0	23.0	3.4	364	0.0	7.6	168.0	0.30		8.11
"	McKay Coal	07/20/77	548	0.49	70.0	65.0	23.7	3.3	293	0.0	64.0	158.0	0.40		7.54
"	McKay Coal	04/05/78	725	0.74	86.5	80.5	39.6	3.9	374	0.0	6.0	305.0	0.30		7.58
"	McKay Coal	06/06/80	603	0.59	60.5	82.1	30.0	4.0	339	0.0	6.2	253.0	0.05	0.3	7.26
"	McKay Coal	05/12/86	771	0.60	98.1	88.5	34.2	3.9	364	0.0	6.8	359.0	0.04	0.3	7.47
S-16	Sub-McKay	09/25/73	3184	1.78	273.0	360.0	190.0	4.4	408	0.0	15.9	2124.0	2.30	1.6	7.83
"	Sub-McKay	02/04/74	3468	1.88	302.0	384.0	209.0	4.2	437	0.0	13.0	2320.0	4.50		7.74
"	Sub-McKay	06/06/74	3254	1.78	328.0	345.0	193.0	4.4	477	3.0	17.8	2108.0	4.50		7.48
"	Sub-McKay	02/05/75	3450	1.85	273.0	407.0	206.0	5.1	458	0.0	14.7	2298.0	4.70		7.77
"	Sub-McKay	07/21/77	3315	1.78	322.0	366.0	196.0	4.6	519	0.0	7.0	2139.0	3.80		7.30
"	Sub-McKay	03/28/78	3347	1.81	310.0	372.0	200.0	4.8	594	0.0	17.0	2127.0	3.80		7.30
"	Sub-McKay	08/15/79	3375	1.85	280.0	391.0	204.0	4.3	586	0.0	16.5	2170.0	3.50	0.8	7.66
"	Sub-McKay	06/05/80	3386	1.87	275.0	391.0	206.0	5.4	615	0.0	15.1	2170.0	1.00	0.9	7.65
"	Sub-McKay	08/16/84	5129	1.87	500.0	584.0	260.0	5.8	839	0.0	28.6	3330.0	7.53	1.3	7.62
"	Sub-McKay	10/28/85	5171	1.98	496.0	585.0	275.0	5.1	893	0.0	24.0	3340.0	5.45	1.5	7.27
"	Sub-McKay	05/15/86	5156	1.97	503.0	587.0	274.0	5.1	865	0.0	23.8	3330.0	6.78	1.5	7.08
"	Sub-McKay	10/08/87	5074	2.06	476.0	569.0	282.0	5.1	904		29.6	3240.0	3.77	1.5	8.18

Appendix B

MAJOR CHEMICAL CONSTITUENTS FOR SELECTED WELLS
GROUND-WATER MONITORING, DECKER AREA
All constituents dissolved and in milligrams per liter except SAR, pH. Negative values indicate below detection limit.
Abbreviations: CDS (calculated dissolved solids), SAR (sodium adsorption ratio)

Well	Aquifer	Sampling date	CDS	SAR	Ca	Mg	Na	K	HCO3	CO3	Cl	SO4	NO3 (N)	B	Lab pH
DS-01A	Spoils	05/02/75	3184	20.67	67.0	66.0	995.0	15.9	1546	0.0	30.0	1248.0		-0.1	7.19
"	Spoils	10/02/75	3394	20.90	66.2	80.1	1068.0	18.5	1928	0.0	20.9	1171.6	4.90	0.1	7.98
"	Spoils	01/06/76	3395	23.16	66.3	70.3	1135.0	17.8	2273	0.0	22.2	947.9	2.90		7.59
"	Spoils	03/24/76	3302	23.43	72.0	56.0	1090.0	17.4	2056	0.0	18.5	1024.7	0.30	0.1	7.46
"	Spoils	08/23/84	2052	20.37	43.2	26.6	690.0	11.5	1318	0.0	7.7	622.0	0.02	0.1	7.54
"	Spoils	05/01/85	2305	20.63	46.3	28.6	724.0	11.9	1660	0.0	10.2	660.0	3.20	0.1	7.61
"	Spoils	10/17/85	2190	20.84	46.9	28.8	735.0	11.9	1360	0.0	10.1	685.0	0.05	0.0	7.36
"	Spoils	10/27/87	2089	19.10	48.4	31.0	692.0	11.5	1344		9.8	620.0	1.46	0.0	7.59
DS-03	Spoils	07/15/76	5383	20.32	168.0	131.0	1445.0	32.0	1205	0.0	31.0	2969.8	0.30	0.2	7.52
"	Spoils	04/12/77	5951	11.45	378.0	260.0	1180.0	58.0	1218	0.0	61.0	3359.0	23.70		7.81
"	Spoils	07/22/77	7541	12.28	520.0	326.0	1450.0	52.0	1425	0.0	65.0	4395.0	0.80		6.93
"	Spoils	04/04/78	7621	12.29	498.0	343.0	1455.0	54.0	1488	0.0	41.0	4463.0	-0.10		6.82
"	Spoils	02/27/79	7047	12.57	466.0	328.0	1448.0	41.7	1342	0.0	44.9	4017.0	5.31		7.30
"	Spoils	08/28/79	6104	13.35	287.0	264.0	1302.0	50.2	1312	0.0	20.0	3500.0	1.81	0.3	7.85
"	Spoils	07/14/80	5370	10.83	360.0	219.0	1056.0	40.2	958	0.0	38.2	3150.0	-0.01	0.4	7.82
"	Spoils	08/23/84	2803	10.03	176.0	89.4	655.0	29.7	1190	0.0	15.2	1250.0	0.01	0.3	7.19
"	Spoils	05/01/85	2503	9.19	149.0	76.3	553.0	26.1	1209	0.0	11.8	1090.0	0.01	0.2	7.28
"	Spoils	10/17/85	2414	9.41	151.0	78.6	572.0	26.6	1080	0.0	11.8	1040.0	0.05	0.2	7.36
"	Spoils	05/06/86	2227	9.05	141.0	71.2	528.0	24.7	1076	0.0	10.6	919.0	0.02	0.2	7.33
"	Spoils	10/14/86	2064	8.80	132.0	66.8	497.0	22.5	1016	0.0	10.0	833.0	0.05	0.2	7.58
"	Spoils	10/27/87	2032	9.20	115.0	62.3	493.0	27.3	1033		8.7	782.0	0.84	0.2	7.60
DS-04	Spoils	07/15/76	1295	21.20	12.7	17.5	496.0	8.0	1369	0.0	18.2	55.5	1.20	-0.1	7.98
"	Spoils	04/11/77	1404	24.21	11.2	14.6	522.0	8.2	1333	63.8	12.0	102.0	0.30		8.80
"	Spoils	07/22/77	1766	26.33	18.4	13.8	613.0	7.4	717	0.0	296.0	446.0	-0.10		7.04
"	Spoils	04/04/78	1611	28.38	14.0	11.0	584.0	6.5	1176	0.0	8.0	391.0	-0.10		7.70
"	Spoils	02/27/79	1436	30.38	10.8	9.2	562.0	6.0	1324	0.0	20.8	158.0	0.19		7.90
"	Spoils	08/28/79	1509	30.26	10.6	10.6	582.0	7.4	1258	0.0	25.4	236.0	1.85	0.0	8.21
"	Spoils	07/14/80	1724	24.28	16.8	21.5	637.0	8.1	1366	20.4	29.2	316.0	0.07	0.1	8.37
"	Spoils	08/23/84	1919	22.00	25.0	30.0	689.0	10.8	1658	0.0	25.8	303.0	0.03	0.1	7.22
"	Spoils	05/01/85	1961	24.18	22.0	29.3	736.0	9.7	1679	0.0	24.9	309.0	0.04	0.0	7.62
"	Spoils	10/17/85	1919	23.82	20.8	27.7	705.0	9.5	1700	0.0	23.5	292.0	0.03	0.0	7.83
"	Spoils	05/08/86	1913	23.66	20.1	28.1	700.0	9.9	1690	0.0	23.3	296.0	0.06	0.0	7.67
"	Spoils	10/14/86	1871	23.39	20.0	27.8	689.0	8.6	1591	0.0	24.3	315.0	0.03	0.0	7.60
"	Spoils	10/27/87	1975	22.12	22.2	32.7	701.0	10.2	1610		26.4	372.0	0.19	0.0	7.80
DS-05A	D-2 Coal	04/14/77	1082	43.65	4.7	1.7	434.0	4.5	1112	63.8	10.0	1.7	-0.10		8.89
"	D-2 Coal	08/22/84	1092	42.89	5.5	1.8	453.0	4.2	1230	0.0	7.1	3.0	-0.01	0.1	7.51
"	D-2 Coal	10/28/87	1049	43.94	4.6	1.8	439.0	3.6	1171		5.9	1.3	0.52	0.0	7.62
DS-05B	Spoils	07/15/76	1234	40.47	6.0	3.5	504.0	6.6	1334	0.0	7.9	30.3	-0.10		8.26
"	Spoils	04/15/77	1095	37.31	5.9	3.0	446.0	4.8	1114	5.3	60.5	1.6	-0.10		8.37
"	Spoils	07/22/77	1038	31.16	6.8	4.0	414.0	6.0	1063	0.0	7.0	56.0	-0.10		8.11
"	Spoils	04/04/78	1149	33.71	8.2	3.9	468.0	5.3	1263	0.0	6.0	20.2	-0.10		7.66
"	Spoils	07/15/80	3028	55.50	9.5	14.8	1173.0	13.9	2447	84.0	11.0	507.0	-0.01	0.1	8.96
"	Spoils	08/22/84	983	24.84	8.4	6.6	396.0	6.9	1043		6.3	33.6	0.04		7.85
"	Spoils	10/16/86	1723	31.54	18.2	11.0	690.0	8.8	1799	0.0	12.0	95.3	0.10	0.0	8.30
"	Spoils	10/28/87	2233	42.63	11.8	13.3	899.0	10.8	2344		13.1	119.0	0.16	0.0	8.30

Appendix B, *continued*

MAJOR CHEMICAL CONSTITUENTS FOR SELECTED WELLS
GROUND-WATER MONITORING, DECKER AREA
All constituents dissolved and in milligrams per liter except SAR, pH. Negative values indicate below detection limit.
Abbreviations: CDS (calculated dissolved solids), SAR (sodium adsorption ratio)

Well	Aquifer	Sampling date	CDS	SAR	Ca	Mg	Na	K	HCO3	CO3	Cl	SO4	NO3 (N)	B	Lab pH
WR-29	Alluvium	02/23/77	615	0.92	97.0	48.5	44.4	4.3	376	0.0	2.8	222.0	0.03		7.28
"	Alluvium	12/17/81	813	0.87	142.0	56.6	48.3	5.2	427	0.0	3.8	330.0	0.05		7.22
"	Alluvium	11/30/82	696	0.71	119.0	51.7	36.7	5.0	365	0.0	3.3	286.0	0.40		7.51
"	Alluvium	04/30/85	617	0.87	99.9	46.8	41.9	4.1	421	0.0	3.1	199.0	0.03	0.1	7.37
"	Alluvium	10/18/85	700	0.76	131.0	56.9	41.4	5.1	538	0.0	2.6	194.0	2.80	0.1	6.77
"	Alluvium	05/05/86	494	0.73	86.0	40.6	32.8	3.8	345	0.0	2.1	158.0	0.06	0.1	7.53
"	Alluvium	10/29/87	624	0.82	106.0	45.4	40.4	4.7	400		4.0	209.0	0.05	0.1	7.27

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Sheet 2—Selected hydrographs (6-11), Decker area.

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