Ground-Water Resources and Potential Hydrologic Effects of Surface Coal Mining in the Northern Powder River Basin, Southeastern Montana

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Prepared in cooperation with the Montana Bureau of Mines and Geology and the U.S. Bureau of Land Management

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By Steven E. Slagle, Barney D. Lewis, and
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Ground-Water Resources and Potential Hydrologic Effects of Surface Coal Mining in the Northern Powder River Basin, Southeastern Montana

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ABSTRACT

The shallow ground-water system in the northern Powder River Basin consists of Upper Cretaceous to Holocene aquifers overlying the Bearpaw Shale—namely, the Fox Hills Sandstone, Hell Creek, Fort Union, and Wasatch Formations, terrace deposits, and alluvium Ground-water flow above the Bearpaw Shale can be divided into two general flow patterns An upper flow pattern occurs in aquifers at depths of less than about 200 feet and occurs primarily as localized flow controlled by the surface topography A lower flow pattern occurs in aquifers at depths from about 200 to 1,200 feet and exhibits a more regional flow, which is generally northward toward the Yellowstone River with significant flow toward the Powder and Tongue Rivers

The chemical quality of water in the shallow ground-water system in the study area varies widely, and most of the ground water does not meet standards for dissolved constituents in public drinking water established by the U S Environmental Protection Agency Water from depths less than 200 feet generally is a sodium sulfate type having an average dissolved-solids concentration of 2,100 milligrams per liter Sodium bicarbonate water having an average dissolved-solids concentration of 1,400 milligrams per liter is typical from aquifers in the shallow ground-water system at depths between 200 and 1,200 feet.

Effects of surface coal mining on the water resources in the northern Powder River Basin are dependent on the stratigraphic location of the mine cut Where the cut lies above the water-yielding zone, the effects will be minimal Where the mine cut intersects a water-yielding zone, effects on water levels and flow patterns can be significant locally, but water levels and flow patterns will return to approximate premining conditions after mining ceases Ground water in and near active and former mines may become more mineralized, owing to the placement of spoil material from the reducing zone in the unsaturated zone where the minerals are subject to oxidation Regional effects probably will be small because of the limited areal extent of ground-water flow systems where mining is feasible

Results of digital models are presented to illustrate the effects of varying hydraulic properties on water-level changes resulting from mine dewatering The model simulations were designed to depict maximum-drawdown situations One simulation indicates that after 20 years of continuous dewatering of an infinite, homogeneous, isotropic aquifer that is 10 feet thick and has an initial potentiometric surface 10 feet above the top of the aquifer, water-level declines greater than 1 foot would generally be limited to within 7 5 miles of the center of the mine excavation, declines greater than 2 feet to within about 6 miles, declines greater than 5 feet to within about 3 7 miles, declines greater than 10 feet to within about 1 7 miles, and declines greater than 15 feet to within 1 2 miles

INTRODUCTION

Vast supplies of low-sulfur coal occur as numerous and widespread lignite and subbituminous deposits in the northern Powder River Basin of southeastern Montana Individual coal beds that occur principally within the Fort Union Formation commonly are 20–30 feet thick, but may be as much as 80 feet thick Thus, the area is attractive as a major source of supply for future energy needs

The increase of coal development in the past few years has fostered concern about its effects on the water resources The coal beds and discontinuous sandstone contained in the Fort Union Formation are important as aquifers, supplying water to numerous domestic and stock wells and springs Surface mining of certain coal beds not only will remove part of the aquifer, but also may cause temporary dewatering of parts of the coal and overlying beds and may change the quality of the ground water in the vicinity of the mine site

Purpose and Scope

In anticipation of widespread development of the coal resources in the northern Powder River Basin, the U S Geological Survey, in cooperation with the Montana Bureau of Mines and Geology and the U S Bureau of Land Management, in July 1974 began an investigation of the water resources and the possible hydrologic effects of development To assess the effects of development, the existing, essentially premining, hydrologic conditions needed to be documented

The first objective of the investigation was to provide baseline data for determining the effects of future coal development on the water resources of the basin To meet this objective, an extensive data-collection program was begun Data collected and compiled for about 2,000 wells in the area included well depth, water levels, well discharge, water use, lithologic logs, and water quality The results of the data-collection phase of the project are given in reports by Slagle and Stimson (1979) for well data and by Lee (1979) for water-quality data

The purpose of this report is to describe the existing hydrologic conditions of the shallow ground-water system above the Bearpaw Shale, and to assess the potential effects of future mining operations on the shallow ground-water system Because of the large extent of the study area and the scarcity of hydrologic data, especially for aquifers at great depths, geologic concepts have been used to extend ground-water data in space Surface geology was reviewed and, where necessary, remapped Subsurface geology was mapped by examination of about 650 geophysical logs of oil and gas wells and test holes Vertically, this study considers all geologic units above the Bearpaw Shale and includes all coal reserves that could be mined by surface methods Results of the geologic investigations of aquifers are published in reports by Lewis and Roberts (1978) and Lewis and Hotchkiss (1981) Results of water-quality studies of the shallow aquifers, including description of the geochemical systems and geochemical and biological processes, are contained in reports of Lee (1981) and Dockins and others (1980)

Knapton and McKinley (1977), Knapton and Ferreira (1980), and Ferreira (1981) describe the surface-water resources of the area Information on surface water-ground water interaction is contained in reports by Druse and others (1981) and Lee and others (1981) Additional data on surface-water quantity and quality are published in U S Geological Survey Water-Supply Papers and in an annual series, Water Resources Data for Montana

Location and Extent of Area

The area of study for this report comprises about 10,000 mi^2 in southeastern Montana The study area is, in general, bounded on the north by the Yellowstone River, on the east by the Powder and Little Powder Rivers, on the south by the Montana-Wyoming State line, and on the west by the Bighorn and Little Bighorn Rivers (fig 1) These borders encompass the Montana part of the Powder River Basin

Physiography

The land surface in the study area typically is rolling uplands dissected by steep-walled valleys Resistant sandstone or clinker caps rugged ridges, mesas, or buttes in many areas Locally, badlands have developed in easily eroded shales Major streams in the area flow on alluvial flood plains that typically are bordered by remnants of alluvial terraces and steep valley walls

Altitudes range from about 4,800 feet in the Wolf Mountains and Little Wolf Mountains in the southwestern and western parts of the area to about 2,200 feet where the Powder River joins the Yellowstone River near Terry, Montana Local relief from hilltops to adjacent valley floors commonly is 100 to 500 feet

Climate

The semiarid climate of southeastern Montana is characterized by cold dry winters, cool moist springs, and hot dry summers Winter cold waves often are broken by extended intervals of warm weather Summers are dominated by hot sunny days and cool nights Average annual temperatures, based on the period of record 1941–70, range from 44 7°F at Broadus, Montana, to 45 9°F at Colstrip according to National Weather Service records (U S Department of Commerce, issued monthly) January normally is the coldest month Average January temperatures range from 15 4°F at Miles City to 21 0°F at Colstrip The warmest temperatures generally occur in July July average temperatures range from 71 2°F at Broadus to 74 4°F at Miles City Several days of maximum temperatures in excess of 100°F are not uncommon

National Weather Service records for 1941–70 show that average annual precipitation ranges from 13 93 inches at Miles City to 16 23 inches at Lame Deer Most precipitation occurs during late spring and early summer

Industry

Other than farming, ranching, and related services, coal mining and coal-fired electric power generation are the major industries in the northern Powder River Basin of Montana Some oil and gas also are produced in the area

About 30 million tons of coal per year were produced commercially in 1980 from five mines within the study area (William R Cox, Montana Department of Labor, written commun , 1981) Producing mines in the Montana part of the Powder River Basin in 1981 are (1) Coal Creek Mine, near Ashland, (2) West Decker Mine, near Decker, (3) Rosebud Mine, near Colstrip, (4) Big Sky Mine, near Colstrip, and (5) Absaloka Mine, about 25 miles west of Colstrip Two mines, Ash Creek and Big Horn, are producing commercial quantities of coal in Wyoming about 10 miles southwest of Decker Applications have been submitted to the Montana Department of State Lands for two additional mines near Decker and Colstrip Several other mines have been proposed for the study area,

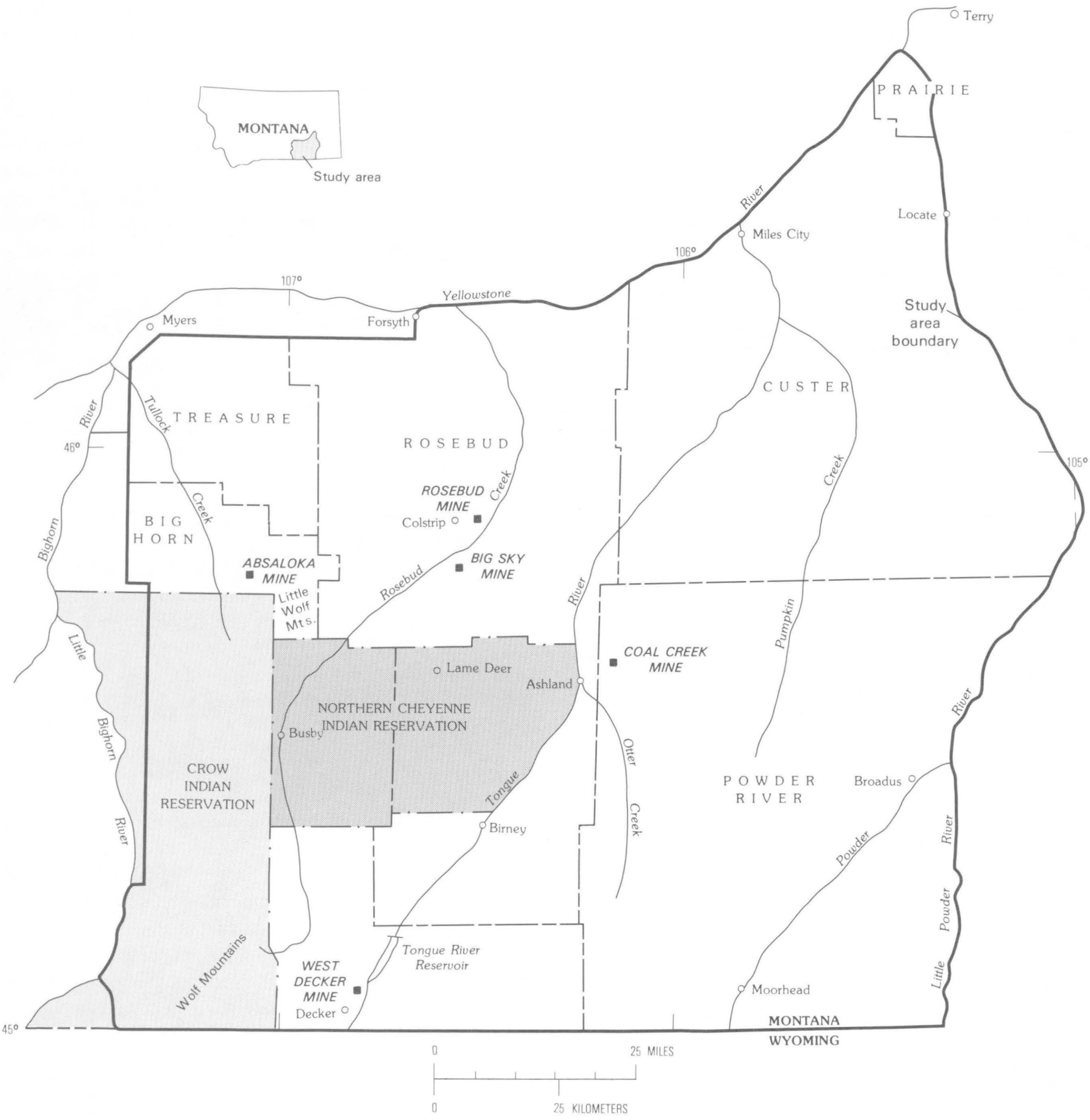


Figure 1. Location of study area.

including one near Decker and one between Birney and Ashland. Several extensions of existing mines also are proposed. Two electric power-generating units are online and application for approval has been filed with the State for two more.

Previous Investigations

Most geologic studies in the area during the past 70 years have been conducted principally for the purpose of coal-bed definition, correlation, and determination of reserves. Most studies have focused on individual coal fields. However, a few geologic studies were regional in scope, such as those of Calvert and others (1912), Combo and others (1949), Matson and Blumer (1973), Culbertson and others (1979), and Law and others (1979).

Regional ground-water studies have been conducted by Perry (1931, 1935) and Swenson (1953). Several ground-water studies in smaller areas have been conducted from 1929 to the present (1981). Ground-water effects related to present coal mining have been studied by Van Voast (1974), Van Voast and Hedges (1974, 1975), and Van Voast and others (1977, 1978)

Acknowledgments

Appreciation is extended to the many residents of the area who permitted access to their property and provided information about their wells Special appreciation is expressed to those who permitted use of their land for test drilling and installation of observation wells Definition of the water resources of the Northern Cheyenne Indian Reservation was aided by data supplied by Thomas J Osborne, Charles B Andrews, and William W Woessner of the Northern Cheyenne Research Project Appreciation also is extended to Julianne F Levings for modifying the computer program, constructing the model, and producing the model simulations used in this report

GEOLOGY

Stratigraphy

Sedimentary geologic units ranging in age from Late Cretaceous to Holocene compose the shallow groundwater system in the northern Powder River Basin (pl 1) The geologic units consist of marine deposits of the Upper Cretaceous Fox Hills Sandstone and continental deposits of the Upper Cretaceous to Holocene Hell Creek Formation, Fort Union Formation, Wasatch Formation, terrace deposits, and alluvium (table 1)

The Upper Cretaceous Bearpaw Shale grades from massive dark shaly claystone and shale in the eastern part of the study area to a sequence of silty sandstone, siltstone, and thin interbeds of shale in the western part This unit is laterally persistent and has a thickness that generally ranges from 600 to 800 feet, except in areas of outcrop where it has been thinned by erosion

The Upper Cretaceous Fox Hills Sandstone is recognized in the subsurface, where it is present, by the use of geophysical logs These logs also indicate that the formation in most of the basin is separable into upper and lower predominantly sandstone units with an intermediate thin shale bed as noted by Gill and Cobban (1973)

The Upper Cretaceous Hell Creek Formation consists of interbedded shale, siltstone, and channel sandstone in the lower part to a locally massive shale with lenticular sandstone and interbedded claystone, thin coal beds, and silty sandstone in the upper part In most of the study area, the formation can be separated in the subsurface into an upper and a lower unit

The Paleocene Fort Union Formation is composed of the Tullock, Lebo Shale, and Tongue River Members in ascending order Interbedded shale, siltstone, sandstone, and thin coal beds of the Tullock Member grade upward into silty or sandy shale and locally sandstone The Lebo Shale Member is composed of predominantly dark shale with interbedded carbonaceous shale, siltstone, and locally thin coal beds The Tongue River Member is alternating sandstone, siltstone, carbonaceous shale, and thick and extensive coal beds

The Eocene Wasatch Formation consists of lenticular sandstone interbedded with shale and coal, and is restricted to the southwestern part of the study area Coal beds in this unit are as thick and laterally persistent as in the underlying Tongue River Member of the Fort Union Formation

Clinker zones crop out along burned coal horizons throughout the Tertiary section Clinker deposits are composed of the residue from burned coal beds, and baked and fused overlying layers

Pleistocene terrace deposits and Pleistocene to Holocene alluvium are the youngest geologic units in the northern Powder River Basin Terrace deposits are composed of interbedded gravel, sand, silt, and clay Terraces are confined mainly to valley sides and uplands along the Yellowstone River, with scattered deposits along the Tongue and Powder Rivers (pl 1) The alluvium is thickest along these same rivers and their major tributaries (Lewis and Roberts, 1978) and is composed of interbedded clay, silt, sand, and gravel

Structure

Many prominent structural features occur in and near the northern Powder River Basin study area (fig 2) The Miles City arch, located in the northeastern part of the study area, is the major positive structural feature Other positive features, outside of but contiguous to the area, are the Black Hills uplift, Porcupine dome, and Bighorn uplift Negative structural features totally or partly within the study area are the Powder River Basin, Williston Basin, Ashland syncline, and Tongue River syncline

Structural features associated with the study area are indicated by a map showing the configuration of the top of the Bearpaw Shale (fig 3) The map indicates that the Bighorn uplift (fig 2) had a greater deformational influence on the northern Powder River Basin than any of the other surrounding positive features, as the dip on the surface of the Bearpaw Shale is greatest on the western flank of the basin The configuration of the top of the Bearpaw shows that the trough of the Tongue River syncline is actually the axial trace of the asymmetrical northern Powder River Basin

Two major faulted areas are adjacent to the study area (fig 2) The Vananda fault is a northeast-trending normal fault just north of the area The northwest-trending

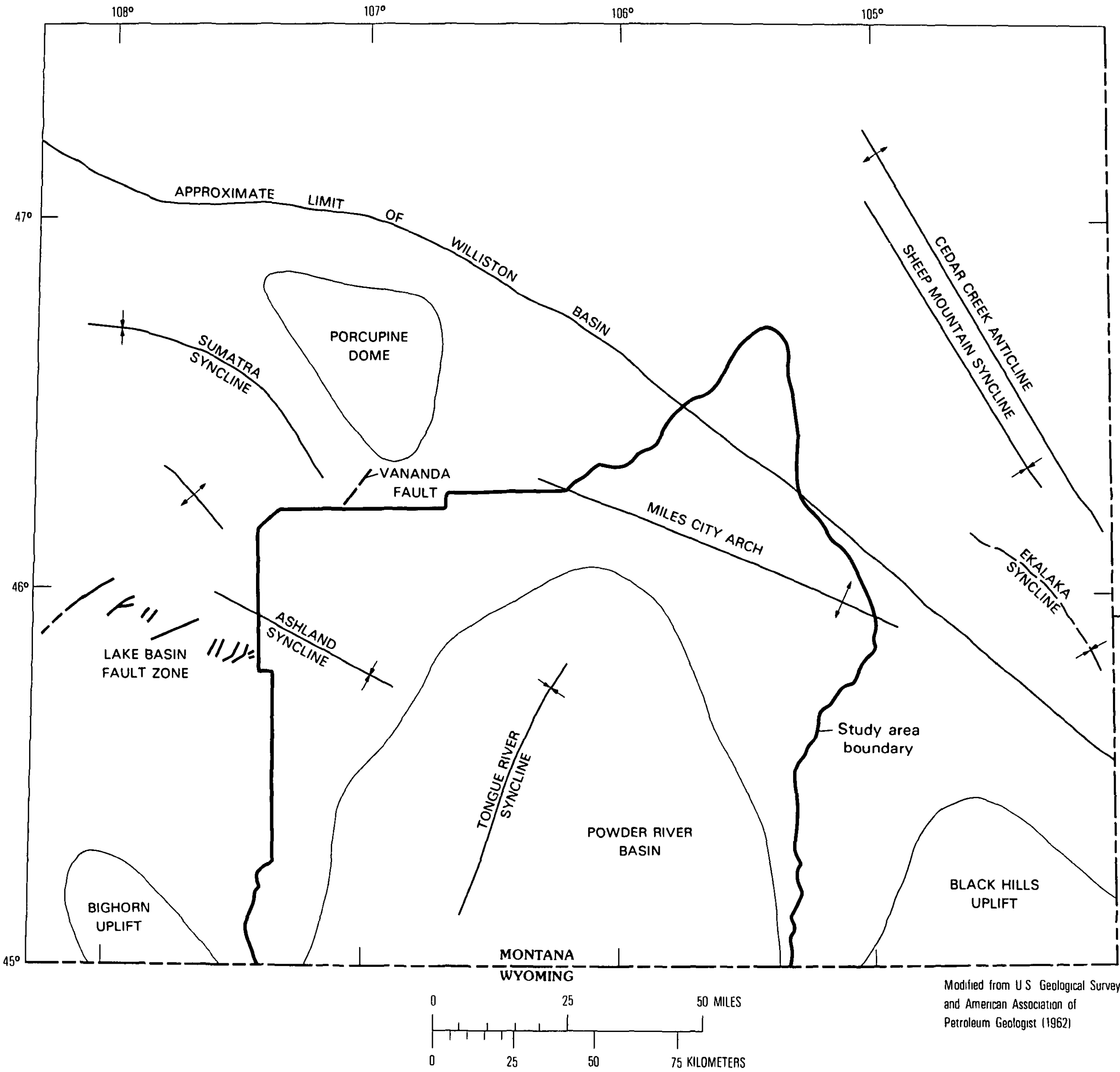


Figure 2. Structural features of southeastern Montana

is composed of a series of en echelon normal faults, each Lake Basin fault zone to the west of the study area, which oriented northeast, bounds the northern extension of the Bighorn uplift

Faults within the study area generally have small lateral or vertical displacement, a few feet in most instances, and most are restricted to geologic units near surface exposures However, a few deep-seated fracture systems are indicated by parallel surface traces of faults and other lineaments (Lewis and Roberts, 1978) A deep-seated fault is indicated by the offset of the structure contours on the top of the Bearpaw Shale in the south-central part of the study area (fig 3)

GROUND-WATER HYDROLOGY

This investigation involved the determination of the occurrence and movement of water contained in shallow aquifers in the northern Powder River Basin The shallow aquifers studied are those at depths less than about 5,000 feet below land surface and stratigraphically above the Bearpaw Shale, maximum depths occur along the structural axis of the Powder River Basin near the southwestern part of the study area

Hydrologic characteristics of aquifers were determined from records of about 2,000 wells Hydraulic properties were determined primarily from lithologic distribu-

Table 1. Generalized section of geologic units in the shallow ground-water system
[Modified from Lewis and Roberts, 1978]

System	Series	Geologic unit		Thickness (feet)	Lithology
Quaternary	Holocene	Alluvium		0–100	Interfingering lenses of clay, silt, sand, and gravel Coarse well-rounded gravel interbedded with finer material is common along the Yellowstone River, beds are mostly reworked terrace deposits Clinker fragments are present in the gravel of smaller streams Unit includes many low-lying terraces adjacent to streams
	Pleistocene	Terrace deposits		0–70	Gravel, sand, silt, and clay Well-rounded pebbles and sand-sized particles of igneous, sedimentary, and metamorphic rocks are common Deposits are restricted mainly to valley sides and upland areas along the Yellowstone River, scattered deposits are in other parts of the study area
Tertiary	Eocene	Wasatch Formation		0–400	Brownish-gray to light-gray fine- to coarse-grained lenticular beds of sandstone and interbedded gray shale and coal Contains a fossiliferous zone of clams and snails Clinker zones crop out along coal horizons Base of unit is the top of the Roland coal bed, as defined by Baker (1929) Conformable contact with underlying unit
	Paleocene	Fort Union Formation	Tongue River Member	0–2500	Light-yellow to light-gray fine- to medium-grained thick-bedded to massive locally crossbedded and lenticular, calcareous sandstone and siltstone, weathers to a buff color Commonly contains light shaly siltstone and shale, and dark carbonaceous shale Contains numerous thick and extensive coal beds as much as 80 feet thick Zones of clinker and baked shale beds crop out along coal horizons Base of unit is defined as the change from predominantly siltstone and sandstone to shale of underlying unit
			Lebo Shale Member	0–800	Predominantly dark shale containing interbeds of light-gray and brown to black carbonaceous shale, siltstone, and locally thin coal beds Shales contain altered and devitrified volcanic ash and brown ferruginous concretions A change from shale to predominantly fine-grained sandstone and shale marks the base of the unit, but locally channel deposits are scoured well into the underlying Tullock Member
			Tullock Member	0–800	Light-gray carbonaceous sandy to silty shale, and locally sandstone Grades downward to interbedded medium-gray to light-gray shale, fine-grained light-gray sandstone and siltstone, and thin but persistent coal beds Base of unit is marked as a change from fine-grained thin-bedded sandstone, siltstone, shale, and coal beds to locally massive channel sandstone and dark-gray shale of the underlying unit (Brown, 1952, Dunlap, 1958)

Table 1. Generalized section of geologic units in the shallow ground-water system—Continued
[Modified from Lewis and Roberts, 1978]

System	Series	Geologic unit	Thickness (feet)	Lithology
Cretaceous	Upper Cretaceous	Hell Creek Formation	0–850	Interbedded gray to brown siltstone and shale, locally lenticular fine- to medium-grained sandstone and often massive shale, and interbedded claystone, thin coal beds, silty sandstone and bentonitic shale in the upper part, grades downward into interbedded carbonaceous shale, sandy shale, siltstone, and claystone with local deposits of gray to brown silty to clayey commonly crossbedded channel sandstone Lower contact is gradational to unconformable with the underlying unit
		Fox Hills Sandstone	0–350	Near-shore sand facies that is the last marine deposit in the area Two members of the unit are recognized Colgate Member—very light gray fine- to medium-grained massive sandstone, unnamed lower member—gray to brownish-gray fine-grained thin-bedded sandstone, with interbedded sandy shale and siltstone Lower contact is gradational
		Bearpaw Shale	0–800	Gray to black marine commonly massive shaly claystone and shale in the eastern part of the area, grades westward into thin-bedded silty sandstone and siltstone and locally thin beds of bentonitic shale Top of unit is the base of the shallow ground-water system

tion in conjunction with hydraulic-conductivity values determined from aquifer tests

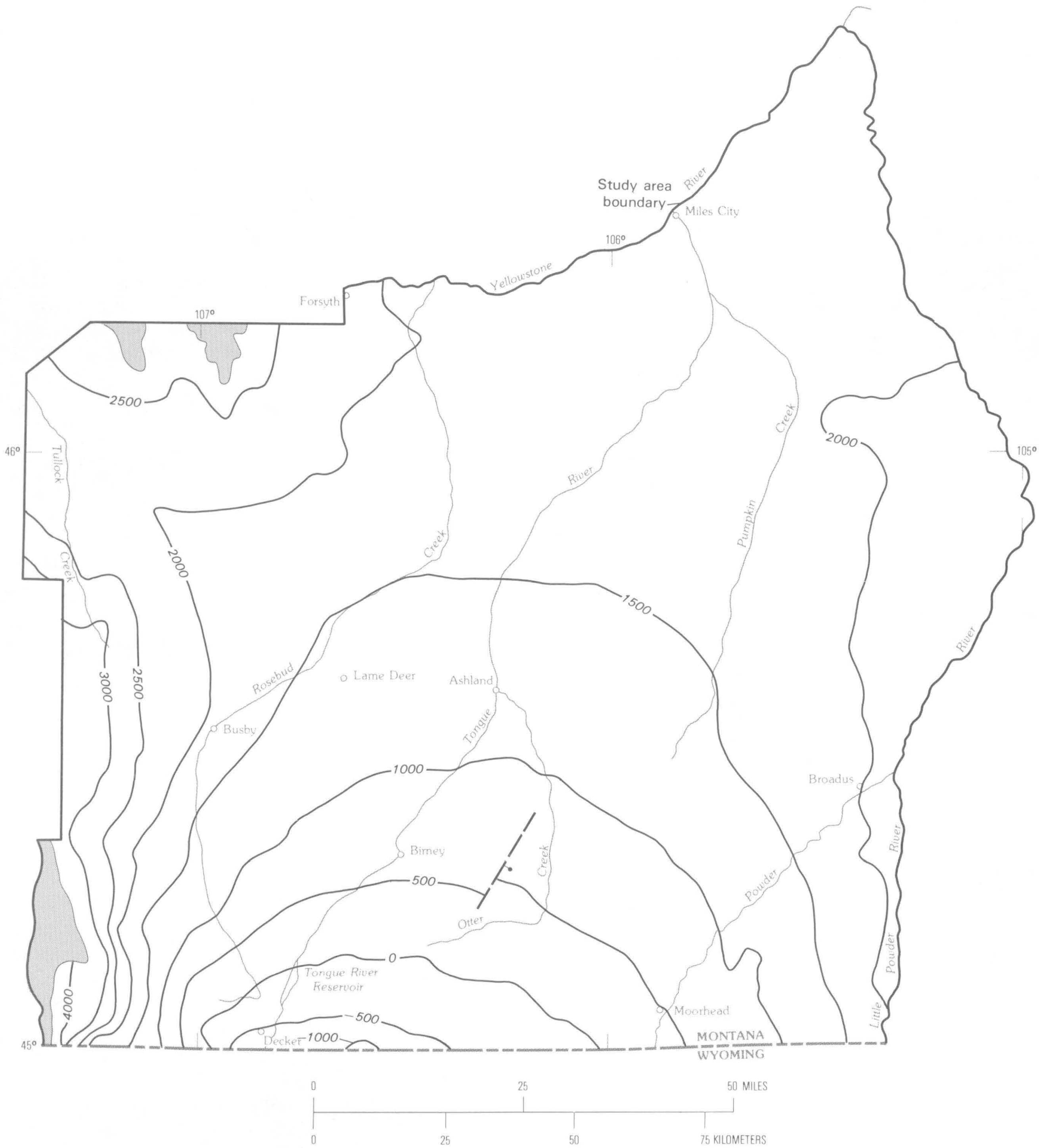
Water-Yielding Characteristics

Bearpaw Confining Layer

The Bearpaw Shale is considered in this study to comprise the lower boundary of the shallow ground-water system, because the thick shale sequence functions as a barrier to the vertical movement of water However, the Bearpaw Shale contains a few thin sandstone stringers that, where saturated, yield small quantities of water to wells These sandstone stringers generally are tapped by wells only in areas where the shale crops out and only where the water in these stringers comprises the first available water below land surface Where younger formations overlie the Bearpaw, drilling normally is terminated at or above the top of the formation and the shale is not explored for additional quantities of water

Fox Hills-Lower Hell Creek Aquifer

The Fox Hills Sandstone, combined with approximately the lower one-half of the Hell Creek Formation, constitutes the most probable source of large quantities of good quality water from the shallow bedrock aquifers in the basin The two units are considered as a single aquifer because of the similarity of lithology and direct hydraulic connection Yields from inventoried wells completed in this aquifer range from 0 5 to 20 gal/min and commonly are about 5 gal/min Yields of as much as 200 gal/min to industrial wells have been reported Although the water generally contains smaller concentrations of dissolved minerals than contained in younger units in the area, the aquifer generally occurs at depths greater than can be economically tapped for stock or domestic supplies, provided shallower water supplies are present Because of the relatively large yields potentially available from the Fox Hills-lower Hell Creek aquifer, it is considered by industry and municipalities to be a good source for possible water supplies



EXPLANATION

AREA OF OUTCROP OF BEARPAW SHALE

500 — STRUCTURE CONTOUR—Shows altitude of top of Bearpaw Shale. Contour intervals 500 and 1000 feet. Datum is sea level

FAULT—Approximately located. Bar and ball on downthrown side

Figure 3. Altitude and configuration of the top of the Bearpaw Shale. Modified from Lewis and Roberts (1978).

Upper Hell Creek Confining Layer

The upper part of the Hell Creek Formation, being primarily composed of claystone, siltstone, and shale, generally is not considered as an aquifer Wells completed in lenticular sandstone or silty sandstone yield as much as 4 gal/min Most wells in the upper Hell Creek are located in or near outcrop areas

Tullock Aquifer

Although a reliable source of water, the Tullock Member of the Fort Union Formation is not used extensively for water supplies at the present time (1981) The aquifer generally is not tapped because it commonly occurs at considerable depth, and sufficient supplies are available from shallower aquifers in most of the area

Because of the interbedding and intertonguing of the material that composes the aquifer, yields at a particular location are difficult to predict Yields to wells completed in the Tullock Member range from about 0 3 to 40 gal/min and generally are about 15 gal/min

Lebo Confining Layer

The Lebo Shale Member of the Fort Union Formation is composed primarily of shale and generally is not considered to be an aquifer However, many wells in the study area are completed in the Lebo—primarily in and near the areas of outcrop These wells generally are completed in isolated siltstone and sandstone stringers or in channel sandstone and generally are completed in the first available water below the surface Yields from wells completed in the Lebo are as much as 35 gal/min, but are more commonly about 7 gal/min Because the Lebo lies at depth in most of the study area and shallower water supplies are available, the Lebo is not frequently explored as a source of water

Tongue River-Wasatch Aquifer

The Tongue River Member of the Fort Union Formation is the major source of water withdrawn from wells in the northern Powder River Basin The Tongue River Member is used primarily because it is a reliable source of water, it directly underlies most of the area, and it commonly is the shallowest and most easily accessible aquifer

Most ground-water supplies are obtained from sandstone and fractured coal beds in the Tongue River Member Because of the heterogeneity of the member, depth to water-producing material and probable yields are difficult to predict

The Wasatch Formation and the Tongue River Member are considered in this report as a single aquifer because of their similar lithology and the limited extent of the Wasatch The Wasatch caps topographically high areas and commonly is not saturated Yields from 515 inventoried wells range from about 0 2 to 150 gal/min, and average about 8 gal/min

Clinker

Clinker, which generally is greatly fractured, is an excellent medium for production of large quantities of water However, it generally is not saturated owing to its occurrence in topographically high areas and its ability to readily drain as a result of large hydraulic conductivity caused by fracturing Clinker is described as a separate unit because of its unique hydraulic character and because it is not necessarily associated with a particular member or formation, in the study area it may occur throughout the Tertiary section where adjacent coal has burned in the subsurface

Alluvium

Where saturated, sand and gravel of alluvium and terrace deposits produce large quantities of water in the northern Powder River Basin Occurrence at shallow depth also makes these deposits one of the most economical and easily obtainable sources of water Alluvium along streams generally is saturated, but terrace deposits commonly occur above the saturated zone Alluvium composed of coarse gravel may yield several hundred gallons per minute to properly constructed wells in local areas along the larger perennial streams Yields of as much as 900 gal/min have been reported from wells completed in the alluvium of the Powder River south of Broadus Yields from alluvium along smaller streams are commonly 30 gal/min or less

Aquifer Properties

The hydraulic conductivity of coal aquifers is due largely to secondary permeability resulting from fracturing Thus, variations in hydraulic conductivity generally reflect the degree of fracturing in the vicinity of the well

Aquifer tests conducted in the study area indicated a range in hydraulic-conductivity values of 0 34 to 6 5 ft/d for coal aquifers and a single value of 2 5 ft/d for the Hell Creek Formation (table 2) The hydraulic-conductivity values were determined from single-well aquifer tests using the Jacob nonequilibrium method (Ferris and others, 1962, p 98–100) for drawdown analysis and the

Theis method (Jacob, 1963, p 283–284) for recovery analysis

Single-well aquifer tests provide only estimates of the hydraulic conductivity, owing to the heterogeneous and anisotropic properties of coal aquifers Stoner (1981) found that single-well drawdown tests in anisotropic coal aquifers can result in hydraulic-conductivity values smaller than actual average values and smaller than values obtained from multiwell aquifer tests The smaller values may be a result of the effects of aquifer dewatering, well entrance losses, or casing storage Results of single-well recovery tests compared more favorably with values obtained from the multi-well tests

Ground-Water Movement

Alternating aquifers and confining zones coupled with complex intertonguing and interfingering within most units result in complicated patterns of ground-water flow Water-quality distribution within the study area indicates that two general flow patterns are present above the Bearpaw Shale An upper flow pattern occurs in aquifers at depths of less than about 200 feet and consists of localized flow that is controlled by topography A lower flow pattern, which is characterized by regional flow generally northward toward the Yellowstone River and significant flow toward the Powder and Tongue Rivers, is present in aquifers at depths of more than about 200 feet The approximate altitude of the water surface in wells less than 200 feet deep is depicted on plate 2 The map, constructed from water levels in wells completed in numerous sandstone lenses and coal beds having many different potentiometric surfaces, approximates a single potentiometric surface that represents composite hydraulic heads

Water enters the shallow ground-water system by surface infiltration, flows downslope, and discharges to streams and rivers In recharge areas, which generally coincide with the topographically higher areas, the altitude of the potentiometric surface decreases with depth, signifying a downward component of ground-water flow Frequently, water moving downward is retarded or intercepted by relatively impermeable material, causing water to move laterally and discharge as contact springs at the land surface

Discharge areas are characterized by an upward component of flow where the altitude of the potentiometric surface increases with depth Water moves upward through the aquifers and confining zones to land surface where it discharges as base flow to streams, evaporates, or is transpired by plants Discharge areas for the aquifers at depths less than 200 feet in the northern Powder River Basin primarily coincide with the valleys of perennial and intermittent streams Discharge areas for the deeper aquifers generally coincide with the major drainages

Vertical movement between the aquifers is known to exist, but the rate of exchange is unknown The rate of vertical movement is dependent primarily on the vertical hydraulic conductivity, the thickness of the confining zone, and the hydraulic-head differential between the aquifers Owing to the complex intertonguing of the geologic units in the northern Powder River Basin, especially the Tertiary deposits, the thickness and distribution of confining zones are difficult and impractical to define over large areas

Investigators in the lignite area of North Dakota, where the geology is similar, have determined that vertical hydraulic conductivity of the confining zones ranges from about 10^{-3} to 10^{-5} ft/d and hydraulic gradients across the confining zones range from about 0 1 to 1 (Moran, Cherry, Fritz, Peterson, Sommerville, Stancel, and Ulmer, 1978) Although these small values would indicate minimal exchange of water between aquifers, the cumulative effect over areas as large as the northern Powder River Basin could be considerable For example, using the above values, leakage through a 1-square-foot area of a confining zone would range from 10^{-6} to 10^{-3} ft^3/d Cumulative leakage over the entire study area would range from about 2,000 to 2,000,000 acre-feet per year

Recharge

The principal sources of recharge to the shallow ground-water system are infiltration of precipitation and seepage from streams and rivers Additional recharge is supplied by deep percolation of applied irrigation water and subsurface ground-water inflow from adjacent areas

Precipitation

The primary source of recharge to the shallow ground-water system is infiltration of rainfall and snowmelt on the outcrops Water that falls on the land surface as rain or snow either runs off, evaporates, is transpired by plants, is retained to supply deficiencies in soil moisture, or percolates to the saturated zone Water that percolates below the zone of evapotranspiration becomes recharge to the shallow ground-water system Miller (1979) estimates that recharge from surface infiltration of rainfall and snowmelt is about 1 percent of the average annual precipitation, or about 80,000 acre-feet per year

Irrigation

A part of the recharge is derived from deep percolation of applied irrigation water and from ditch losses not evaporated or consumed by plants This recharge is primarily confined to the alluvium, as most irrigated land is in the stream valleys

The quantity of recharge from irrigation cannot be estimated, because documentation is not available for the

Table 2. Summary of aquifer tests

Location of well	Depth of well (feet)	Geologic unit	Lithology	Thickness of tested interval (feet)	Length of test (minutes)	Discharge (gallons per minute)	Transmissivity (feet squared per day)		Hydraulic conductivity (feet per day)	
							Drawdown	Recovery	Drawdown	Recovery
NW¼ SE¼ SE¼ sec 18, T 1 N , R 54 E	400	Hell Creek Formation	Sandstone	90	420	12	223	--	2 5	--
NW¼ NE¼ SE¼ SE¼ sec 32, T 8 S , R 44 E	183	Anderson coal bed of Tongue River Member[1]	Coal	31	180	4 4	157	157	5 1	5 1
NW¼ NW¼ NW¼ NW¼ sec 34, T 8 S , R 45 E	67	Anderson coal bed of Tongue River Member[1]	Coal	10	300	2 0	13	--	1 3	--
NW¼ SW¼ NW¼ SW¼ sec 34, T 8 S , R 45 E	253	Anderson coal bed of Tongue River Member[1]	Coal	22	155	2 7	20	--	91	--
SE¼ SE¼ NW¼ NW¼ sec 14, T 9 S R 43 E	262	Anderson coal bed of Tongue River Member[1]	Coal	28	300	2 9	30	43	1 1	1 5
NW¼ NW¼ SW¼ SW¼ sec 7, T 9 S , R 44 E	94	Anderson coal bed of Tongue River Member[1]	Coal	32	1,500	3 0	12	11	38	34
NW¼ NW¼ NE¼ NE¼ sec 8, T 9 S , R 44 E	110	Anderson coal bed of Tongue River Member[1]	Coal	33	360	4 6	205	215	6 2	6 5

[1]Of Fort Union Formation

values of many variables involved, such as amount and distribution of applied water, total acreage irrigated, distribution of consumptive use, and amount and distribution of ditch losses Most recharge resulting from irrigation probably is retained only temporarily Water that reaches the saturated zone raises the water table in the alluvium to above normal levels, which induces lateral flow and results in increased ground-water discharge to the stream Much of the water recharged as a result of irrigation is recirculated to the stream from which it was obtained

Streams and Rivers

Intermittent and ephemeral streams serve as a major source of recharge during times of runoff Some recharge occurs from runoff resulting from summer storms but is limited by the short duration and intensity of the storms Most recharge from runoff results from spring snowmelt The longer duration of streamflow during snowmelt provides greater opportunity for infiltration, except when infiltration is limited by frozen ground

Perennial streams serve primarily as drains for the ground-water system However, in some reaches where the stream level is above the water table, the streams supply water for recharge Considerable recharge occurs from perennial streams during intervals of high streamflow caused by storm or snowmelt runoff Losses from the perennial streams during periods of high flow recharge the alluvium, thereby raising the water table Most of this recharged water is returned to the stream as base flow during subsequent low-flow periods

Subsurface Inflow

Subsurface inflow from Wyoming supplies a small amount of recharge to the shallow ground-water system in the Montana part of the Powder River Basin Subsurface inflow enters Montana primarily in three areas along the Tongue River, along Hanging Woman Creek, and between the Powder River and the Little Powder River (pl 2) Total inflow in these three areas is calculated by using

Darcy's equation to be between 500 and 1,000 acre-feet per year

Discharge

Water in the shallow ground-water system of the northern Powder River Basin, for the most part, is undisturbed by man and is essentially in equilibrium, thus, long-term discharge is equal to recharge Ground water is discharged through streams and rivers, evapotranspiration, wells, springs and seeps, and subsurface outflow from the area

Streams and Rivers

The primary mode of discharge from the ground-water system is to perennial streams and rivers Most of the ground water drained from the area by streams and rivers is derived from aquifers less than about 200 feet deep and originates as recharge within the same surface-drainage basin Some water moves upward from a deeper flow system through confining zones and discharges to the major streams Water in the bedrock aquifers that does not drain directly to perennial streams infiltrates into the alluvium along intermittent and ephemeral streams This water, in general, flows through the alluvium in a downstream direction, and that part not lost to evapotranspiration or wells eventually is discharged to a perennial stream

Most ground water drained from the study area is discharged as base flow through Rosebud Creek and the Tongue, Powder, and Yellowstone Rivers Estimates of the volume of ground water discharged by the streams were obtained through streamflow measurements made during the fall, when interception by evapotranspiration was minimal and base flow more closely represented losses from the ground-water system

Streamflow measurements in late October and early November 1977 (Lee and others, 1981, Druse and others, 1981) indicated that streamflow near the mouths of these streams was 0 04 ft^3/s for Otter Creek, 13 6 ft^3/s for Rosebud Creek, and 233 ft^3/s for the Tongue River The flow of Otter and Rosebud Creeks was derived entirely from ground-water inflow The flow of the Tongue River included releases from the Tongue River Reservoir Net gain in flow, excluding tributary inflow, between the dam and the mouth was 77 ft^3/s

Average annual flow for the Tongue River near Miles City for 34 years of record is 318,800 acre-feet Total flow for the 1977 water year was 278,100 acre-feet, which is about 13 percent less than the long-term average Total flow for Rosebud Creek for the 1977 water year was 23,960 acre-feet or about 56 percent less than the average annual flow of 54,770 acre-feet for 5 years of record at Rosebud Creek at mouth, near Rosebud Only part of the total annual flow is from aquifer discharge, the rest is derived from surface runoff from storms and snowmelt

Long-term streamflow-gaging records at Moorhead and near Locate can be used to estimate the ground-water contribution to the Powder River Mean flow for October at Moorhead for 44 years of record is 185 ft^3/s and mean flow for October at Locate for 37 years of record is 214 ft^3/s The only tributary that generally contributes appreciable flow to the Powder River during October is the Little Powder River Mean flow for October for the Little Powder River near Broadus for 18 years of record is 6 60 ft^3/s Inflow to the Powder River from Mizpah Creek during October generally is less than 0 25 ft^3/s The above figures indicate that the ground-water contribution to the Powder River between Moorhead and Locate is about 22 ft^3/s

Ground-water interaction with the Yellowstone River can be estimated by use of streamflow records from U S Geological Survey streamflow-gaging stations at Forsyth and Miles City with adjustments for inflow from Rosebud Creek and the Tongue River During the 4 years following the establishment of the gage at Forsyth, the differences in flow between Forsyth and Miles City computed for 10–day intervals in October and November ranged from an average gain of about 110 ft^3/s in October-November 1980 to an average gain of 730 ft^3/s in November 1979 Most of the gain is derived from the study area, because the drainage area of the reach of the Yellowstone River between Forsyth and Miles City south of the river is much larger than the drainage area north of the river

Evapotranspiration

Discharge of ground water by evapotranspiration occurs primarily from alluvium along streams where the water table is shallow The rate of evapotranspiration is dependent upon many factors including depth to water, type and density of vegetation, and climate The greatest evapotranspiration occurs during the growing season when plant growth is active, temperatures are warm, and solar radiation is large owing to the greater number of daylight hours

The area of potential evapotranspiration was assumed to coincide with the area of alluvium in the stream valleys The total area of alluvium in the study area was determined by planimetering the alluvium shown on the geologic map of Lewis and Roberts (1978) Alluvium occurs beneath 1,200 mi^2, a small part (12 percent) of the 10,000 mi^2 study area

Potential evapotranspiration was calculated using a method developed by Blaney and Criddle (1950) for estimating consumptive use (evapotranspiration) by various crops and is based on their assumption that evapotranspiration from an alfalfa field is approximately equal to lake evaporation Where sufficient moisture is available, consumptive use is expressed by the equation

$$U=K\sum_{1}^{\eta}\frac{T \cdot P}{100}, \qquad (1)$$

where

$U=$ consumptive use, in inches,

$K=$ empirical consumptive-use coefficient, which is dependent on the type and location of the crop,

$\eta=$ number of months,

$T=$ mean monthly temperature, in degrees Fahrenheit, and

$P=$ monthly percentage of total daytime hours during the year

Using the above method, the calculated potential annual evapotranspiration was 35 28 inches at Busby, 35 83 inches at Broadus, and 36 85 inches at Miles City These values represent the annual potential evapotranspiration if sufficient moisture is available However, annual precipitation in the study area is much less than the potential evapotranspiration, so sufficient moisture would be available only where the water table is very shallow or where deep-rooting plants, such as alfalfa, can obtain moisture directly from the ground-water reservoir

If all water lost by evapotranspiration is derived from ground water, if evapotranspiration occurs only in areas of alluvium, and if sufficient water is available, then the annual discharge of ground water by evapotranspiration from the northern Powder River Basin is about 2,000,000 acre-feet Sufficient moisture is not always available so this figure can be regarded as a maximum The actual volume of ground water lost through evapotranspiration is much less

Wells

The shallow ground-water system in the northern Powder River Basin is essentially undeveloped Although the number of wells is large, the density of wells and the quantity of water withdrawn are small in relation to the quantity of water discharged by natural means The nearly 2,000 wells that have been inventoried in the study area represent only part of the total number of wells that exist The density of the inventoried wells averages about one well for every 5 mi^2 The actual density is probably nearer to one well for every 2–3 mi^2 or 3,000 to 5,000 wells total Most wells in the study area are used for stock and domestic purposes, with the number of wells used for stock exceeding those used for domestic or other purposes Most stock wells are used only when livestock are in pasture, therefore, they are pumped only part of each year The yield from most wells is controlled by the capacity of the pumping system and not by the hydraulic properties of the aquifer Discharge by wells creates little stress on the ground-water system, because of the sparse density of wells, limited pumping time, and less than maximum yields

Average measured discharge of 697 wells in the basin is 9 4 gal/min If 3,000 wells are present, the annual discharge by stock wells is 11,000 acre-feet, assuming that stock wells constitute 50 percent of the total number of wells and that the stock wells are used 50 percent of the time If 5,000 wells are present, the annual discharge from stock wells would be 19,000 acre-feet

Annual pumpage for domestic use can be estimated using per capita consumption and the number of persons served The National Water Well Association (1977) states that daily per capita consumption may be as much as 150 gallons when outdoor water use is considered If 1,500 domestic wells are present in the study area and the average household consists of 3 2 persons, the total annual discharge from domestic wells would be about 800 acre-feet If 2,500 domestic wells are present, the annual discharge would be about 1,300 acre-feet The total annual discharge by stock and domestic wells would range from about 12,000 to 20,000 acre-feet or 0 022 to 0 038 inch of water if applied evenly over the 10,000 mi^2 study area

Springs and Seeps

Because of the lenticular nature of the bedding and high topographic relief in the study area, numerous contact springs and seeps are present The more than 430 springs and seeps that have been inventoried constitute only a part of the springs in the area About 980 springs are shown on U S Geological Survey 7½-minute topographic maps All springs are not shown on topographic maps, therefore, the total number of springs and seeps is not known

Discharges ranging from 0 1 to 950 gal/min have been measured, estimated, or reported for 194 springs and seeps Average discharge for the inventoried springs and seeps is 5 2 gal/min One spring, near Decker, which reportedly yields 950 gal/min, is considered to be anomalously large The average discharge does not include this abnormally large value

The total amount of water discharged through springs and seeps can only be estimated, because of unknown factors such as actual number present and discharge rates Assuming a total of 2,000 springs and seeps, which is about twice the number shown on topographic maps, and an average discharge of 5 2 gal/min, the discharge from the northern Powder River Basin through springs and seeps would be about 16,800 acre-feet per year

Subsurface Outflow

A small amount of water flows from the study area to Wyoming as subsurface outflow just west of the Tongue River and the Powder River However, as this water enters the alluvium along each respective river, it flows in a downstream direction and re-enters the study area as streamflow or as subsurface flow in the alluvium

As the northern part of the western boundary of the study area basically coincides with the Tullock Creek-Little Bighorn River drainage divide, little water leaves by subsurface outflow through this area Water leaves the area by subsurface outflow along the western part of the northern boundary of the study area, but travels only a short distance, generally less than 6 miles, and discharges to the Yellowstone River

CHEMICAL QUALITY OF GROUND WATER

Water-Use Standards

Domestic supply and livestock watering constitute the most common uses of ground water in the northern Powder River Basin Some ground water is used for irrigation

Primary and secondary drinking water standards (table 3) established by the U S Environmental Protection Agency (1977, 1979) may be used as guides to the suitability of water for domestic use Primary standards pertain to public water supplies and include substances known to be toxic to humans in small quantities An excess concentration of any of the constituents constitutes a basis for rejection of the supply Secondary standards are to be complied with unless no better supply is available

Livestock raising is a major industry throughout the area and stock consumption is an important water use McKee and Wolf (1971, p 112) suggest the following limits of dissolved-solids concentration for various types of stock

Livestock	Dissolved solids concentration, in milligrams per liter
Poultry	2,860
Pigs	4,290
Horses	6,435
Cattle (dairy)	7,150
Cattle (beef)	10,000
Sheep (adult)	12,900

Some investigators (see McKee and Wolf, 1971, p 113) indicate that these values are much too large for optimum growth and development of livestock Also, certain major ions may be more limiting than the sum of all constituents For example, stock can tolerate the greatest dissolved solids when the primary constituents in the water are sodium and chloride Water containing a large concentration of sulfate is much less desirable

The suitability of ground water for livestock watering in southeastern Montana can be assessed by reference to classifications developed by the South Dakota Agriculture Experiment Station and by the Montana State College, Agriculture Experiment Station (McKee and Wolf, 1971, p 113)

<table>
<tr><th rowspan="2">Classification</th><th colspan="2">Dissolved-solids concentration, in milligrams per liter</th></tr>
<tr><th>Montana</th><th>South Dakota</th></tr>
<tr><td>Excellent</td><td rowspan="2">0–2,500</td><td>0–1,000</td></tr>
<tr><td>Good</td><td>1,000–4,000</td></tr>
<tr><td>Fair</td><td>2,500–3,500</td><td rowspan="2">4,000–7,000</td></tr>
<tr><td>Poor</td><td>3,500–4,500</td></tr>
<tr><td>Unfit</td><td>More than 4,500</td><td>More than 7,000</td></tr>
</table>

The suitability of water for irrigation use is dependent on the concentrations of dissolved solids and specific ions as well as factors such as soil type, soil drainage, and crop type Sustained application of water containing large dissolved-solids concentrations can result in increased salt concentrations in the root zone The part of the applied irrigation water that remains in the soil, the soil solution, tends to become more concentrated as relatively pure water is utilized by plants or lost upward through capillary action and evaporation If the root zone is not leached, the salt concentration of the soil solution will increase until it reaches the limit of solubility of the salt

According to McKee and Wolf (1971, p 107) the maximum concentration of dissolved solids considered suitable for best crop growths of all types of plants, including salt-susceptible plants, is about 1,000 mg/L (milligrams per liter) A dissolved-solids concentration of about 3,150 mg/L generally is the maximum for the safe watering of any plant, provided that drainage is excellent and each watering is of sufficient volume to leach the root zone

Large concentrations of sodium and sulfate are primary contributors to salinity problems in southeastern Montana Large concentrations of sodium in irrigation water can cause accumulations of sodium ions and a breakdown of granular soil structure The result is deflocculation of the soil, which results in a sealing of soil

Table 3. Drinking water standards

	Maximum contaminant level		
	Primary standard[1], in milligrams per liter	Secondary standard[2], in milligrams per liter	Equivalent trace-constituent concentration[3], in micrograms per liter
Arsenic	0 05	--	50
Barium	1	--	1,000
Cadmium	010	--	10
Chloride	--	250	--
Chromium	05	--	50
Copper	--	1	1,000
Dissolved solids	--	500	--
Fluoride	[4]2 2	--	--
Iron	--	3	300
Lead	05	--	50
Manganese	--	05	50
Mercury	002	--	2
Nitrate (as N)	10	--	--
Selenium	01	--	10
Silver	05	--	50
Sulfate	--	250	--
Zinc	--	5	--

[1]U S Environmental Protection Agency (1977)
[2]U S Environmental Protection Agency (1979)
[3]The U S Geological Survey reports trace-constituent concentrations in micrograms per liter
[4]Range based on the annual average of maximum daily air temperatures of 53 8 to 58 3°F

pores and a decrease in soil permeability Additional increases in sodium percentage causes continued deterioration of the soil and an increase in pH, producing alkali soil McKee and Wolf (1971, p 110) indicate that to prevent harmful effects on soil structure, sodium needs to be less than 50 to 60 percent of total cations

The solubilities of sodium sulfate and magnesium sulfate are greater than the tolerance limit of many plants Therefore, toxic soil-solution concentrations may result from sustained application of water containing large sulfate concentrations Critical concentrations of sulfate in irrigation water are dependent on soil drainage, quantity of water applied, and concentration of dissolved constituents, especially chloride Chloride concentrations in water in the study area are commonly small, thus, sulfate is the determining ion Considering the mean chloride concentration of 17 mg/L for ground water from 665 sampled wells and springs in the study area, critical sulfate concentrations range from about 150 to 700 mg/L, depending on soil conditions

Dissolved Constituents and Distribution

Quality of shallow ground water in southeastern Montana ranges widely as a result of differing geochemical controls, geology, and hydrology A general assessment of water quality can be made if depth of producing zone, location within the area, and lithology are considered

Most shallow ground water in the northern Powder River Basin does not meet recommended standards (table 3) of the U S Environmental Protection Agency for public drinking water However, some water at shallow depths in recharge areas contains less than the 500 mg/L dissolved solids recommended for public supply

Common-constituent concentrations (table 4) indicate some significant differences in water quality with depth Springs averaged 1,630 mg/L of dissolved solids with sodium, magnesium, calcium, sulfate, and bicarbonate being the dominant ions Water from wells less than 200 feet deep was dominated by various combinations of sodium, magnesium, calcium, sulfate, and bicarbonate with sodium and sulfate as the most common dominant ions, and contained an average dissolved-solids concentration of 2,100 mg/L Water from wells between 200 and 1,200 feet deep was dominated by sodium and bicarbonate with an average dissolved-solids concentration of 1,400 mg/L (fig 4) Many waters contained a sufficient concentration of hydrogen sulfide to impart a definite odor Doc-

Table 4. Summary of selected common constituents in water from wells and springs[1]
[Constituents are dissolved and concentrations are reported in milligrams per liter]

Source of water	Number of samples		Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potasium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids
Springs	149	Minimum	9 5	3 0	6 6	2	5	0	15	1 3	160
		Mean	110	140	240	10	580	2	830	8 0	1,630
		Maximum	400	510	1,800	31	1,500	37	5,500	36	5,260
Well depths less than 200 feet	375	Minimum	1 7	3	3 2	1	20	0	0	4	110
		Mean	120	120	410	8	650	2	1,100	13	2,100
		Maximum	460	680	1,900	48	2,000	53	4,400	120	6,300
Well depths greater than 200 feet	141	Minimum	1 0	1	13	1	230	0	1	3 0	390
		Mean	32	27	450	4	850	14	390	36	1,400
		Maximum	350	330	1,700	14	2,000	440	3,300	770	5,720

[1]From Lee (1981, p 5)

kins and others (1980) report that dissolved sulfide is present in ground waters of southeastern Montana in concentrations that generally are less than 1 mg/L but can be as much as 3 to 4 mg/L The probable source of the sulfide is bacterially promoted sulfate reduction

Water at depths of less than 200 feet generally comprises the upper chemical zone Maps of percent sodium plus potassium (fig 5) and percent sulfate (fig 6) in water from springs and wells less than 200 feet deep indicate sodium and sulfate enrichment of water as recharge waters enter the aquifers and move downgradient Because flow patterns of water at depths of less than 200 feet generally coincide with the topography, the influence of an individual recharge area is limited in areal extent This condition suggests a cellular pattern of small recharge-discharge cells, as shown on the maps of percent sodium plus potassium (fig 5) and percent sulfate (fig 6)

Trace-constituent concentrations (table 5) vary throughout the area and most are less than the maximum contaminant levels established by the U S Environmental Protection Agency (1977, 1979) Maximum concentration of iron was 53,000 µg/L (micrograms per liter) and strontium was 9,000 µg/L (table 5) Manganese and boron concentrations in excess of 1,000 µg/L also were reported A summary of radiochemical and miscellaneous-constituent concentrations in water from wells in the northern Powder River Basin is given in table 6 The reported concentrations of total nitrogen were 6 2 mg/L or less for all samples except one

Ground-water supplies are generally suitable (fair to excellent) for livestock watering Most water in the shallow ground-water system in southeastern Montana contains concentrations of sodium or dissolved solids that exceed maximums developed by the U S Salinity Laboratory Staff (1954) and are not suitable for irrigation Some supplies may be used if water-application rates are sufficient to thoroughly leach the soil A few wells are used for irrigation even though the salinity and sodium hazards of the water are large

Processes and Factors Controlling Concentration of Mineral Constituents

A generalized conceptual model of the shallow ground-water system (fig 7) was developed from the observed chemical composition of water, probable mineral-water interactions, aqueous chemistry, geology, and hydrology in southeastern Montana (Lee, 1981) The section depicted in figure 7 may vary in length from 2 to 20 miles from the recharge area (A) to the discharge area (D) Vertical exaggeration is about 50

At point A, chemical composition would represent recharge waters dominated by magnesium, calcium, and bicarbonate, with significant amounts of sodium and sulfate, but having a small dissolved-solids concentration As the water percolates through the system, sodium and sulfate enrichment results in larger percentages of sodium and sulfate and larger dissolved-solids concentrations at B At C, chemical composition would represent a mixture of water at B and recharge water that has percolated through the very permeable clinker The mixing results in a solution containing a smaller dissolved-solids concentration than at B with a chemical composition approaching that for recharge water, that is, a lesser percentage of sodium and sulfate At D, water quality is predominantly sodium and sulfate (developed by sodium and sulfate enrichment), which may discharge as base flow to the stream In the deep coal bed at E, sulfate reduction may dominate the geochemistry of the ground water, producing

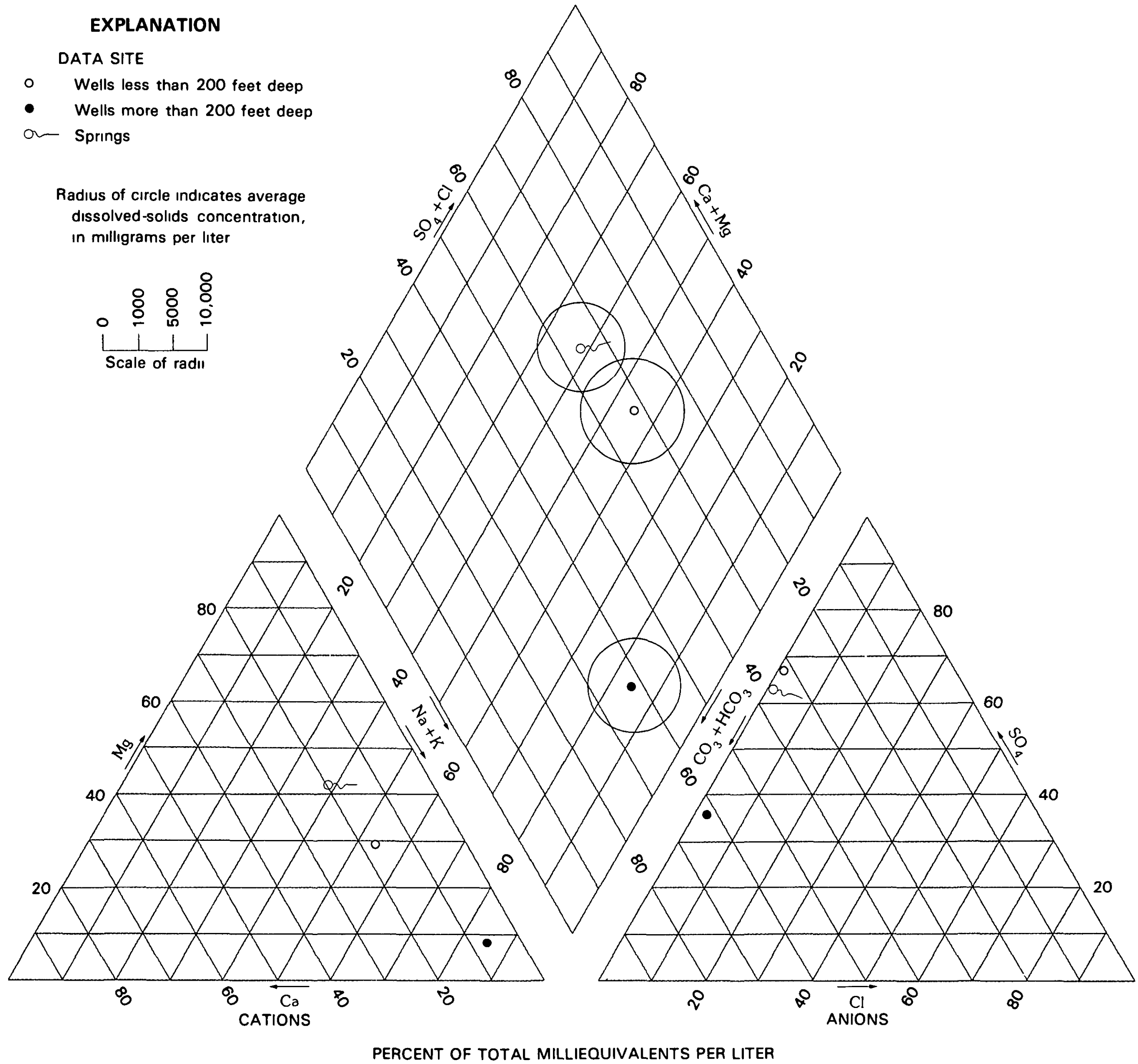


Figure 4. Trilinear diagram of average percentages of chemical constituents in water from wells and springs

a sodium bicarbonate water with a chemical composition that is almost indistinguishable from water of deeper aquifers At F, water of the deeper regional zone (whose chemical character probably developed similar to water at E) would be dominated by sodium and bicarbonate Finally at G, upward leakage would result in a chemical composition similar to a composite of waters from D, E, and F Chemical character of water at G would be determined by the dominant water supply from D, E, or F

Much of the water quality in the shallow system depends on minerals in the aquifers through which the waters flow Probable mineral reactions within the aqueous phase are

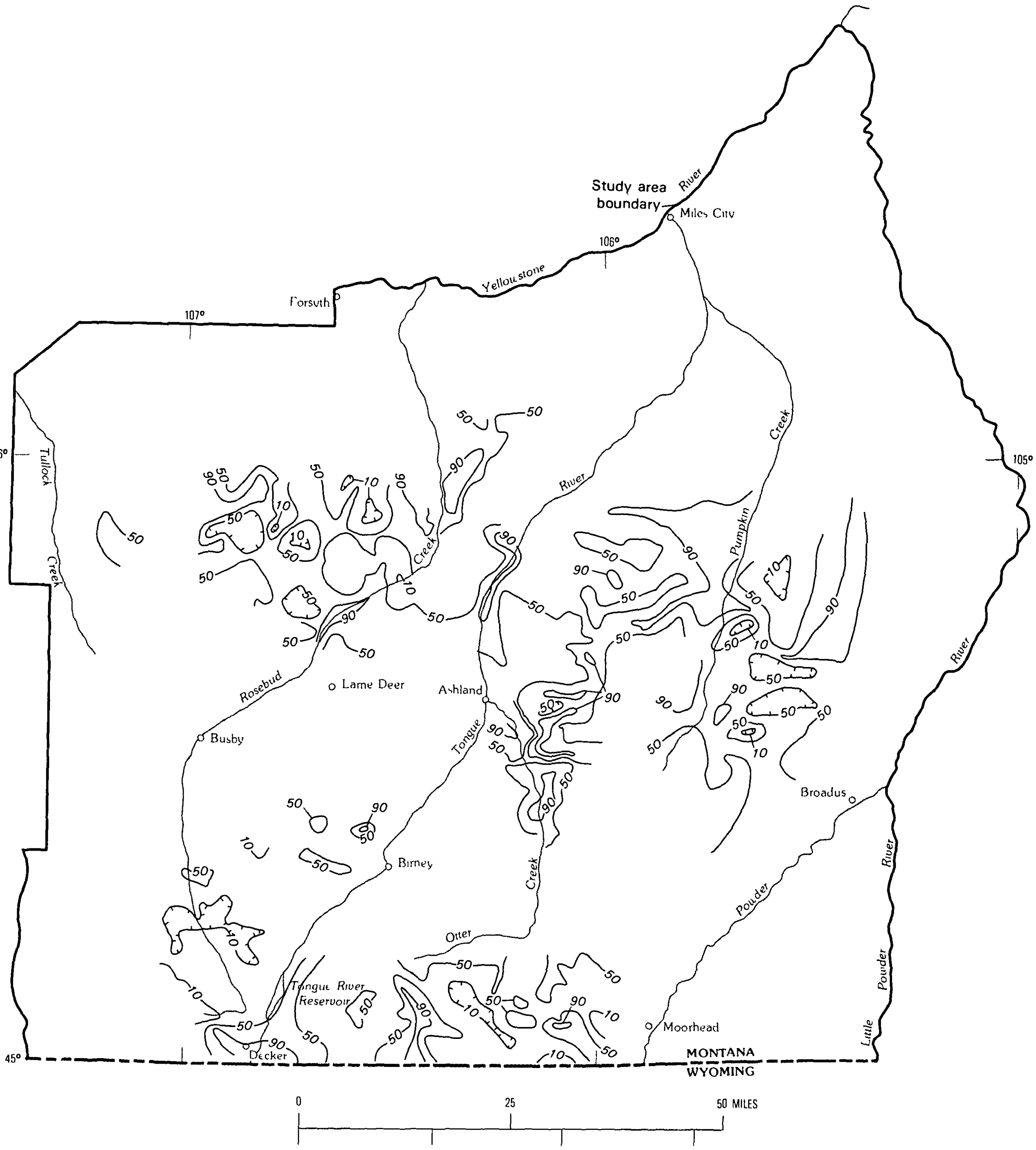
$$Ca^{+2}+HCO_3^{-}\rightleftharpoons \underset{\text{(calcite)}}{CaCO_3}+H^{+} \quad (2)$$

$$Mg^{+2}+HCO_3^{-}\rightleftharpoons \underset{\text{(magnesite)}}{MgCO_3}+H^{+} \quad (3)$$

$$Ca^{+2}+Mg^{+2}+2HCO_3^{-}\rightleftharpoons \underset{\text{(dolomite)}}{Ca,Mg(CO_3)_2}+2H^{+} \quad (4)$$

$$9H_2O+2H_2CO_3+\underset{\text{(albite)}}{2NaAlSi_3O_8} \rightleftharpoons 2Na^{+}+2HCO_3^{-}+4H_4SiO_4+\underset{\text{(kaolinite)}}{Al_2Si_2O_5(OH)_4} \quad (5)$$

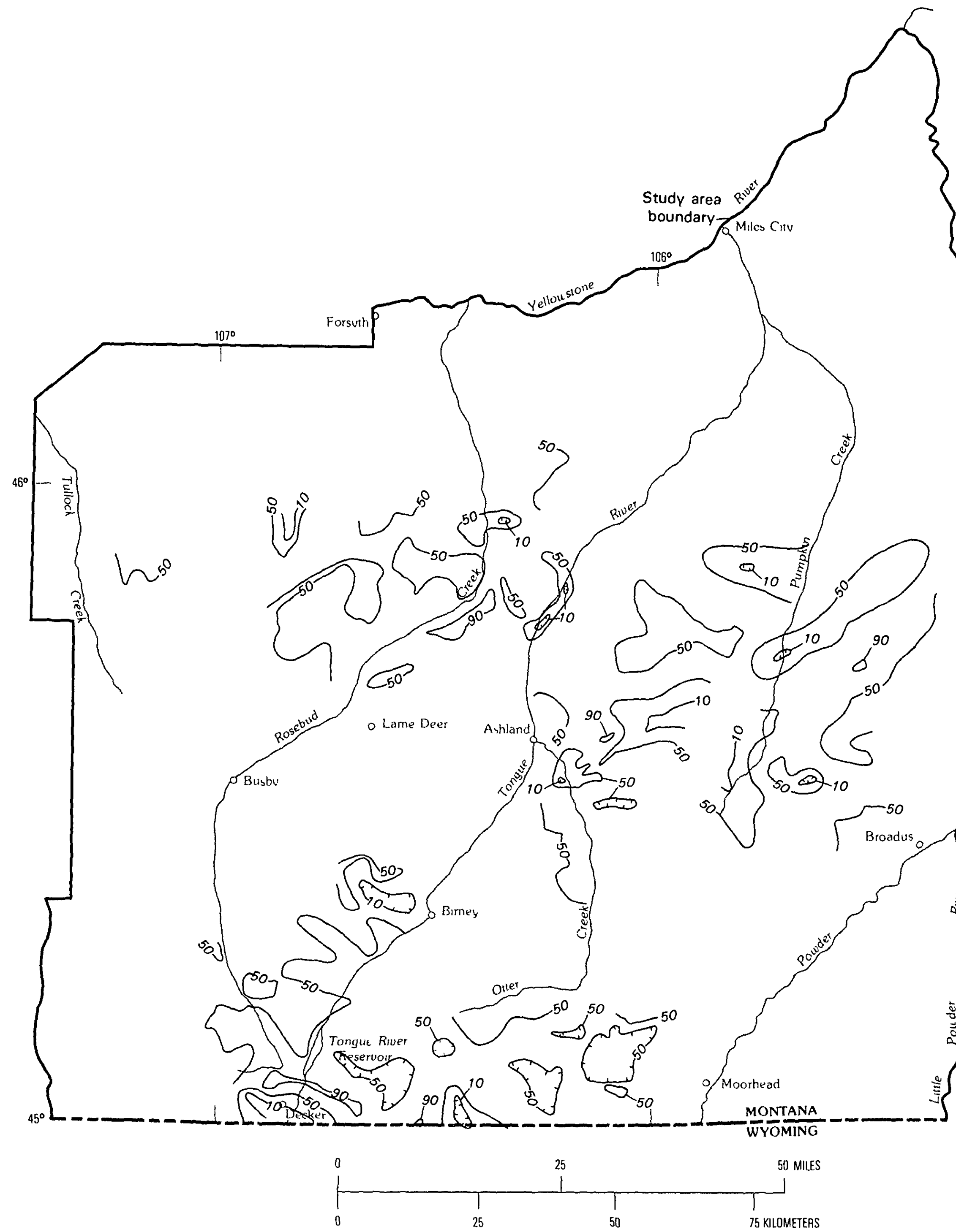
$$Ca^{+2}+Mg^{+2}+4Na^{+}\text{ (on sediment)} \rightleftharpoons Ca^{+2},\ Mg^{+2}\text{ (on sediment)}+4Na^{+} \quad (6)$$



EXPLANATION

——50—— LINE OF EQUAL RATIO OF SODIUM PLUS POTASSIUM TO TOTAL CATIONS IN MILLIEQUIVALENTS PER LITER—Interval 40 percent

Figure 5. Percent sodium plus potassium in the upper 200 feet of the shallow ground-water system Modified from Lee (1981)



EXPLANATION

——50—— LINE OF EQUAL RATIO OF SULFATE TO TOTAL ANIONS IN MILLIEQUIVALENTS PER LITER—Interval 40 percent

Figure 6. Percent sulfate in the upper 200 feet of the shallow ground-water system Modified from Lee (1981)

Reactions 2, 3, and 4, as written from left to right, would result in indirect sodium and sulfate enrichment by removing calcium, magnesium, and bicarbonate from solution Equations 5 and 6 would enrich sodium directly in solution The sediment in reaction 6 could be smectite clay minerals, coal, or carbonaceous shale having large exchange capacities

Sulfate enrichment in ground water occurs by pyrite oxidation or gypsum dissolution (Lee, 1981, p 12) as follows

$$2FeS_2+7O_2+2H_2O \rightleftharpoons 2Fe^{+2}+4SO_4^{-2}+4H^+ \quad (7)$$
(pyrite)

$$CaSO_4\ 2H_2O \rightleftharpoons Ca^{+2}+SO_4^{-2}+2H_2O \quad (8)$$
(gypsum)

Sulfate depletion may occur chemically by bacterially promoted sulfate reduction (Dockins and others, 1980)

$$SO_4^{-2}+2CH_2O=H_2O+CO_2+HCO_3^-+HS^- \quad (9)$$

Mixing of ground waters of differing chemical compositions can cause increases or decreases in percentage of sodium or sulfate, thereby creating apparent geochemical anomalies Mixing of a shallow ground water enriched in sodium and sulfate with relatively fresh recharge water would decrease sodium and sulfate percentages with respect to the shallow ground water Mixing of a shallow ground water with water dominated by sodium and bicarbonate from a deep regionally extensive aquifer would decrease the percentage of sulfate but show little or no change in sodium percentage with respect to shallow ground water These two mixing phenomena would appear as geochemical trend reversals in figure 6 such as along the Tongue River about 20 miles north of Ashland

EFFECTS OF MINING ON GROUND-WATER RESOURCES

Various phases of mining operations will affect the ground-water reservoir in different ways Effects of the mining itself will differ from those of processing and plant operations Effects of processing and plant operation occur primarily as a result of increased withdrawals from the ground-water reservoir, whereas effects of the mining process could involve interruption of ground-water flow patterns, removal of aquifers, and possible alteration of the chemical quality of the ground water In this report, the effects of the mining process itself are emphasized

Water Levels and Flow Patterns

The effects of mining on water levels and flow patterns are dependent on the location of the mine with relation to the geology and the ground-water system Surface coal mines located above the potentiometric surface will

Table 5. Summary of trace constituents in water from selected wells[1]
[Constituents are dissolved and concentrations are reported in micrograms per liter]

Constituent	Number of samples	Concentration		
		Minimum	Mean	Maximum
Aluminum, Al	57	10	80	470
Arsenic, As	61	0	1	4
Barium, Ba	57	0	120	600
Boron, B	60	5	230	1,100
Cadmium, Cd	57	0	0	1
Chromium, Cr	57	0	30	100
Copper, Cu	63	0	4	30
Iron, Fe	65	0	180	53,000
Lead, Pb	57	0	28	100
Lithium, Li	57	10	100	360
Manganese, Mn	57	0	220	4,600
Mercury, Hg	61	0	3	1 7
Molybdenum, Mo	57	0	19	100
Selenium, Se	52	0	1	6
Strontium, Sr	57	100	2,200	9,000
Vanadium, V	56	0	22	100
Zinc, Zn	57	0	100	500

[1]Modified from Lee (1979)

have little, if any, effect on water levels and flow patterns Possible effects would be limited to increased recharge from seepage through the pit floor

Mines, which are located below the potentiometric surface but above water-yielding zones in areas where confined ground-water conditions exist, also will have little effect on water levels and flow patterns Some upward leakage will occur through the confining zones between the aquifer and the pit floor, particularly if mining activities destroy or damage the integrity of the confining zones If confining zones are not destroyed or damaged, the amount of upward leakage would not significantly exceed premining values Such leakage could cause minor, localized depressions on the potentiometric surfaces Changes in potentiometric surfaces probably would be of less magnitude than natural water-level trends and, therefore, probably would not be detectable without intensive monitoring before and during mining

The greatest potential for alteration of water levels and flow patterns occurs where mines intersect a water-yielding zone The magnitude and areal extent of changes in water levels and flow patterns are dependent on many variables including

(1) The areal extent of the flow system penetrated by the mine,
(2) the thickness of the saturated interval penetrated by the mine,
(3) the hydraulic head at the mine site,
(4) the horizontal and vertical distribution and magnitude of hydraulic conductivity and storage coefficient surrounding the mine site,
(5) the distance to and types of hydrologic boundaries,
(6) the size and shape of the mine cut,
(7) the length of time the mine is in operation

The maximum practical overburden thickness that presently can be removed during surface coal mining is about 200 to 250 feet, thereby essentially limiting mining to the upper part of the shallow ground-water system Thus, alteration of potentiometric surfaces and flow patterns in the upper part of the shallow ground-water system, which is composed of numerous flow cells of limited areal extent, essentially will be confined to the flow cell in which the mine is located

The varied lithology within the stratigraphic units will help to limit the effects of mining on water levels and flow patterns Intertonguing sandstone, siltstone, and shale characterized by truncated units and abrupt facies changes compose a system of numerous lenticular aquifers and confining zones of limited areal and vertical extent Coal beds, which generally are continuous beneath large areas, are transected by fracture systems that are not interconnected over large distances and provide only limited

Table 6. Summary of radiochemical and miscellaneous-constituent concentrations in water from selected wells[1]

[Concentrations are reported in milligrams per liter (mg/L), except where indicated as micrograms per liter (µg/L) or picocuries per liter (pCi/L)]

Constituent	Number of samples	Concentration Minimum	Concentration Mean	Concentration Maximum
Total sulfide, S	50	0 0	0 6	3 0
Dissolved fluoride, F	65	1	1 2	5 0
Dissolved bromide, Br	50	0	2	1 3
Dissolved iodide, I	49	00	01	18
Dissolved silica, SiO_2	65	5 8	11 8	31
Total nitrogen, N	63	14	2 61	14
Total phosphorus, P	64	00	10	71
Dissolved gross alpha as U-nat (µg/L)	59	7 1	32 5	140
Suspended gross alpha as U-nat (µg/L)	59	4	4 5	47
Dissolved gross beta as Sr^{90}/Y^{90} (pCi/L)	59	1 9	12 1	150
Suspended gross beta as Sr^{90}/Y^{90} (pCi/L)	59	4	2 5	19
Total organic carbon, C	41	1	11 1	83
Dissolved organic carbon, C	11	7	2 6	5 0

[1]Modified from Lee (1979)

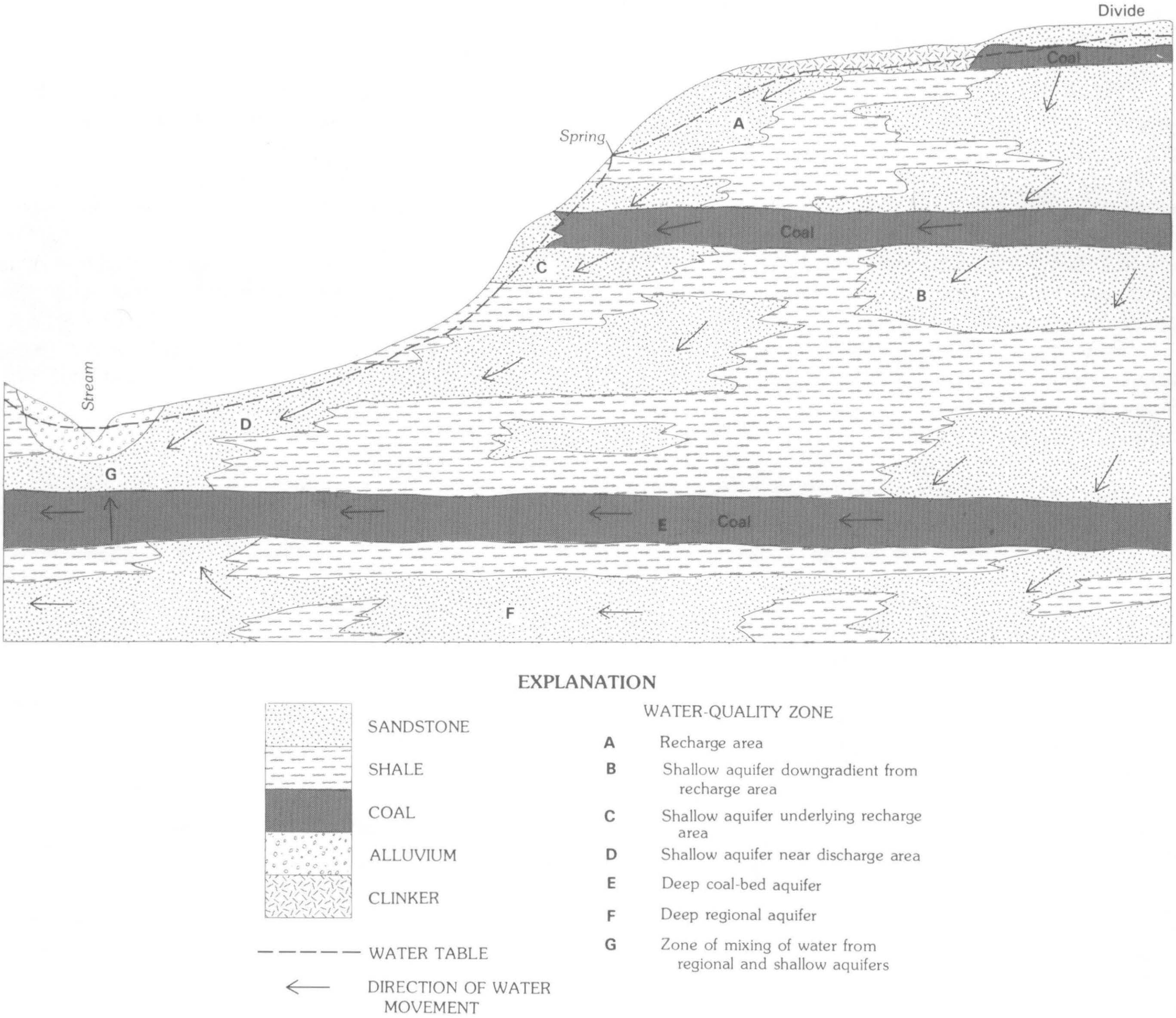


Figure 7. Generalized conceptual model of the shallow ground-water system. Modified from Lee (1981).

paths for the movement of ground water and limited areal migration of water-level declines.

The lithologic distribution imposes a complicated system of ground-water flow, especially where the system is stressed. Water flows relatively freely through local zones of large hydraulic conductivity (sandstone and fractured coal beds) and much less freely through zones of small hydraulic conductivity (shale and non-fractured coal). As a result, drawdown effects of water being withdrawn from a zone of large hydraulic conductivity tend to be restricted by intervening small-conductivity materials, which retard the flow from nearby large-conductivity zones. Consequently, each sandstone lens or fracture system not contiguous with another essentially can be considered as an individual aquifer with available recharge limited to leakage through the surrounding confining zones. Drawdown effects on nearby large-conductivity zones will be dependent on rate of leakage through low-conductivity zones and the ratio of the hydraulic conductivities.

Faulting further complicates flow patterns in the shallow ground-water system. Van Voast and Hedges (1975) indicate that faults in the northern Powder River Basin generally function as barriers to ground-water flow. Fault zones also may function as recharge boundaries because fractures commonly are more abundant near faults. No faults that function as recharge boundaries have been identified in the study area. Fault boundaries, whether barriers or recharge boundaries, tend to limit areal migration of water-level changes resulting from mining.

Detailed local geologic and hydrologic information is needed to accurately predict the effects of mining at any particular site Data collected during the mine-plan phase of development can fulfill this need

Postmining Water Levels and Flow Patterns

Upon completion of mining, withdrawals from the shallow ground-water system will cease, the final mine cut will be filled, and the system will begin re-establishment of equilibrium flow conditions Flow will continue toward and begin filling the depression in the potentiometric surface created by the mine dewatering

Water levels generally will begin to rise, most rapidly near and within the former mine Initially, water levels just beyond the periphery of the area of water-level decline created by mining might decline slightly in response to supplies required to fill the depression in the potentiometric surface Lateral inflow and surface infiltration will cause water levels to continue to rise until an equilibrium flow pattern is attained and premining water levels surrounding the former pit are approximated Water-level configuration and flow patterns within the spoils that fill the former mine will be modified from premining conditions, owing to the altered lithologic distribution Evaluation of the effects of mining on water levels and flow patterns at any particular mine site will require intricate geologic and hydrologic mapping

Productivity of Wells

The effects of mining on potential productivity of wells surrounding the mined area are related directly to the change in water level at a well site In areas where ground water is under artesian pressure, reduction of water levels may involve only a reduction in hydraulic head, rather than actual dewatering of the aquifer

Where the potentiometric surface declines to a level below the top of the water-yielding material (below the base of the confining material), the aquifer becomes unconfined and dewatering of the aquifer occurs, resulting in a reduction of saturated thickness at the well site Because of actual reduction in saturation, effects on productivity are greater where dewatering occurs

In the northern Powder River Basin, many wells are not being pumped at capacity The yield of these wells is limited by well design or the capacity of the pumping system used and not by the hydraulic properties of the aquifer Reduction in capacity of the wells will not affect the usage unless capacity is reduced to less than the present production

Water levels, and hence productivity of wells, will be affected primarily in aquifers that occur stratigraphically above the base of the mine and that are hydraulically connected to the mine Water levels in aquifers below the mine, in aquifers not hydraulically connected with the mine, and in aquifers outside the local flow system in which the mine is located essentially will be unaffected

Postmining Productivity of Wells

As water levels begin to adjust and rise toward an approximation of their premining configuration, the potential productivity of wells will increase toward premining rates in the areas outside the spoil materials Data from existing mines indicate that the ability of spoils to transmit water generally is as great or greater than the coal they replace Thus, as water levels rise, the potential productivity of wells completed in spoil materials probably will approach and may exceed that of wells that could have been completed in the mined coal

Chemical Quality of Water

Previous investigations of surface coal mines were largely in the East where rainfall is greater and more pyrite and organic sulfur are present These studies were concerned primarily with acid-mine drainage to surface waters Although similar reactions may occur in the West, only a small amount of surface water flows from the mines to the streams Ground water, rather than surface water, is most susceptible to change

Replacement of overburden material, consisting largely of sandstone, siltstone, and shale as well as some coal and other carbonaceous material, will result in changes in hydraulic properties of the aquifer, including alteration of flow paths and exposure of fresh mineral surfaces This combination provides the opportunity for rapid chemical reactions and increased mineralization of ground water In addition, minerals that are stable in the reduced state in the saturated zones likely will be in the unsaturated zone and subject to oxidation

Studies by R L Houghton (U S Geological Survey, written commun , 1982) in western North Dakota have shown that the quality of shallow ground water is controlled mainly by chemical processes occurring in the unsaturated zone For the most part the reactions occur naturally, but are accelerated by surface mining Houghton and Moran, Groenewold, and Cherry (1978) emphasize that a primary contributor to dissolved solids in the ground water is the dissolution of gypsum Gypsum is generated in spoil materials by the oxidation of iron sulfide minerals and the dissolution of calcite These investigators believe that mineralization of water in reclaimed spoils can be decreased by selective placement of overburden material Placing salt-rich material (obtained from near-surface horizons) above the water table and organic-rich and clay-rich materials below the water table can limit significant degradation of water quality Returning material obtained from below the water table to the saturated zone will decrease further oxidation and limit the availability of sulfate Effects of plumes of mineralized water that may develop in an aquifer may not appear for years, depending on aquifer properties, downgradient withdrawals, discharge to streams, and the proximity of wells to the plume

Van Voast and Hedges (1975) and Van Voast and others (1977, 1978) discussed the effects of surface coal mining near Decker and Colstrip, Montana They indicated the possible development of plumes of water containing large concentrations of sulfate and nitrate from explosives, but stated that the effects on water quality would be minor Shale present in overburden materials also may serve as a possible source of nitrogen Power and others (1974) state that nitrification of exchangeable NH_4^+ nitrogen contained in shales in the Tongue River Member occurs readily after exposure to atomospheric conditions Dockins and others (1980) found that sulfate-reducing bacteria re-establish themselves in the spoils aquifer, however, the short-term effects are minor on waters having a large sulfate concentration

M E Crawley (U S Geological Survey, oral commun , 1979) indicated that cation exchange has enriched the spoils water with respect to sodium at the Gascoyne Mine, which is about 50 miles east of the Montana-North Dakota line Together with the large sulfate concentration resulting from pyrite oxidation, cation exchange helped create the sodium sulfate plume

The potential water-quality problems and the lack of information on mine spoils in southeastern Montana necessitate additional intensive studies Such studies need to define the chemical reactions taking place in the spoils and the transport mechanisms of chemical species migrating through the spoils and into the undisturbed aquifers

Simulated Effects of Mining on Water Levels

To illustrate possible effects of mine dewatering on surrounding water levels, digital models were constructed to depict the influence of varying hydraulic properties and geologic conditions The hydraulic and geologic settings that were simulated do not represent any particular site, but are representative of typical conditions in the northern Powder River Basin The models present a general picture of the effects on water levels that can be expected as a result of dewatering of excavations that penetrate a water-yielding zone

A model described by Trescott and others (1976) was used for the simulations This model is designed to simulate in two dimensions the response of an aquifer to an imposed stress A variable-grid spacing was used, with the smallest grid spacing being near the excavation to provide better definition of the effects of the stress on water levels in that area Hydraulic-head-controlled flux nodes (Hutchinson and others, 1981, p 16–21) were placed in a rectangular pattern about 9 miles distant from the excavation The effect of the flux nodes is to simulate constant-head boundaries at an effective distance of about 60 miles from the excavation, so that any boundary effect on the results would be negligible The results, therefore, simulate an areally extensive aquifer Dewatering of the excavation was simulated by leakage

The purpose of the models is to illustrate the effects of changes in hydraulic head, hydraulic conductivity, storage coefficient, mine-cut size, slope of the initial potentiometric surface, and effects of hydrologic boundaries Effects of changes in any one of these parameters are illustrated and compared with a base model, which depicts a homogeneous, isotropic, infinite aquifer having a thickness of 10 feet, a hydraulic conductivity of 0 5 ft/d, and a storage coefficient of 10^{-4} The initial potentiometric surface is placed 10 feet above the top of the aquifer The aquifer simulated in the model represents the coal bed to be mined or the overburden above the target coal bed

The results of these models, which were designed to depict maximum-drawdown situations, indicate that after 20 years of continuous dewatering of an aquifer 10 feet thick with an initial hydraulic head 10 feet above the aquifer, water-level declines greater than 1 foot generally would be limited to within about 7 5 miles of the center of the mine excavation, declines greater than 2 feet to within about 6 miles, declines greater than 5 feet to within about 3 7 miles, declines greater than 10 feet to within about 1 7 miles, and declines greater than 15 feet to within 1 2 miles

Because the aquifer is assumed to be confined, the drawdown effects spread more rapidly for a greater distance than if the aquifer was unconfined or would become unconfined as a result of mine dewatering The models assume that the aquifer is essentially of infinite areal extent, but in many instances the areal extent of the effects of mining on drawdown will be limited by the extent of the aquifer The mine cut, in most examples, is one-fourth mile wide by 1 mile long and is assumed to be completely dewatered instantaneously In actuality, the pit probably will be smaller in size, excavation and dewatering depth will progress through some time interval, and the pit will be moved areally as mining progresses The models do not account for recharge by infiltration of water from rainfall and snowmelt, leakage from overlying or underlying aquifers, or conversion from confined to unconfined conditions

The results of the models are illustrated in map and graphic forms The progression of water-level declines through time for the assumed base conditions is depicted in figure 8 Ideally, the water-level contours would appear as smooth concentric ovals around the excavation The plots were computer generated, and irregularities in the contours result from the rounding of output-data values and the wide grid spacing used in the model

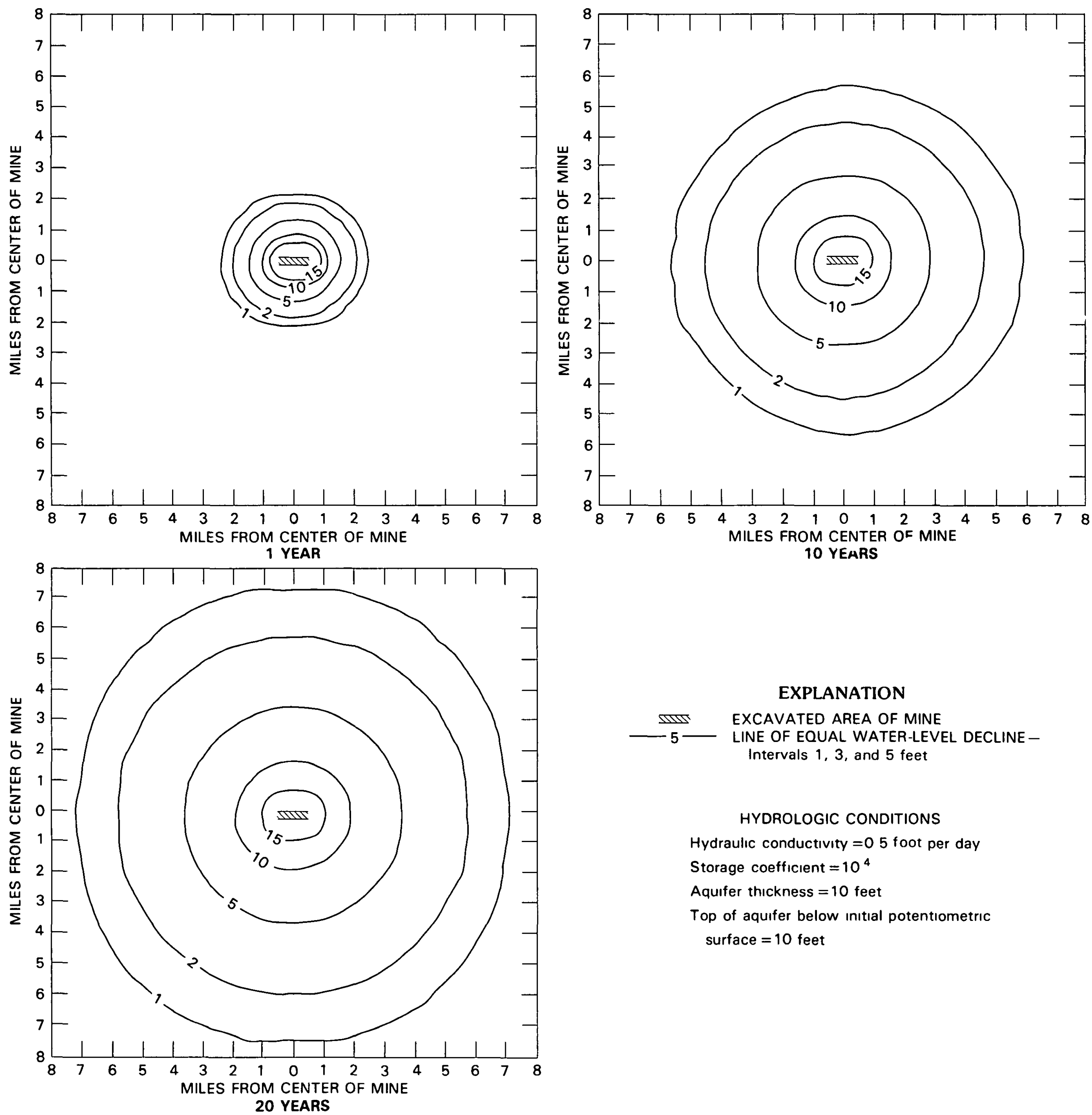
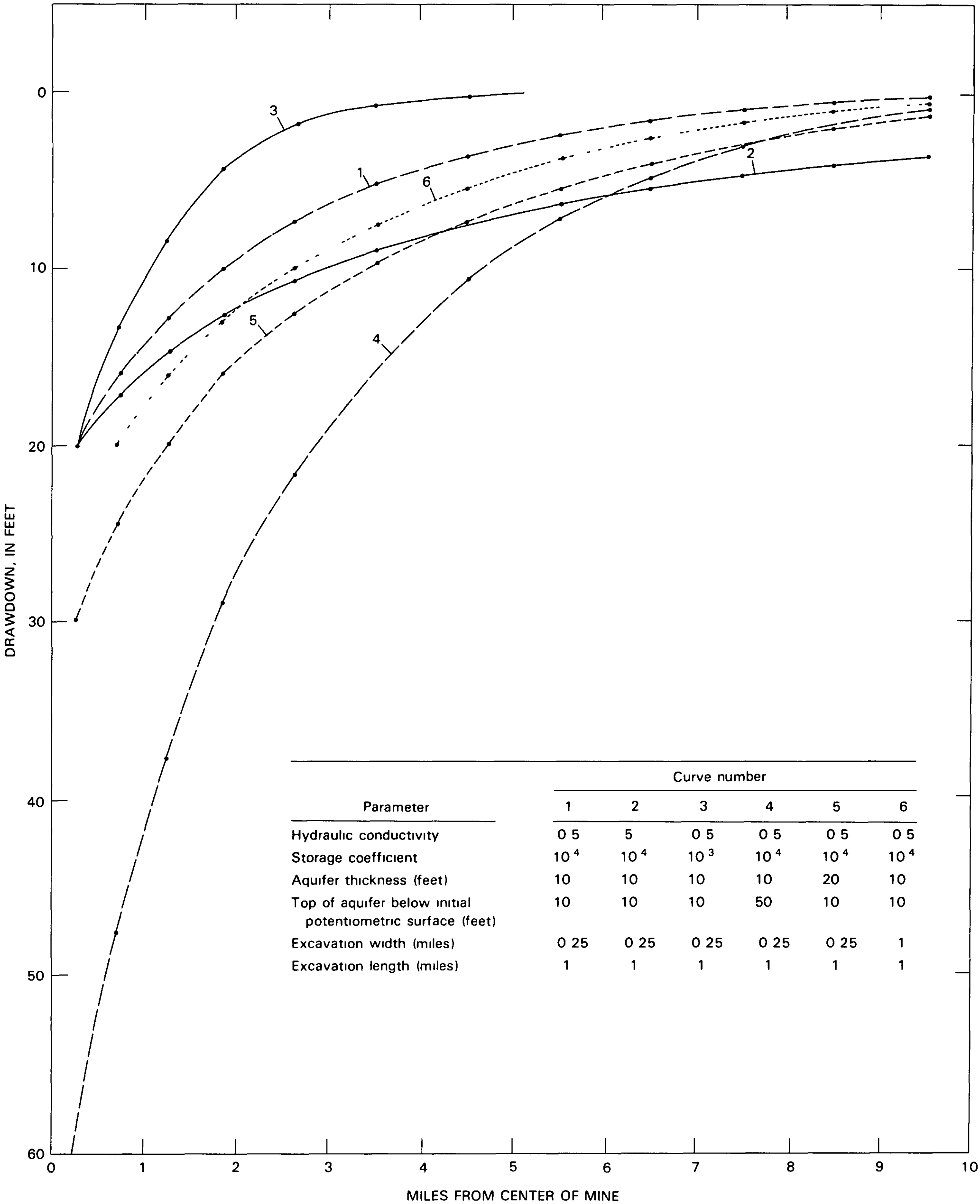


Figure 8. Configuration of the cone of depression around a dewatered excavation in a homogeneous, isotropic aquifer after 1 year, 10 years, and 20 years of continuous dewatering

The effects on water levels of changes in hydraulic conductivity, storage coefficient, aquifer thickness, depth of mine below the initial potentiometric surface, and size of excavation are illustrated in figure 9 Each curve illustrates the effect of modifying one parameter in the base model The effect of each change can be determined by comparison with curve 1 Curve 2 was developed by increasing the hydraulic conductivity from 0 5 ft/d to 5 ft/d, curve 3 by increasing the storage coefficient from 10^{-4} to 10^{-3}, curve 4 by changing the top of the aquifer from 10 to 50 feet below the initial potentiometric surface, curve 5 by increasing the aquifer thickness from 10 feet to 20 feet, and curve 6 by increasing the excavation width from one-fourth mile to 1 mile A curve developed by changing the initial potentiometric surface from horizontal to a slope of 50 ft/mi is not shown because it was essentially the same as curve 1, the maximum deviation from curve 1 was 0 1 foot Comparisons of the curves shown



Parameter	Curve number 1	2	3	4	5	6
Hydraulic conductivity	0 5	5	0 5	0 5	0 5	0 5
Storage coefficient	10^{4}	10^{4}	10^{3}	10^{4}	10^{4}	10^{4}
Aquifer thickness (feet)	10	10	10	10	20	10
Top of aquifer below initial potentiometric surface (feet)	10	10	10	50	10	10
Excavation width (miles)	0 25	0 25	0 25	0 25	0 25	1
Excavation length (miles)	1	1	1	1	1	1

Figure 9. Comparison of the effects of differing physical and hydrologic properties on drawdown in a homogeneous, isotropic aquifer after 20 years of continuous dewatering of an excavation

in figure 9 indicate that the increase in drawdown caused by depth of excavation below the potentiometric surface, increased thickness of the aquifer, or areal extent of the excavation (curves 4, 5, and 6) generally is largest near the excavation and becomes progressively smaller with distance At a distance of about 9 miles from the excavation the drawdowns are similar, having a maximum difference of about 1 foot The area affected is not altered significantly Changes in hydraulic-conductivity and storage-coefficient values significantly alter the drawdown configuration and the area affected An increase in hydraulic conductivity (curve 2) results in a flatter drawdown curve and a larger area of influence, whereas an increase in storage coefficient (curve 3) produces a steeper curve and smaller area of influence

The effects of boundary conditions in the aquifer on the areal configuration of the cone of depression are shown in figures 10, 11, and 12 The boundaries are designed to illustrate the effects of lateral changes in hydraulic conductivity or the influence of surface-water bodies The boundaries depicted may be considered to represent various geologic situations For example, an aquifer with a hydraulic conductivity of 5 ft/d adjacent to an aquifer with a hydraulic conductivity of 0 5 ft/d could represent a facies change from sandstone to shale, a lateral transition from a fractured coal to a non-fractured coal, or faulted sandstone against shale The effects of an excavation being located in an area of the aquifer having a small hydraulic conductivity (0 5 ft/d) bounded by an area of larger hydraulic conductivity (5 ft/d) are shown in figure

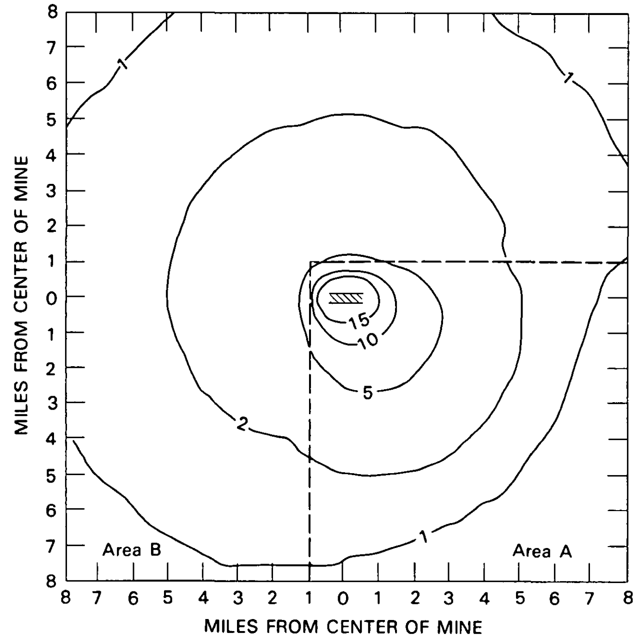


Figure 10. Influence of hydrologic boundaries on the cone of depression around an excavation in a homogeneous, isotropic aquifer after 20 years of continuous dewatering

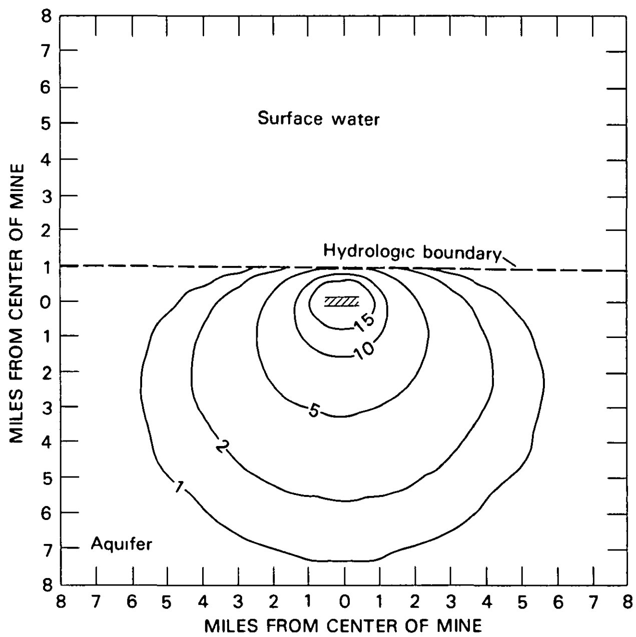


Figure 11. Influence of surface water on the cone of depression around an excavation in a homogeneous, isotropic aquifer after 20 years of continuous dewatering

10 The effects of a nearby surface-water body (lake or perennial stream) that recharges the aquifer are shown in figure 11

Comparison of effects of various boundary conditions are shown by the profiles in figure 12 Curve 1 is that of the base model and is shown for comparative purposes All other curves reflect the effects of various boundary conditions

Effects of Existing Mines

Cooperative and individual studies by the Montana Bureau of Mines and Geology and U S Geological Survey (1978) pertaining to the effects of mining near existing mine sites have, in general, indicated that

(1) Ground-water inflow to active mine pits generally is small in volume and, in some instances, pumping from the pits has not been necessary

(2) Mine effluents, where pumping is necessary, are mixtures of ground waters that in most places discharge to the surface naturally, and have not created serious water-quality changes

(3) Water-level declines locally can be significant during active mining operations, but water levels recover toward premining positions when mining ceases

(4) Mine spoils generally transmit water at rates equal to or greater than the natural aquifers, and the ability to transmit water is greatest along the base of the spoil materials

(5) Mineralization of ground water in mined areas locally can be large, but regionally the problem is small because of the small percentage of ground-water systems where mining is feasible

(6) Presently used ground-water supplies that are permanently lost owing to mining can be replaced by completing wells in deeper aquifers

Summaries of the results of studies by the Montana Bureau of Mines and Geology (Montana Bureau of Mines and Geology and U S Geological Survey, 1978) at four mines in the study area follow

Absaloka Mine

The Absaloka Mine, since it was opened in 1974, has disturbed about 300 acres of land Pumping from the mine has not been necessary because of the small inflow resulting from the poor productivity of the aquifers Water levels in observation wells near the mine have not declined Little water has entered the spoils Water samples collected from the spoils contained about 2,200 mg/L of dissolved solids Dissolved-solids concentration of water from undisturbed aquifers in the area ranges from about 100 to 5,000 mg/L

Rosebud Mine

The Rosebud Mine, which has been in operation since 1924 except for a 10–year interval between 1958 and 1968, has disturbed about 10,000 acres Occasionally, inflow to the mine has been large enough to require pumping Water levels in observation wells near the mine have not shown perceptible declines A saturated zone of as much as 20 feet is now present in the spoils Aquifer tests using wells in the spoils indicate that the spoils trans-

HYDROLOGIC CONDITIONS
Storage coefficient $=10^{-4}$
Aquifer thickness =10 feet
Top of aquifer below initial potentiometric surface =10 feet
Excavation width =0 25 mile
Excavation length =1 mile

Curve	Hydraulic conductivity, in feet per day: Area A	Area B	Type of boundary
1	0 5	0 5	None
2	0 5	5	Lithologic
3	5	0 5	Lithologic
4	0 5	0 5	Surface water
5	5	5	Surface water

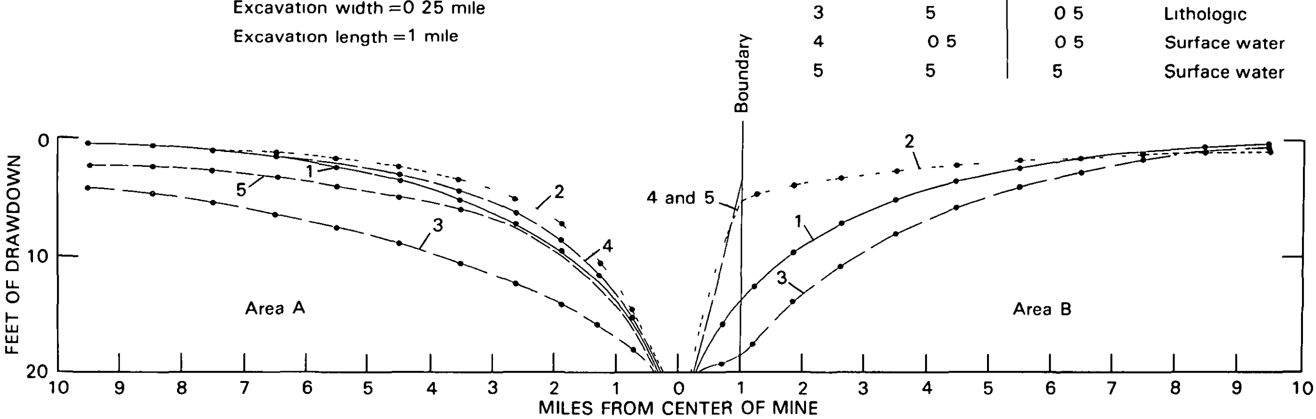


Figure 12. Comparison of the effects of hydrologic boundaries on the cone of depression around an excavation in a homogeneous, isotropic aquifer after 20 years of continuous dewatering

mit water at least as efficiently as the undisturbed aquifers they replaced

Dissolved-solids concentrations of water from the spoils generally are larger than those of water from the coal bed being mined, but the natural diversity of water quality in the area makes comparison difficult The water quality in and near the mined area has a tendency to change continually, but a trend toward either increasing or decreasing salinity is not apparent Dissolved-solids concentrations of water from undisturbed aquifers in the area range from about 400 to 6,000 mg/L

Ponding of surface runoff near the mine attenuates peak flows and alters the time distribution of streamflow Rather than peak flows occurring mainly during spring runoff, streamflow is now more evenly distributed throughout the year Downstream irrigation-diversion structures were designed to divert water during spring runoff, and they have no mechanisms to permit the bypass of normal streamflow Thus, the alteration of streamflow distribution can result in continuous water application in some areas and waterlogging of irrigated lands

Big Sky Mine

The Big Sky Mine has disturbed about 800 acres of land since it was opened in 1969 Inflow to the mine is of sufficient quantity to require pumping Effluent from the mine is a mixture of local ground waters, and degradation of water quality has not resulted Water levels have declined about 6 feet within one-quarter mile of the mine, but beyond 1 5 miles west of the mine, declines have been less than 1 foot Aquifer tests of wells indicate that the spoils are much more capable of transmitting water than are the aquifers being mined Water from the spoils contains relatively large dissolved-solids concentrations, some greater than 7,000 mg/L Ground-water quality in the area varies, but no trend toward increasing or decreasing salinity has been noted

West Decker Mine

Since being opened in 1972, the West Decker Mine has disturbed about 1,000 acres of land Hydrologic conditions at West Decker differ from most existing or potential mine sites in the area The Tongue River Reservoir just east of the mine serves as a hydrologic boundary that limits the migration of water-level declines Ground-water inflow to the mine is sufficient to require pumping Effluent from the mine is a mixture of ground water that would discharge to the reservoir under natural conditions Water levels near the pit have declined as much as 40 feet Declines have been more than 10 feet within 2 miles west of the pit Aquifer tests indicate that the spoils are at least as capable of transmitting water as the coal they replaced Ground water has readily entered the spoils after the pit is backfilled, and water levels have risen as much as 30 feet in and near backfilled areas since 1975

Dissolved-solids concentrations of some samples of water from the spoils have exceeded 6,000 mg/L The primary constituents are sodium and sulfate Dissolved-solids concentrations of the water contained in the coal aquifers range from about 1,000 to 2,000 mg/L Sodium and bicarbonate are the primary constituents

The natural ground-water gradient at the site is toward the reservoir After mining is completed and dewatering of the pit has ceased, water from the spoils will flow toward and discharge to the reservoir Because ground-water discharge is small, water-quality changes in the reservoir probably will be negligible

SUMMARY

The geologic framework for the shallow aquifers in the northern Powder River Basin is composed of sedimentary units ranging in age from Late Cretaceous to Holocene Geologic units that compose the shallow ground-water system consist of Upper Cretaceous marine deposits of the Fox Hills Sandstone overlain by Upper Cretaceous to Holocene continental deposits of the Hell Creek Formation, Fort Union Formation, Wasatch Formation, terrace deposits, and alluvium The maximum thickness of the section is about 5,000 feet Prominent structural features in and near the study area include the Miles City arch, Black Hills uplift, Porcupine dome, Bighorn uplift, Ashland syncline, Tongue River syncline, Williston Basin, and Powder River Basin

Flow in the ground-water system above the Bearpaw Shale can be divided, in general, into two flow patterns Aquifers that generally are at depths of less than about 200 feet have a localized flow pattern, which is controlled by the surface topography Aquifers that generally are at depths greater than about 200 feet have a regional flow pattern, with flow generally northward toward the Yellowstone River and significant flow toward the Powder and Tongue Rivers

The primary source of recharge to the shallow ground-water system is infiltration of rainfall and snowmelt on the outcrops Part of the recharge is derived from seepage from intermittent and ephemeral streams during times of runoff, and part from deep percolation of applied irrigation water and ditch losses that primarily recharge the alluvium Some water is added to the system by subsurface inflow from outside the area

The primary mode of discharge from the shallow ground-water system is through perennial streams and rivers Lesser amounts of water are discharged through evapotranspiration, wells, springs and seeps, and subsurface outflow from the area

The chemical quality of shallow ground water in the northern Powder River Basin ranges widely Most

shallow ground water in the study area does not meet recommended standards for public drinking water established by the U S Environmental Protection Agency Because of large sodium, sulfate, or dissolved-solids concentrations, most water is unsuitable for irrigation Water from depths less than 200 feet contained an average dissolved-solids concentration of 2,100 mg/L, with sodium, magnesium, calcium, sulfate, and bicarbonate being the primary ions Water from depths between 200 and 1,200 feet was dominated by sodium and bicarbonate and had an average dissolved-solids concentration of 1,400 mg/L Many ground waters sampled contained a sufficient concentration of hydrogen sulfide to impart a definite odor The probable source of the hydrogen sulfide is bacterially promoted sulfate reduction

The effects of mining on water levels and flow patterns will be dependent on the location of the mine cut in relation to the potentiometric surface, water-yielding materials, and confining zones The hydrologic effects of mining also will be restricted by limited areal and vertical extent of overburden aquifers, fracture patterns in the coal aquifers, and faulting The effects of mining on potential productivity of wells are related directly to the change in water level at a well site

Upon completion of mining, the ground-water system will begin reestablishment of equilibrium flow conditions Water levels will rise until premining water levels surrounding the former mine site are approximated Water-level configuration and flow patterns within the spoils will be modified owing to the altered lithologic distribution As water levels rise, well yields affected by water-level declines will increase toward premining rates

Replacement of overburden material will result in the exposure of fresh mineral surfaces and provide the opportunity for renewed chemical reactions Sulfate-reducing bacteria have been reported to re-establish themselves in spoils aquifers

Mathematical models were used to illustrate the effects of mining on water levels and flow patterns that may result from varying hydraulic properties that are typical of rocks in the northern Powder River Basin The results of these models, which were designed to depict maximum-drawdown situations, indicate that after 20 years of continuous dewatering of an aquifer 10 feet thick with an initial hydraulic head 10 feet above the aquifer, water-level declines greater than 1 foot generally would be limited to within about 7 5 miles of the center of the mine excavation, declines greater than 2 feet to within about 6 miles, declines greater than 5 feet to within about 3 7 miles, declines greater than 10 feet to within about 1 7 miles, and declines greater than 15 feet to within 1 2 miles

Cooperative and individual studies of effects of existing mines on the availability and quality of ground water by the U S Geological Survey and the Montana Bureau of Mines and Geology have indicated that the volume of ground-water inflow to mine pits probably will be small, mine effluents have not created serious water-quality problems, water-level declines can be significant locally during mining but water levels will recover to approximate premining positions after mining ceases, mine spoils generally transmit water at rates equal to or better than the undisturbed aquifers, mineralization of ground water due to mining occurs only locally, and deeper aquifers are available to replace water supplies that are permanently lost due to mining

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