# GEOHYDROLOGY AND POTENTIAL EFFECTS OF COAL MINING IN 12 COAL-LEASE AREAS, POWDER RIVER STRUCTURAL BASIN, NORTHEASTERN WYOMING

By James L. Fogg, Michael W. Martin, and Pamela B. Daddow

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| Multiply | By | To obtain |
|---|---|---|
| acre | 4,047 | square meter |
| foot (ft) | 0.3048 | meter |
| gallon per minute (gal/min) | 0.06309 | liter per second |
| mile (mi) | 1.609 | kilometer |
| square mile ($mi^2$) | 2.590 | square kilometer |

The following term and abbreviation for chemical concentration also are used in this report:

milligrams per liter (mg/l)

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

# GEOHYDROLOGY AND POTENTIAL EFFECTS OF COAL MINING IN 12 COAL-LEASE AREAS, POWDER RIVER STRUCTURAL BASIN, NORTHEASTERN WYOMING

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## ABSTRACT

The geohydrology of 12 coal-lease areas in the Powder River structural basin is described in relation to the mining proposed for each area. The description of the hydrology includes identification of recharge and discharge areas, directions of ground-water movement, and possible effects of mining. Understanding the ground-water hydrology of the 12 coal-lease areas will improve the understanding of the shallow ground-water system in the basin.

The Paleocene Fort Union Formation, Eocene Wasatch Formation, and Quaternary alluvium comprise most of the surface geology of the Powder River structural basin. The most productive aquifers in the shallow ground-water system are alluvial deposits, sandstone beds, and fractured coal beds. Well yields range from less than 10 gallons per minute in many parts of the basin up to 1,000 gallons per minute from clean, coarse-grained material along some of the rivers. Water in the northern part of the basin tends to be more mineralized than water in the southern part of the basin. Median dissolved-solids concentrations for water from wells in Campbell County (northern part of the basin) was more than 1,200 milligrams per liter compared to a median value of about 400 milligrams per liter for water from wells in Converse County (southern part of the basin).

Local ground-water flow systems are most likely to be affected by coal mining in the lease areas. Local flow systems develop where ground water flows from a topographic high to an adjacent low; the local systems have flow paths ranging in length from a few thousand to several thousand feet. Ground-water recharge generally occurs in topographically high areas, especially where these areas are capped by permeable clinker outcrops. Ground-water discharge generally occurs in topographically low areas, especially where these areas contain springs, perennial streamflow, or evidence of subirrigation.

The potential effects of coal mining in the lease areas include alteration of ground-water flow systems and changes in water quality. Alteration of ground-water flow systems includes disruption of recharge and discharge areas and decreased flow to wells and springs. Changes in water quality will result from chemical reactions occurring in backfill material, from hydraulic connection between previously isolated aquifers, and from coal gasification. Surface mining, proposed for 11 of the 12 lease areas, generally will affect only local ground-water flow systems. Underground mining, proposed for 3 of the 12 lease areas, and in-situ coal gasification, proposed for 1 of the 12 lease areas, also could affect intermediate and regional flow systems.

The aquifers that would be affected by mining include alluvium and water-yielding coals and sandstones in the Wasatch and Fort Union Formations. Water-level declines in coal aquifers generally will extend less than 4 or 5 miles from the mines, and water-level declines in overburden sandstone aquifers generally will extend less than 2 or 3 miles from the mines. Mining of lease areas that contain extensive outcrops of permeable clinker will decrease recharge to the local ground-water flow systems. Mining of lease areas in or near locations of ground-water discharge may decrease discharge to nearby streams, springs, and flowing wells. Mining also will destroy the wells in the coal-lease areas and may affect water levels in nearby wells outside the lease areas.

Mining also will affect the quality of ground water available in the lease areas. Concentrations of dissolved solids in water from spoil aquifers generally are two to three times greater than in water from undisturbed coal aquifers. Large concentrations of dissolved solids (greater than 5,000 milligrams per liter) or dissolved sulfate (greater than 3,000 milligrams per liter) or both in spoil water occasionally may render the water unsuitable for livestock watering. Water suitable for domestic use generally is available only in the southern part of the basin, and mining of lease areas in this part of the basin likely will leave spoil water unsuitable for domestic use. Excessive nitrate (greater than 100 milligrams per liter) and selenium (greater than 0.10 milligram per liter) concentrations, such as those measured in spoil water at one existing mine, could render spoil water unsuitable for livestock or domestic use.

## INTRODUCTION

The Powder River structural basin of northeastern Wyoming and southeastern Montana contains more coal than any other structural basin of similar size in the United States (Lowry and others, 1986). Much of this coal is owned by the Federal government. Prior to 1971, Federal coal deposits could be developed by obtaining a noncompetitive (preference right) lease from the U.S. Bureau of Land Management. In 1971, the U.S. Department of the Interior placed a moratorium on coal leasing in response to public concern that the lands were being leased for speculation rather than for development. The moratorium was lifted in 1979 when the Department of the Interior issued new regulations implementing the Federal Coal Leasing Amendments Act of 1976 (U.S. Bureau of Land Management, 1985, p. 16).

The Federal Coal Leasing Amendments Act of 1976 abolished noncompetitive (preference right) leasing, subject to valid existing rights. Existing rights in the Wyoming part of the Powder River structural basin include preference-right lease applications for 12 different coal-lease areas. Federal law requires the U.S. Bureau of Land Management to analyze the environmental impact of leasing coal in these areas. The U.S. Geological Survey is cooperating with the Bureau of Land Management to describe the ground-water hydrology of these coal-lease areas and to identify potential effects of mining on the ground-water resources of each lease area.

## Purpose and Scope

The purpose of this report is to describe the geohydrology of 12 coal-lease areas in the Powder River structural basin in relation to the mining proposed for each area. The description of the geohydrology of each of the lease areas focuses on the shallow ground-water system and includes identification of recharge and discharge areas, directions of ground-water movement, and potential effects of mining. The shallow ground-water system in the Powder River structural basin is not well defined because of the discontinuous nature of the aquifers in the basin. Understanding the ground-water hydrology of these 12 coal-lease areas will improve understanding of the shallow ground-water system in the basin.

Several assumptions were used to define the scope of the study. On the basis of previous investigations of ground-water flow in the Powder River structural basin, the authors assumed that the primary effects on ground water from coal mining in the lease areas would be on the local flow system only. Ground-water movement in the local flow system is assumed to be shallow (generally less than 500 ft deep) and controlled by the local topography and lithology. Topographically high areas are assumed to be recharge areas for the local flow system, especially where these areas are capped by permeable clinker outcrops (rock baked by burning coal beds). Topographically low areas, such as areas along major stream channels, are considered potential discharge areas, especially where these areas contain springs, perennial streamflow, or evidence of subirrigation.

The scope of work included delineating areas of clinker and coal outcrops on topographic maps of each coal-lease area (pls. 1, 2, and 3) to identify local recharge areas; using existing information on perennial streams, springs, and subirrigated areas (Rusmore and others, 1985), and low-level, color-infrared aerial photographs to identify possible discharge areas; and plotting existing wells (other than monitoring wells) on the maps of each coal-lease area. Where water-level data were available, the data were used with identified recharge and discharge areas to determine the local flow system. Geologic sections were used to illustrate the coal seams to be mined and to assist in determining which wells may be affected by mining.

The first part of this report is a description of the general geohydrology of the Wyoming part of the Powder River structural basin. The second part of the report is a general discussion of the effects of coal mining on ground-water hydrology. The third part of the report contains site-specific discussions of the ground-water hydrology and potential effects of mining for each of the 12 coal-lease areas.

Although there was little information available on the ground-water hydrology of some of the lease areas, no new data were collected for this study. Existing data were compiled from U.S. Geological Survey computer files of well location and completion information, Wyoming State Engineer files of well-completion reports and geologic logs, and U.S. Geological Survey Coal Resource Occurrence and Coal Development Potential maps. Low-level, color-infrared aerial photographs were supplied by the U.S. Bureau of Land Management.

## Location and Description of the Area

The 12 coal-lease areas are located in the Wyoming part of the Powder River structural basin in Campbell, Converse, Johnson, and Sheridan Counties (fig. 1). The Powder River structural basin is bounded in Wyoming by the Black Hills uplift, the Hartville uplift, the Laramie Mountains, the Casper arch, and the Bighorn Mountains; the structural basin also extends northward into Montana. Four of the coal-lease areas are in Campbell County, four lease areas are in Converse County, and one lease area is in Sheridan County. Two coal-lease areas straddle the Campbell County-Johnson County line, and one lease area straddles the Campbell County-Converse County line.

The land surface of the Powder River structural basin is predominantly plains, tablelands, and rolling hills. Occasional breaks in the gently rolling topography occur where stream channels have eroded into the plains. In the southern part of the basin, large areas of shale have been dissected into badlands, and a few sand dunes occur along the edge of the basin. In the northern part of the basin, red clinker-topped buttes and pine-forested escarpments form the highest areas, and cottonwood trees line the larger streams. A more detailed description of the topography of the basin is presented by Rankl (1986, p. 14-15).

## Previous Investigations

The earliest studies in the Powder River structural basin concerned the energy resources of the basin. Mapel (1959) lists 12 coal fields in the Wyoming part of the structural basin that have been studied for the purpose of coal-bed definition, correlation, and determination of reserves. The location of the coal fields is shown in figure 2. More recently, the U.S. Geological Survey published a series of Coal Resource Occurrence and Coal Development Potential Maps for more than one hundred 7.5-minute quadrangles in the Wyoming part of the Powder River structural basin (Intrasearch, 1979a-p). Gary B. Glass, Wyoming State Geologist, has attempted to correlate the principal coal beds in this part of the basin (fig. 3). Other early geologic studies were done in the southern part of the basin as a result of interest in the uranium resources of the basin (Sharp and Gibbons, 1964; Sharp and others, 1964).

After the original studies of individual coal fields and uranium deposits, interest increased for studies of larger parts of the basin or of the entire Powder River structural basin. Hodson and others (1973), in the first comprehensive summary of the water resources of the basin, addressed the availability and quality of surface and ground water in the Wyoming part of the basin. Lewis and Hotchkiss (1981) defined the shallow hydrogeologic units above the Bearpaw Shale for the entire Powder River structural basin, including Montana. Hagmaier (1971) made the first attempt to describe qualitatively the regional ground-water flow system in the basin.

Public concern about regional hydrologic effects from coal development prompted additional efforts to define a regional ground-water flow system for the basin. Daddow (1986) developed a potentiometric-surface map for water in the Wyodak-Anderson coal, which is mined extensively in Wyoming. Koch and others (1982) modeled the shallow ground water in the basin by treating the entire system (less than 700 ft deep) as a single confined aquifer with an

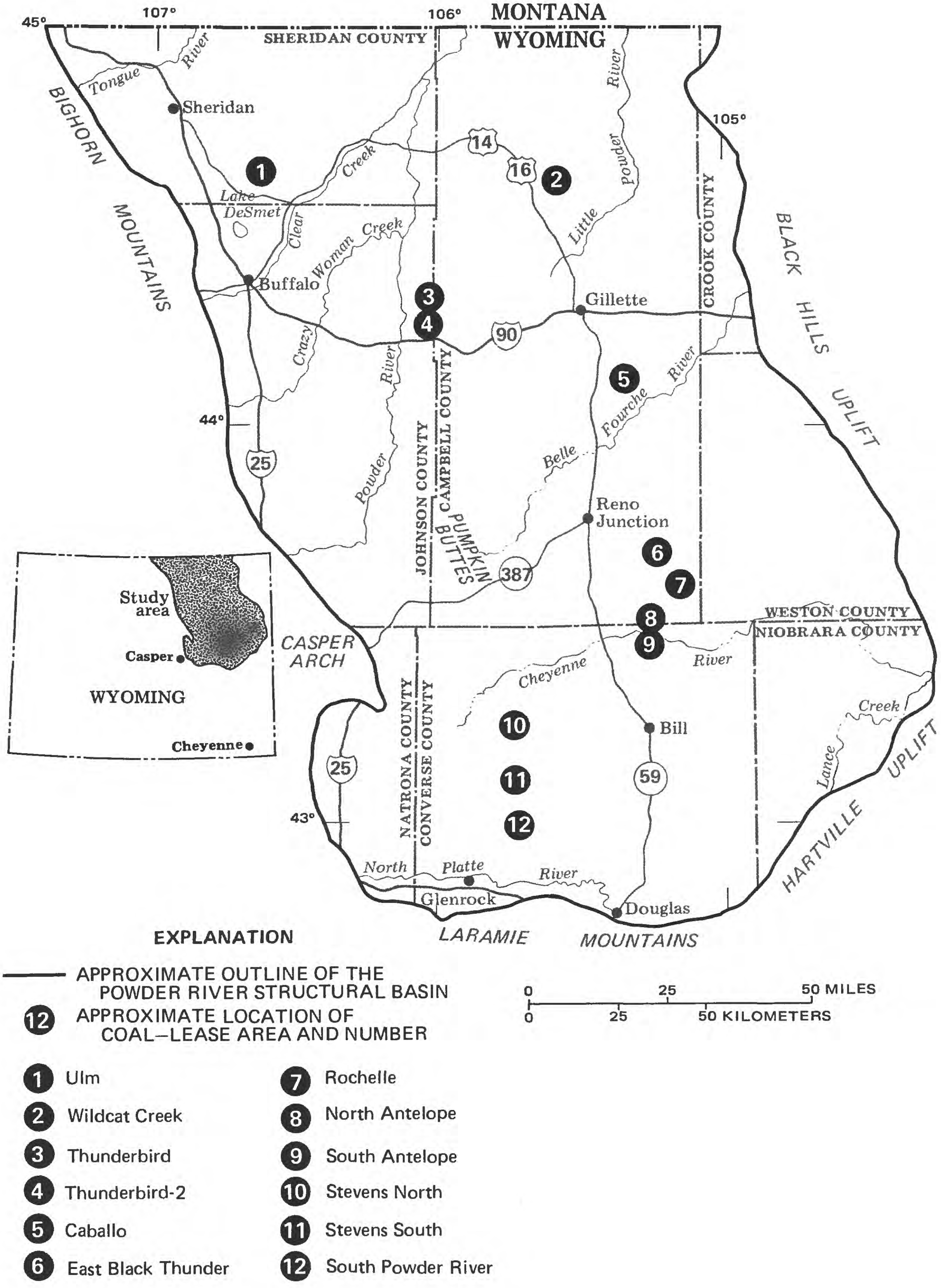

Figure 1.--Location of study area and coal-lease areas.

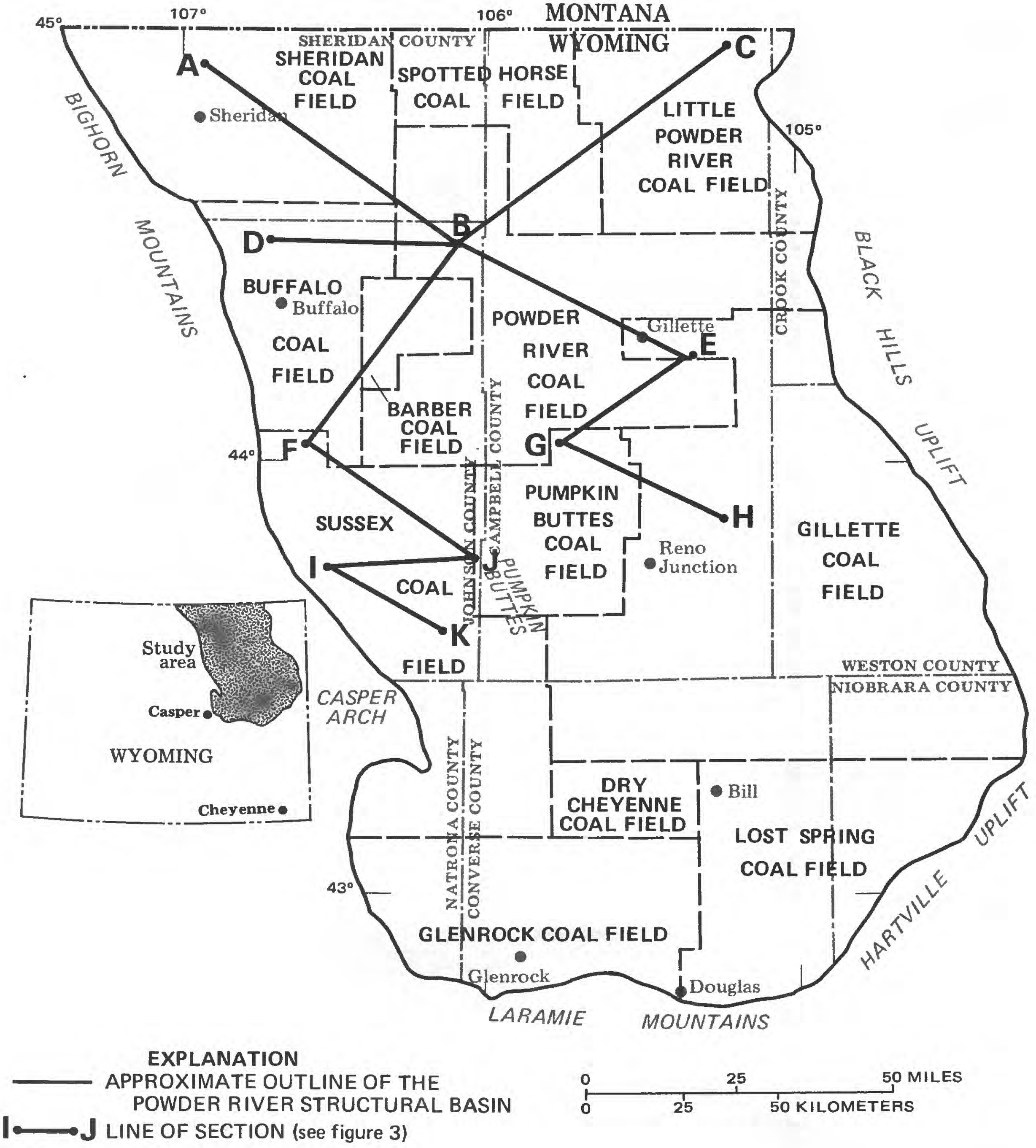

Figure 2.--Coal fields [modified from Glass (1976); reprinted from the Wyoming Geological Association and published with permission].

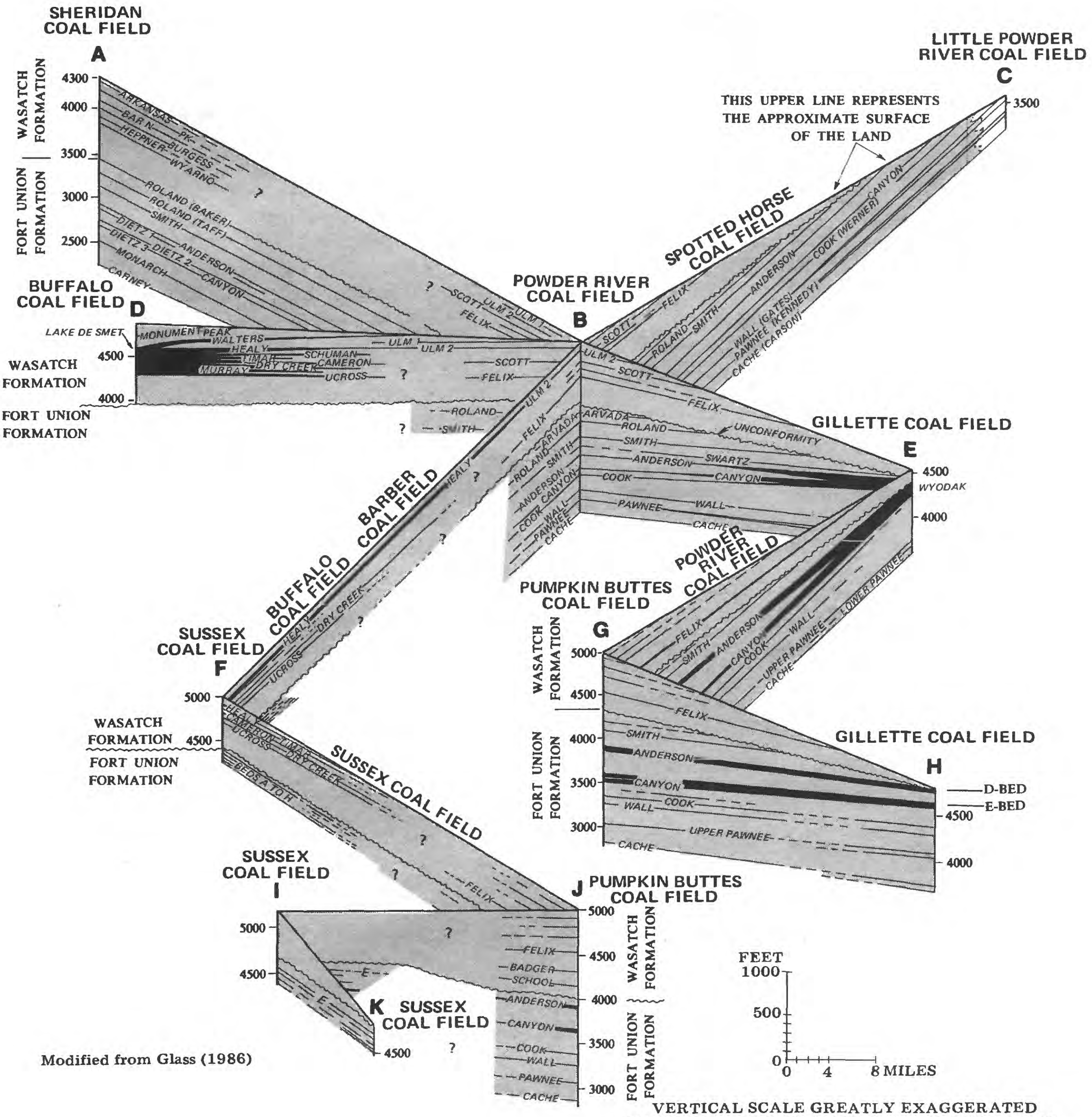

Figure 3.--Correlation of principal coal beds (location shown in figure 2).

underflow term to account for leakage at the bottom. Hotchkiss and Levings (1986) developed a five-layer model to describe regional ground-water movement in units above the Bearpaw Shale of Late Cretaceous age. Rankl and Lowry (1990) looked for evidence of regional ground-water discharge in an attempt to verify the regional flow models; they found little evidence of ground-water discharge from a regional flow system and concluded that local ground-water systems are much more likely to be affected by coal development than the regional flow system.

The hydrologic effects of coal development also have been investigated at specific sites. A study of the effects of surface coal mining on the hydrology of the Horse Creek coal-lease area in Montana (McClymonds, 1985) is one of several investigations of lease-size areas in southeastern Montana. Researchers in the coal industry publish an annual report of monitoring data collected at existing mines in the vicinity of Gillette, Wyoming (Gillette Area Groundwater Monitoring Organization, 1984).

### Acknowledgments

Appreciation is extended to the many individuals who provided information used in this report. The authors are indebted to Bion H. Kent and Carol L. Molnia, U.S. Geological Survey, for their help in obtaining coal test-hole data from Coal Resource Occurrence and Coal Development Potential maps. Frank B. Kistner of the U.S. Bureau of Land Management also provided information on many test holes in the Powder River basin. Special appreciation is expressed to Gretchen L. Meyer, Daniel J. Kotansky, and P. Michael Brogan of the U.S. Bureau of Land Management for providing color infrared aerial photographs and other information on the lease areas. Appreciation is also extended to William F. Kearney of the Wyoming Department of Environmental Quality for information on alluvial valley floors and modeling efforts in the basin.

## GENERAL GEOHYDROLOGY

### Geology

Three sedimentary geologic units ranging in age from Paleocene to Quaternary comprise most of the surface geology in the Wyoming part of the Powder River structural basin (fig. 4). The geologic units are the Paleocene Fort Union Formation, the Eocene Wasatch Formation, and Quaternary alluvium (not shown in fig. 4). These geologic units constitute the shallow ground-water system in this report and are discussed here because aquifers in these units will be affected by mining operations. Older geologic units that crop out around the edge of the basin are not discussed because aquifers in those units will be unaffected by actual mining operations.

The Fort Union Formation consists of as much as 3,450 ft of fine-grained sandstone and interbedded shale and coal (Hose, 1955, pl. 8) and is the most important coal-bearing formation in the Powder River structural basin. The Fort Union is composed of the Tullock, Lebo Shale, and Tongue River Members, in ascending order. The Tullock Member, which is as much as 1,900 ft thick (Lewis and Hotchkiss, 1981, pl. 4), is fine-grained sand, jointed coal, and

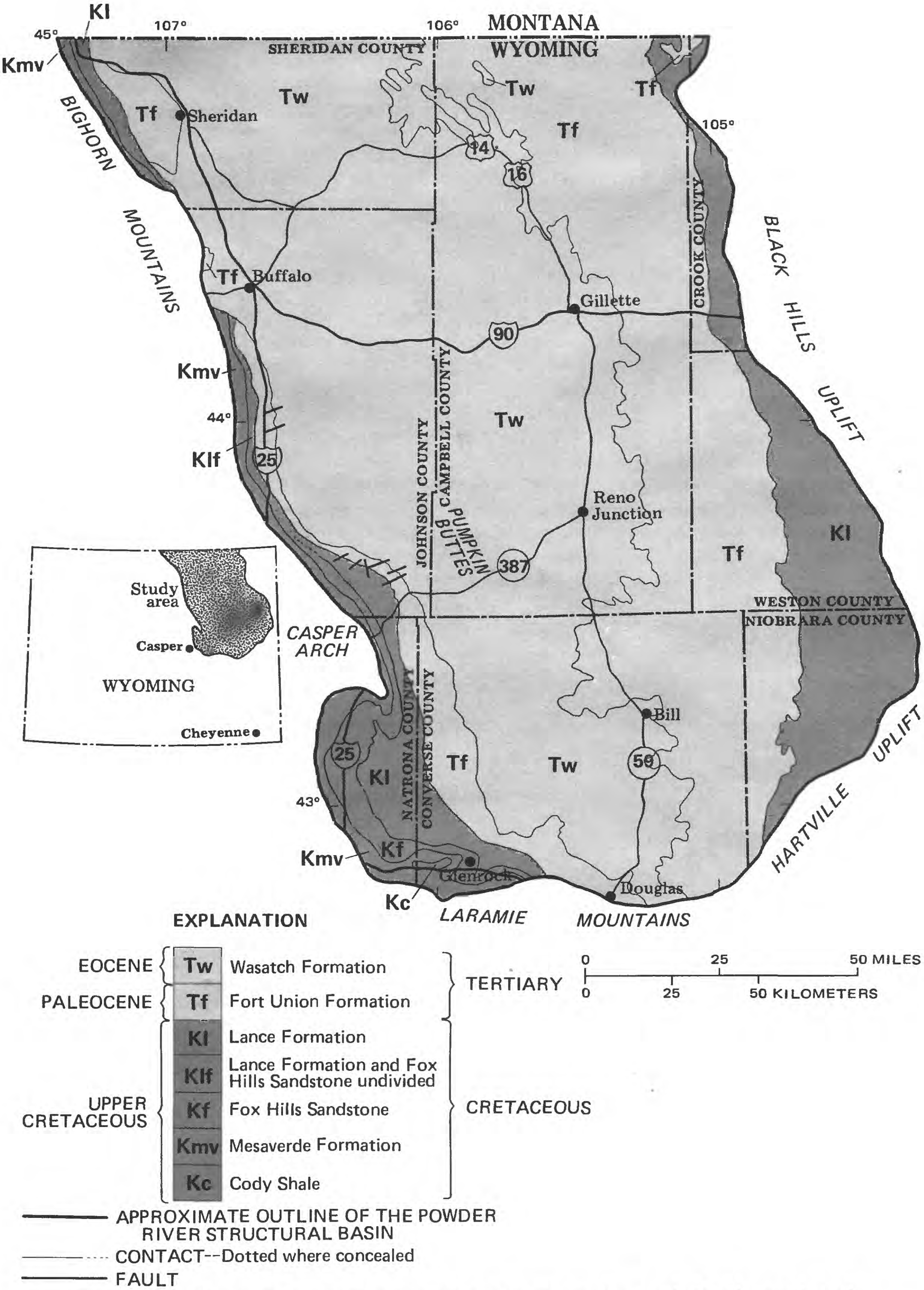

Figure 4.--Bedrock geologic map [modified from Glass (1976); reprinted from the Wyoming Geological Association and published with permission].

clinker interbedded with shale. The Lebo Shale Member, which is as much as 3,000 ft thick (Lewis and Hotchkiss, 1981, pl. 3), is composed of dark shale, with interbedded carbonaceous shale, siltstone, and locally thin coal beds. The Tongue River Member, which is as much as 1,800 ft thick (Glass, 1976, p. 211), is composed of alternating beds of sandstone, siltstone, shale, and coal. The Tongue River Member contains seven to nine major coal beds (Glass, 1986, p. 26) and many discontinuous, lenticular sandstone layers. Most of the mining proposed for the coal-lease areas is in coal beds of the Tongue River Member; however, the only coal bed in this member that is mined at present (1986) is the Wyodak coal bed.

The Wyodak coal bed has been correlated in many parts of the Powder River structural basin and has different names in different parts of the basin. The coal bed has been called the Wyodak-Anderson and the Anderson-Canyon coal bed. The Wyodak coal bed crops out in central Campbell County and dips westward to a depth of more than 2,000 ft in eastern Johnson County (N.M. Denson, U.S. Geological Survey, written commun., 1982). North of Gillette, the Wyodak coal bed separates into an Upper Wyodak and Lower Wyodak. In places, the Upper Wyodak separates into the Smith, Swartz, and Anderson coal beds, and the Lower Wyodak separates into the Canyon and Cook coal beds (Kent and others, 1980). The Wyodak also separates into the Anderson (D bed) and the Canyon (E bed) southward from Gillette. West of Gillette, the Wyodak coal bed separates into the Anderson and Canyon coal beds, with the two beds each 10 to 65 ft thick. Coal beds equivalent to the Wyodak also are tentatively correlated in the vicinity of Sheridan, Wyoming, 80 mi west of Gillette (Glass, 1986, p. 26). The Wyodak combines with other coals to form a 200-ft-thick coal seam (1,000 ft deep) in western Campbell County where in-situ coal gasification has been proposed for the Thunderbird-2 coal-lease area.

The Wasatch Formation consists of fine- to coarse-grained lenticular beds of sandstone and interbedded shale and coal and is at the land surface in most of the central part of the Powder River structural basin. The thickness is about 1,575 ft in the Pumpkin Buttes area (Sharp and others, 1964, pl. 13), becoming generally thinner toward basin margins (Hodson and others, 1973, pl. 3). The Wasatch Formation is the second most important coal-bearing formation in the Powder River structural basin, with as many as eight thick, persistent coal beds (Glass, 1976, p. 217). The thickest Wasatch coal bed, the Lake DeSmet coal, locally exceeds 200 ft in thickness near Lake DeSmet on the west side of the basin (Mapel, 1958, p. 221; Mapel, 1959, p. 85; Obernyer, 1980, p. 40).

The Wasatch Formation and the Tongue River Member of the Fort Union Formation have similar lithologies and have been grouped together as a single aquifer that is isolated from other water-yielding units in the basin by the Lebo Shale Member (Lewis and Hotchkiss, 1981; Hotchkiss and Levings, 1986). Both the Wasatch Formation and the Tongue River Member of the Fort Union Formation contain numerous thick, areally extensive coal beds and discontinuous, lenticular sandstone beds that are aquifers. The combined sand content of the two units ranges from 21 to 91 percent, with a mean value of 54 percent (Lewis and Hotchkiss, 1981, pl. 1), but the units also contain substantial shale that restricts ground-water movement. Intensely fractured clinker deposits are common in the outcrop of both formations.

Quaternary alluvium, which forms the terraces and floodplains of the structural basin, consists of unconsolidated silt, sand, and gravel deposits. The thickness of the alluvium (not shown in fig. 4) generally is less than 50 ft, but it may be as much as 100 ft in some valleys near mountains (Hodson and others, 1973, pl. 3). Alluvium overlying the Wasatch and Fort Union Formations generally is fine to medium grained; however, coarse alluvial deposits do occur in valleys (fig. 1) of the Tongue, Powder, Little Powder, Belle Fourche, Cheyenne, and North Platte Rivers, and Clear, Crazy Woman, and Lance Creeks (Hodson and others, 1973, pl. 3).

## Hydrology

One of the earliest descriptions of ground-water flow in the Powder River structural basin is provided by Hagmaier (1971, p. 23), who defined three types of flow systems on the basis of their relation to the topography and the length of flow path involved:

1. A local flow system is developed where ground water flows from a topographic high to an adjacent low and has a flow path ranging in length from a few thousand to several thousand feet.
2. An intermediate flow system is developed where ground water flows from a topographic high to some low in the basin and has a flow path that ranges in length from several thousand feet to a few miles.
3. A regional flow system is developed where ground water flows from the highest to the lowest regionally significant topographic features and has a flow path ranging in length from a few miles to several tens of miles.

Hagmaier (1971, fig. 8) recognized that flow systems of different sizes--local, intermediate, and regional--could be superimposed on one another.

In the southern part of the Powder River structural basin, ground-water movement in local and intermediate flow systems generally is eastward toward the valley of the Cheyenne River. In the western part of the Cheyenne River drainage, ground water as deep as 500 ft moves toward stream valleys. About 30 mi downstream, larger valleys affect ground-water movement to a depth of about 1,000 ft. Deeper ground water moves northward in a regional flow system that passes under the easterly moving water in the local and intermediate flow systems (Hagmaier, 1971, p. 43-47).

In the northern part of the Wyoming part of the Powder River structural basin, ground-water movement in the regional flow system is northward, with intermediate and local flow systems toward the major stream channels. Because of the numerous, deep, flowing wells along the Powder River, Hagmaier (1971, p. 48) identified the valley of the Powder River as a discharge area for regional flow. Other perennial streams were identified as discharge areas for intermediate and local flow systems (Hagmaier, 1971, p. 53).

Recent ground-water modeling studies of the Powder River structural basin confirm Hagmaier's (1971) description of ground-water movement in the basin. Koch and others (1982, p. V-55, 56) constructed a water-level contour map using water levels from wells completed in many different strata less than

500 ft deep. The water-level contours indicate easterly ground-water movement toward the Cheyenne River in the southern part of the basin and northerly ground-water movement, with a substantial component of flow toward the Powder River, in the northern part of the basin. Hotchkiss and Levings (1986, fig. 12) used water levels from wells completed in many different strata to approximate a single potentiometric surface for the entire Wasatch-Tongue River aquifer. The potentiometric surface indicates ground-water movement toward the Cheyenne River in the southern part of the basin and northerly ground-water movement toward the Tongue, Powder, and Little Powder Rivers in the northern part of the basin. The potentiometric surface also indicates ground-water movement toward the Belle Fourche River on the eastern side of the basin.

Although water-level data presented in recent modeling studies confirm Hagmaier's (1971) description of the ground-water flow system, evidence of discharge from a regional flow system is lacking. Rankl and Lowry (1990) investigated the quality of water from springs and wells throughout the structural basin (Wyoming and Montana) and detected little geochemical evidence of ground-water discharge from a south-to-north regional flow system. Rankl and Lowry (1990) also analyzed streamflow hydrographs for the Powder River and seven streams that originate within the structural basin for indications of base flow during the nongrowing season; they detected no evidence of measureable ground-water discharge to the Powder River or five of the basin streams. Only the Little Powder River and Otter Creek (in Montana) had measureable flow that might be attributed to ground-water discharge. Rankl and Lowry (1990) concluded that regional ground-water discharge along major stream valleys is evaporated or transpired along valley sides and bottoms, with no measureable contribution to streamflow. Rankl and Lowry (1990) also concluded that the effects of coal mining on ground-water hydrology likely would be limited to local flow systems.

The local ground-water flow systems are substantially affected by topography and the presence of almost impermeable shale layers that impede the downward movement of water. Water enters the local flow systems through surface infiltration and moves down the hydraulic gradient, that is, from areas of higher hydraulic head to areas of lower hydraulic head. In recharge areas, which generally coincide with the topographically higher areas, the altitude of the hydraulic head decreases with depth, indicating a downward component of ground-water flow. Where downward-moving water is retarded or intercepted by relatively impermeable material, water will move laterally and discharge as contact springs at the land surface. If downward-moving water is not intercepted by impermeable material, it will continue moving downward until the hydraulic head begins to increase with depth. Where the hydraulic head increases with depth, water will move upward and will discharge as springs or seeps, evaporate, or be transpired by plants (Slagle and others, 1985, p. 10).

## Aquifer Yields and Water Quality

The most productive aquifers in the shallow ground-water system are alluvial deposits, sandstone beds, and fractured coal beds. The limited thickness and areal extent of most alluvial deposits precludes widespread use as a major source of water. The sandstone beds are lenticular and generally do not extend more than a few miles; whereas, coal aquifers are more areally extensive (U.S. Department of the Interior, 1981, p. 36). Coal aquifers are recharged at coal outcrops around the basin and where intensely fractured clinker deposits cap burned coal beds. Ground-water flow in the coal aquifers generally follows the dip of the coal beds or the local topography or both. Coal beds also may be perched aquifers that discharge as springs where the coal beds intersect the land surface.

Well yields from the shallow aquifers in the basin are variable. Yields sufficient for livestock watering and domestic supply, the two most prevalent uses of ground water in the basin, generally can be obtained from shallow wells (less than 500 ft deep) completed in the Wasatch Formation and the Tongue River Member of the Fort Union Formation. Wells in the northern part of the basin that are completed in the Wasatch Formation and the Tongue River Member of the Fort Union Formation may produce 10 to 50 gal/min; wells completed in these formations in the southern part of the basin may yield as much as 500 gal/min to a properly constructed well (Hodson and others, 1973, pl. 3; Lewis and Hotchkiss, 1981, pl. 1). Yields sufficient for municipal and industrial supply generally are obtained from the Tullock Member of the Fort Union Formation or some deeper aquifer. Wells completed in aquifers in the Tullock Member of the Fort Union Formation typically yield 15 to 40 gal/min (Lewis and Hotchkiss, 1981, pl. 1), but yields of 150 gal/min or more are possible (Hodson and others, 1973, pl. 3). Most alluvium in the basin is too fine grained to yield much water; however, clean, coarse-grained material along rivers may yield as much as 1,000 gal/min (Hodson and others, 1973, pl. 3; Lewis and Hotchkiss, 1981, pl. 1).

Multiple water levels are present throughout the basin because of the lenticular nature of the sandstone beds. Flowing wells are common along major stream valleys, but water will not rise to the land surface in higher interstream areas (U.S. Department of the Interior and others, 1974, p. I-209, 210). Gas released from the coal may cause some wells to flow at land surface; however, the proportion of hydraulic head caused by gas pressure is not known.

The chemical quality of water from the shallow aquifers in the basin also is variable. Chemical analyses of water from the Fort Union Formation indicated dissolved-solids concentrations ranging from about 250 mg/L to about 5,600 mg/L (Larson, 1984; Larson and Daddow, 1984). The water is mostly a sodium bicarbonate and, to a lesser extent, a sodium sulfate type (Hodson and others, 1973, pl. 3). Similar analyses of water from the Wasatch Formation indicated dissolved-solids concentrations ranging from about 150 mg/L to as much as 8,200 mg/L (Larson, 1984; Larson and Daddow, 1984). Water from the Wasatch Formation also is a sodium bicarbonate or a sodium sulfate type (Hodson and others, 1973, pl. 3). In both formations, water tends to be more mineralized in the northern part of the structural basin than in the south. Median dissolved-solids concentrations for water from the Fort Union and Wasatch Formations are 1,230 mg/L and 1,220 mg/L, respectively, in Campbell County, compared to median values of only 390 mg/L and 420 mg/L, respectively, in Converse County (Larson, 1984).

The large range in quality of water in the shallow aquifers of the Wasatch and Fort Union Formations is caused by chemical changes that occur as water moves through the geologic units. As water moves down through the formations, the chemical type is altered by cation exchange and sulfate reduction (U.S. Department of the Interior, 1981, p. 36). Water from wells less than 200 ft deep generally is hard (calcium magnesium sulfate type), whereas water from deeper wells generally is soft (sodium bicarbonate type) (Riffenburg, 1925, p. 46).

The quality of water in most alluvial aquifers also is variable, with dissolved-solids concentrations ranging from about 250 mg/L to about 6,600 mg/L (Larson, 1984; Larson and Daddow, 1984). Water in the alluvium in the southwest part of the basin and in the Powder River valley generally is more mineralized than water in the alluvium in other parts of the basin; water in the alluvium near the Bighorn Mountains and the Black Hills generally is less mineralized than water in the alluvium elsewhere in the basin (Hodson and others, 1973, pl. 3). The water is chemically similar to that in the upper part of the bedrock aquifers but may contain larger concentrations of dissolved solids because of concentration by evapotranspiration (U.S. Department of the Interior, 1981, p. 36).

Ground water of suitable quality for livestock watering generally is available throughout the Powder River structural basin, whereas water of suitable quality for drinking generally is available only in the southern part of the basin and near basin margins. Most ground-water samples collected in Campbell, Converse, Johnson, and Sheridan Counties had dissolved-solids concentrations substantially less than 5,000 mg/L, indicating little threat to livestock (Larson, 1984, p. 20, 24, 34, 48). However, only 11 percent of the ground-water samples collected in Campbell County had dissolved-solids concentrations less than the 500-mg/L secondary drinking-water standard recommended by the U.S. Environmental Protection Agency (1986) as reported by Larson (1984, p. 20). This compares with 51 percent of the ground-water samples in Converse County that had dissolved-solids concentrations less than the 500-mg/L recommended limit (Larson, 1984, p. 24).

## POTENTIAL EFFECTS OF COAL MINING ON GROUND-WATER HYDROLOGY

The potential effects of coal mining on the ground-water hydrology of the 12 coal-lease areas include alteration of ground-water flow systems and changes in water quality. Alteration of ground-water flow systems includes disruption of recharge and discharge areas and decreased flow to wells and springs. Changes in water quality will result from chemical reactions occurring in backfill material, from hydraulic connection between previously isolated aquifers, and from coal gasification. Surface mining, proposed for 11 of the 12 lease areas, generally will affect only local ground-water flow systems. Underground mining, proposed for 3 of the 12 lease areas, and in-situ coal gasification, proposed for 1 of the 12 lease areas, could affect intermediate and regional flow systems.

The aquifers that would be affected by mining include the alluvium and water-yielding units in the Wasatch and Fort Union Formations. Aquifers in formations below the Fort Union would be affected only if they are developed for water supplies for increased population or mining operations. This report includes only the hydrologic effects of the mining operation itself. A site-specific discussion of the effects of mining in each lease area is presented in a subsequent section.

The hydrologic effects that will occur during mining are discussed separately from those long-term effects that will remain after the mining is completed. This is a somewhat arbitrary distinction. Mining will progress through a lease area for several years, and post-mining conditions may exist in one part of the lease area while active mining or pre-mining conditions exist in other parts of the area.

## Effects During Mining

Except in recharge areas, surface mining will have little effect on ground-water hydrology where mining is above water-yielding units. Where mining is above the water table, surface runoff into the mine may become a very local source of recharge to underlying aquifers. Where the mine excavation is deeper than the potentiometric surface of confined aquifers below the coal, the pit may become a discharge area for upward leakage from the aquifers. The quantity of such leakage would depend upon the thickness and hydraulic characteristics of the confining beds.

If surface mining intercepts water-yielding units, the local ground-water flow system will be altered. The lowest coal to be mined and all aquifers above it will be removed. The affected aquifers will discharge at the mine face in the pit, and ground-water levels will decline in the vicinity of the mine. Local ground-water flow in the affected aquifers will be toward the mine pit instead of toward pre-mining discharge areas.

The extent of water-level declines in the vicinity of the mine will depend on such factors as pit size and shape, duration of mining, and aquifer geometry and hydraulic characteristics. Hasfurther and others (1982, p. 10) compared measured water-level declines at two surface coal mines in the eastern Powder River structural basin with simulated water-level declines from a two-dimensional, ground-water flow model; they concluded that water-level declines in the coal aquifers generally will be limited to a 2- to 3-mi radius of the mine. Water-level declines in overburden sandstone aquifers generally would extend throughout smaller areas because of the extremely lenticular nature of the sandstone beds in the overburden. Analysis of water-level data from existing mines (Gillette Area Groundwater Monitoring Organization, 1985) indicates that water-level declines in the coal aquifers generally extend less than 4 or 5 mi from the mines and water-level declines in the overburden aquifers generally extend less than 2 or 3 mi from the mines.

Local ground-water flow toward the mine and declining water levels in the vicinity of the mine will affect the availability of ground water in and around the lease area. In a recharge area, ground-water inflow to the mine may mean less recharge for surrounding aquifers. Some recharge will still occur because of seepage from the pit; however, most ground-water inflow will be pumped into sedimentation ponds or used for mining operations or both. In a discharge area, ground-water inflow to the mine may mean decreased ground-water discharge to nearby streams, springs, and flowing wells. Where ground-water inflow to the mine is from aquifer storage, with no measureable change in aquifer recharge or discharge, water-level declines will occur in nearby wells completed in the aquifers intersected by the pit.

Local ground-water flow toward the mine and declining water levels in the vicinity of the mine also can affect the interchange between ground water and surface water in and around the lease area. For example, if mining takes place near a stream that was gaining water from ground-water discharge during pre-mining conditions, water-level declines near the pit could cause a reversal of ground-water flow. Then, rather than the stream gaining water from ground water, it would lose water to ground water. The result would be a decrease in streamflow.

Underground mining and underground coal gasification also will affect the availability of ground water where operations are conducted below the water table. Underground mining and coal gasification will require mine dewatering, thus lowering water levels and altering the ground-water flow system. Water levels will decline in nearby wells completed in the dewatered aquifers, and ground-water discharge to nearby springs and flowing wells in these aquifers may be decreased.

## Long-Term Effects

After the mined area is reclaimed, the ground-water flow system will be changed. Mining destroys the layering of sandstone, shale, and coal, and the effect of reclamation is to inset into the existing hydrologic system a relatively homogeneous section of spoil. Initially the spoil material will be unsaturated, and ground water will continue to flow toward the mined area. Eventually an equilibrium water table will develop in the spoil. The level of the water table will depend on the porosity and permeability of the spoil material, ground-water recharge from adjacent aquifers, and infiltration of precipitation and streamflow on the surface of the spoil. Depending on the level of the water table that develops in the spoil, the reclaimed area may become a recharge area or a discharge area for the local ground-water flow system.

The ability of the spoil to be a recharge area will depend upon the condition of the spoil material when it is placed back into the system. Spoil-placement techniques during reclamation can have a substantial effect on the permeability of the spoil. For example, dragline-dumped spoil material may have permeability and effective porosity many times that of truck-dumped spoil that has been compacted by truck and scraper wheels (Rahn, 1976, p. 31). Recharge will increase where reclamation practices produce an increase in surface infiltration and soil moisture retention. However, if the pre-mining land surface was formed on highly fractured clinker deposits, recharge rates in the reclaimed area will be lower than pre-mining recharge rates because the permeability of clinker is an order of magnitude greater than even the dragline-dumped spoil (Rahn, 1976, p. 48).

Ground-water discharge in a reclaimed area will occur where the water table in the spoil material intersects the land surface. A high water table may develop in the spoil because of local infiltration of precipitation and streamflow on the reclaimed surface. A high water table also may develop in the spoil where water in confined aquifers adjacent to the mine has sufficient hydraulic head to move to the land surface. The water moves laterally in the confined aquifers until it reaches the area where the confining shale layers have been removed by mining. Water moves into the spoil material and mixes with water from other confined and unconfined aquifers contiguous with the spoil. The water table that results in the spoil represents a composite hydraulic head for all the aquifers contributing water to the spoil material.

Underground mining and coal gasification also are likely to cause permanent changes in the ground-water flow system. Subsidence of overburden materials above mine cavities has been documented at underground mines and a coal-gasification test site in the Powder River structural basin (Dunrud and Osterwald, 1980; Saulnier and others, 1983). Subsidence causes fractures in the overburden and results in interconnection of previously isolated aquifers. Perched aquifers may be drained, and associated springs may go dry. Subsidence also creates depressions in the land surface that can collect water and increase recharge through the fractures. In the coal-lease area where in-situ gasification is proposed, the burn chamber may be filled with a mud cement after the coal is burned in an attempt to prevent subsidence of overburden materials; however, the resulting hydraulic properties of this cement are unknown.

Surface mining, underground mining, and underground coal gasification also will have long-term effects on ground-water quality. During mining, the ground-water gradient is toward the mine; thus, changes in water quality that occur within the mined area likely will not move offsite. After reclamation, the local ground-water flow system will change, and contaminants from the mined area may move offsite and affect the quality of water in nearby aquifers.

At surface mines, chemical reactions between water and the fresh surfaces of disturbed spoil material likely will increase the concentrations of dissolved solids. The quality of water in spoil aquifers varies; it generally is two to three times as mineralized as water from undisturbed coal aquifers, but typically is no more mineralized than the most mineralized ground water in the area (Van Voast and Hedges, 1975, p. 26-27; U.S. Department of the Interior, 1981, p. 54-55; U.S. Bureau of Land Management, 1984, p. 94). Chemical analyses of 453 water samples from undisturbed coal aquifers in the basin had a median dissolved-solids concentration of about 1,250 mg/L, with 90 percent of the samples containing less than about 2,500 mg/L. Chemical analyses of 215 water samples from spoil aquifers in the basin had a median dissolved-solids concentration of about 3,150 mg/L, with 90 percent of the samples containing less than about 5,000 mg/L (Naftz, 1990). Increases in dissolved sulfate and calcium comprise most of the increase in dissolved solids in the spoil aquifers (Rahn, 1976, p. 41).

Changes in ground-water quality also will occur where water from different aquifers mix in the mined-out areas. At surface mines, water from previously isolated aquifers will mix in the backfilled spoil material. At underground mines, interconnection of previously isolated aquifers will result from subsidence-induced fractures in the overburden. In both situations, water of different quality likely will be mixed, and water quality will improve or deteriorate, depending on the existing water quality in the affected aquifers.

At present (1986), acid mine drainage is not a problem in the Powder River structural basin. The pH of ground water in the basin ranges from about 6.5 to 9.0 in samples from wells completed in undisturbed aquifers (Larson and Daddow, 1984) and from about 6.0 to 8.0 in samples from wells completed in spoil aquifers (Gillette Area Groundwater Monitoring Organization, 1985). Except for selenium, trace elements naturally occurring in the sediments are only sparingly soluble at the ranges of pH generally occurring in the ground water; therefore, trace elements are not a problem at present (1986). Selenium, when oxidized to the selenate form, is mobile at elevated pH (Levinson, 1980, p. 880). Oxidation of selenium-bearing sulfides, such as pyrite, is possible when overburden material is exposed to the atmosphere during coal removal.

The chemical quality of water in reclaimed areas occasionally may affect the suitability of the water for livestock watering. Agricultural and domestic uses of ground water will be affected little as the quality of most ground water in the basin already is unsuitable for these uses. About 10 percent of 215 water samples from spoil aquifers had dissolved-solids or sulfate concentrations or both greater than water-quality standards established for livestock use (5,000 mg/L for total dissolved solids and 3,000 mg/L for sulfate) (Wyoming Department of Environmental Quality, 1980, p. 9-11). In addition, nitrate concentrations greater than 100 mg/L and selenium concentrations greater than 0.10 mg/L have been measured in water from the spoil aquifer at one mine in the eastern part of the basin (Gillette Area Groundwater Monitoring Organization, 1985). These concentrations also exceed water-quality standards for livestock use and are more than 10 times the water-quality standards established for human consumption (Wyoming Department of Environmental Quality, 1980, p. 9).

Offsite water-quality degradation that results from spoil water migrating into adjacent coal aquifers will be affected by geochemical processes occurring in the coal. Recent laboratory experiments demonstrate that spoil water moving through a coal aquifer likely will undergo changes in chemical quality. Dissolved-solids concentrations decreased an average 210 mg/L, or 5 to 10 percent, in batch-mixing experiments using spoil water and coal from two mines in southeastern Montana (Davis and Dodge, 1986, p. 6-7).

Underground coal gasification may cause water-quality changes that are markedly different from the water-quality effects of conventional surface and underground mining. Because this mining method has been proposed only for the Thunderbird-2 coal-lease area, these potential changes will be addressed in the site-specific discussion for that lease area.

## SITE-SPECIFIC GEOHYDROLOGY AND POTENTIAL EFFECTS OF COAL MINING

The location of the 12 coal-lease areas within the Powder River structural basin is shown in figure 1 by site numbers 1-12. Site-specific maps of these areas are presented on plates 1, 2, and 3, with generalized geologic sections showing the approximate stratigraphic location of the coal beds in each of the areas.

## Ulm Coal-Lease Area

The Ulm coal-lease area (site 1, fig. 1) is in the northwestern part of the Wyoming Powder River structural basin in southeastern Sheridan County. Coal-lease applications for this area have proposed mining the Ulm-1 and Ulm-2 coal beds (also known as the Walters and Healy coal beds) by surface-mining methods. These coal beds are virtually horizontal in this area, with the base of the Ulm-2 coal bed at an altitude of about 4,400 ft (area A, pl. 1), and the Ulm-1 coal bed about 110 ft above the Ulm-2 coal bed. Overburden thickness ranges from no overburden at the coal outcrops to about 100 ft in the higher areas.

Little is known about the shallow ground-water hydrology in the vicinity of the Ulm coal-lease area. Most of the lease area is situated on a topographic high that forms a drainage divide between streams tributary to Piney Creek to the south and streams tributary to Wagner Prong and Dow Prong to the north and northwest. Analysis of available water-level data indicates that the area also forms a ground-water divide for the local flow system. Local ground-water flow in the southeastern one-third of the lease area is to the south toward Piney Creek; whereas, ground water in the rest of the lease area moves to the north and northwest toward Wagner Prong and East Fork and Middle Fork Dow Prong and their tributaries (area A, pl. 1).

Several factors indicate that the Ulm coal-lease area is in a recharge area for the local ground-water flow system. The lease area contains extensive outcrops of permeable coal and clinker that allow recharge by precipitation and ephemeral streamflow (area A, pl. 1). The high topographic position of the lease area and the movement of ground water away from this topographic high also indicate that the lease area is in a recharge area.

Most ground-water discharge in the vicinity of the Ulm coal-lease area occurs outside the boundaries of the lease area. Several springs issue from coal and clinker deposits near the northwestern part of the lease (area A, pl. 1). In addition, the alluvium of Piney Creek to the south, Wagner Prong to the north, and East Fork and Middle Fork Dow Prong to the northwest is subirrigated with ground water (Rusmore and others, 1985, pl. 5). Most ground-water flow to the alluvium of these streams is evaporated or transpired; however, some ground-water flow likely helps to maintain the base flow of Piney Creek, Wagner Prong, and Dow Prong. Analysis of low-level, color-infrared aerial photographs indicates that subirrigated areas also occur in places along some of the tributaries of Piney Creek, Wagner Prong, and East Fork and Middle Fork Dow Prong. The subirrigated areas along these tributary streams are quite small as the local ground-water flow system contributing to these areas also is small. Some ground water may move down these drainages and contribute to subirrigation of the alluvium along Piney Creek to the south, Wagner Prong to the north, and Dow Prong to the northwest.

Ground water is withdrawn from the local flow system by several livestock and domestic wells in and around the lease area. Records of the U.S. Geological Survey and the Wyoming State Engineer indicate five wells are within the lease area (area A, pl. 1). In addition, several wells around the lease area are completed in or above the coal beds. Many of the wells near the coal-lease area are very shallow, and likely are recharged by subsurface flow in a local draw or infiltration of precipitation through the clinker outcrop.

Analysis of existing water-quality information indicates that most ground water in the vicinity of the Ulm coal-lease area is suitable for livestock watering, but unsuitable for domestic consumption. No water-quality analyses are available for wells within the lease area. Dissolved-solids concentration in water from a well completed in the Wasatch Formation just east of the lease area was 1,090 mg/L, and the dominant ions were sodium and bicarbonate. Analyses of samples from three other wells completed in the Wasatch and one spring issuing from the Wasatch within about 5 mi of the lease area indicated some change in water quality with depth. Two wells greater than 100 ft deep yielded sodium bicarbonate type water, with dissolved-solids concentrations of about 900 mg/L. The spring and a well only 60 ft deep yielded calcium bicarbonate type water, with dissolved-solids concentrations of only 242 mg/L for the spring and 672 mg/L for the well. The water in the alluvium of Piney Creek may be more mineralized than that in the bedrock aquifers. A well completed in the alluvium near the mouth of Piney Creek yielded magnesium calcium sulfate water with a dissolved-solids concentration of 1,700 mg/L (Hodson and others, 1973, pl. 2; Larson and Daddow, 1984, p. 36).

During mining of the Ulm coal-lease area, the local ground-water flow system will be changed. The clinker overburden and all of the aquifers down to and including the Ulm-2 coal bed will be removed. Aquifers intercepted by the mine will discharge to the pit, and ground-water levels will decline in the vicinity of the mine. Local ground-water flow in the immediate vicinity of the mine will be reversed, so that instead of being a ground-water divide and a recharge area, the lease area will become a discharge area for local flow. Assuming water-level declines in this area will be similar to those at existing mines in the eastern part of the basin, declines generally will not extend more than about 5 mi from the mine (Hasfurther and others, 1982; Gillette Area Groundwater Monitoring Organization, 1985). Maximum water-level decline should not be below an altitude of about 4,400 ft, the altitude of the base of the Ulm-2 coal bed. Declines in water levels near the mine will not extend to the alluvium of Piney Creek, Wagner Prong, and East Fork and Middle Fork Dow Prong because water levels along these streams are well below the altitude of the base of the Ulm-2 coal bed.

Replacement of spoil material into the mined area will leave permanent changes in the local ground-water flow system after mining. Initially ground water will continue to flow toward the mined area until a new equilibrium water table develops in the backfilled spoil. As water levels in the spoil rise to about pre-mining levels, the area may once again be a recharge area for the local flow system. However, recharge to the local flow system from the reclaimed area will be less than before mining because the permeability of backfilled spoil will be less than the permeability of undisturbed clinker (Rahn, 1976, p. 48). The result would be decreased ground-water movement toward the subirrigated areas along Piney Creek, Wagner Prong, and East Fork and Middle Fork Dow Prong. It is unknown whether the decreased recharge from the mined area would have any measureable effect on streamflow in Piney Creek, Wagner Prong, or Dow Prong. The permanent effect of mining on the springs near the northwestern part of the lease area will depend on the level of the water table that develops in the spoil. If the layer of rock from which the spring issues is not disturbed, and if the post-mining water table is high enough to saturate this layer, the springs may reappear at or near their former locations.

Mining likely will destroy the five wells within the coal-lease area, and it may affect water levels in nearby wells outside the lease area. Water levels in offsite wells in the vicinity of the mine likely will decline as a result of pit dewatering during mining operations. Water-level declines during mining operations likely will depend on the proximity of the well to the mined area and the hydraulic connection through the aquifer between the mine and the well. Wells that could be affected by dewatering of the mine include four wells in section 16 and one well in each of sections 10, 14, and 23, T. 54 N., R. 81 W. These wells are completed in or above the coal beds. Most of the other wells near the lease area should not be affected because they are less than 10 ft deep and likely receive recharge from a local draw or clinker outcrop, or because they are near part of the lease area where the coal is well above the local water table. Wells affected by mine-dewatering operations likely will have some recovery of water levels after mining ceases, the height of recovery depending on the level of water table that develops in the spoil.

The quality of water that will develop in the spoil aquifer is unknown. Water from three wells completed in or near the coal beds was a sodium bicarbonate type and had dissolved-solids concentrations ranging from about 900 mg/L to almost 1,100 mg/L (Larson and Daddow, 1984, p. 36). Assuming that water in the spoil aquifer will be two to three times more mineralized than water in the undisturbed aquifers (U.S. Department of the Interior, 1981, p. 54-55; U.S. Bureau of Land Management, 1984, p. 94), dissolved-solids concentrations in the spoil water would range from about 2,000 to 3,000 mg/L. As water moves from the spoil material into the surrounding aquifer system, water quality in nearby wells may deteriorate because of an increase in dissolved-solids concentration. The magnitude of the increase will depend on the proximity of the well to the mined area and the hydraulic connection between the mine and the well; however, the suitability of the water for livestock watering should be unaffected. Mineralized water from the spoil aquifer also may move into the alluvium of Piney Creek, Wagner Prong, and East Fork and Middle Fork Dow Prong, causing an increase of salts in the soils of the alluvium and a possible increase in the salinity of streamflow.

## Wildcat Creek Coal-Lease Area

The Wildcat Creek coal-lease area (site 2, fig. 1) is in the northeastern part of the Wyoming Powder River structural basin, about 20 mi north of Gillette in northern Campbell County. Preference-right lease applications for this lease area have proposed mining the Anderson, Dietz (where present), and Canyon coal beds by surface-mining methods. The coal beds dip gently to the west in this area (generally less than 3°), with the base of the Canyon coal bed at an altitude between 3,750 and 3,800 ft at the western edge of the lease area (area B, pl. 1). The Anderson coal may be as much as 100 to 150 ft above the Canyon coal in some places; however, in other places, the Anderson and Dietz coals join to form one thick bed just above the Canyon coal (area B, pl. 1). (The Dietz coal bed did not appear in the coal test-hole data used to construct the geologic sections for area B on plate 1.) Overburden thickness generally is less than 200 ft, except in some of the higher areas. Interburden thickness varies considerably as there is large variation in the thickness of the coal beds.

The local ground-water flow system in the Wildcat Creek coal-lease area is controlled by the local topography and by the lithology of the coal beds. Local ground-water flow follows the surface drainage toward Horse Creek, Wildcat Creek, and the Little Powder River (area B, pl. 1). King (1974) identified ground-water movement toward Wildcat Creek and the Little Powder River for aquifers less than 500 ft deep in the southern part of the lease area. Analysis of available water-level data on file with the U.S. Geological Survey and the Wyoming State Engineer also indicates ground-water movement toward Horse Creek in the northern part of the lease area. Shallow ground water also moves laterally through the coal beds and, if not interrupted by the land surface, may move downdip to the northwest (Daddow, 1986).

Recharge to the local ground-water system occurs from precipitation on higher interstream areas and from ephemeral streamflow across coal and bedrock outcrops. Much of the upland on both sides of Horse, Wildcat, and Boxelder Creeks is capped with permeable clinker deposits and is a recharge area for the local ground-water system. Ephemeral streamflow in channels tributary to Horse, Wildcat, and Boxelder Creeks and the Little Powder River also recharges the local system where these channels cross outcrops of the Anderson and Canyon coal beds (area B, pl. 1).

Ground water is discharged from the local flow system by evapotranspiration of water in the alluvium, and from springs at the base of clinker and coal outcrops. The alluvium of Horse Creek, Wildcat Creek, the Little Powder River, and several tributaries is subirrigated by ground water from the local flow system (Rusmore and others, 1985, pl. 6). Some of this ground water likely moves down the valleys toward the Little Powder River; however, much of it is evaporated and transpired by the subirrigated hayfields that occur along these streams. Ground water also is discharged from springs issuing from the clinker and coal beds; most of these springs are north of Horse Creek or east of Boxelder Creek (area B, pl. 1).

Ground water is withdrawn from the local flow system by many livestock and domestic wells in and around the coal-lease area. Records of the U.S. Geological Survey and the Wyoming State Engineer indicate 20 wells are within the lease area (area B, pl. 1). In addition, many nearby wells outside the lease area obtain water from the alluvium along Horse Creek and Wildcat Creek. South and west of the lease area, more than one-half of the wells obtain water from coal and overburden aquifers.

The quality of ground water in and around the Wildcat Creek coal-lease area is dependent on the source of water and the depth from which it is pumped. Water quality generally is suitable for livestock watering, but unsuitable for domestic consumption. Chemical analyses of two water samples from wells completed in the alluvium of Horse Creek and Wildcat Creek indicated sodium bicarbonate type water in both samples, with dissolved-solids concentrations between 500 and 1,000 mg/L (Larson and Daddow, 1984, p. 16-19). Chemical analyses of four water samples from the Fort Union Formation (three wells and one spring) indicated changing water quality with depth. Water from two wells greater than 400 ft deep in the Fort Union was a sodium bicarbonate type, with dissolved-solids concentrations of about 1,000 mg/L. Water from a well only 173 ft deep in the Fort Union was a calcium sodium sulfate bicarbonate type and had a dissolved-solids concentration of 2,740 mg/L.

Water from the spring issuing from the Fort Union north of Horse Creek contained only 209 mg/L of dissolved solids and was a calcium bicarbonate type (Larson and Daddow, 1984, p. 16-19).

Mining the Wildcat Creek coal-lease area will alter the local ground-water flow system. The clinker overburden will be destroyed, and local recharge will be intercepted by the pit. All of the aquifers down to and including the Canyon coal bed will be removed by the mining operations, and water levels will decline in the vicinity of the mine. Based on analyses of water-level changes at existing mines (Hasfurther and others, 1982; Gillette Area Groundwater Monitoring Organization, 1985), water-level declines generally will not extend more than about 5 mi from the mine, and maximum water-level declines will not go below an altitude of about 3,750 ft, the altitude of the base of the Canyon coal bed. Where water-level declines extend to the alluvium of Horse Creek, Wildcat Creek, or the Little Powder River, subirrigation of these areas will decrease, and ephemeral and intermittent streamflow in these channels may be decreased.

Removal of the clinker overburden and placement of spoil material back into the mined area will produce permanent changes in the local ground-water flow system after mining. As a new water table develops in the spoil material, the reclaimed area may become a new recharge or discharge area for the local flow system. Because the permeability of backfilled spoil will be less than the permeability of undisturbed clinker (Rahn, 1976, p. 48), recharge to the local flow system from the reclaimed area will be less than before mining. Subirrigation of the alluvium along Horse and Wildcat Creeks likely will be decreased. If the surface of the reclaimed area is much lower than adjacent, undisturbed areas of clinker, ground water may move from the undisturbed clinker toward the reclaimed area, and springs may develop near the contact between the spoil and the undisturbed material.

Mining will destroy wells and springs within the coal-lease area and may affect water levels in nearby wells outside the lease area. The 20 wells that are within the lease area likely will be destroyed by mining. Wells outside the lease area may be affected by mine dewatering. Water levels in these wells may decline to some extent, depending on the distance from the mine and whether or not the water-yielding zones are interrupted by the mining operation. Wells completed in the alluvium of Horse Creek and Wildcat Creek could be affected by decreased recharge to the local ground-water system. Several wells along Wildcat Creek are completed below the coal and likely will be unaffected by the mining. Wells affected by mine-dewatering operations will have some recovery of water levels as a new water table develops in the spoil. Water levels in the alluvial wells along Horse Creek and Wildcat Creek likely will depend, in part, on the level of the water table that develops in the backfilled spoil material.

The quality of water that will develop in the spoil aquifer is difficult to predict. Water in the area is already extremely variable in quality. The water from the shallow well in the Fort Union (2,740 mg/L of dissolved solids) may be representative of the most mineralized water in the area, yet this sample may be a good estimate of the quality of water that will develop in the spoil material. However, if the quality of water from the shallow well in the Fort Union is typical of water in the undisturbed coal aquifers, then dissolved-solids concentrations in the spoil water may be as much as 5,000 to

6,000 mg/L (U.S. Department of the Interior, 1981, p. 54-55; U.S. Bureau of Land Management, 1984, p. 94). Concentrations of dissolved solids greater than 5,000 mg/L would render the water unsuitable for livestock watering according to state water-quality standards (Wyoming Department of Environmental Quality, 1980, p. 9-11). After mining, this mineralized spoil water may move offsite and cause an increase of salts in the soils of the alluvium and a deterioration in water quality in nearby wells.

## Thunderbird Coal-Lease Area

The Thunderbird coal-lease area (site 3, fig. 1) is in the central part of the Wyoming Powder River structural basin, about 20 mi west of Gillette, 5 mi east of the Powder River, and just north of Interstate Highway 90 in western Campbell and eastern Johnson Counties. Preference-right lease applications for this area have proposed mining the Ulm coal bed by surface-mining methods. The Ulm coal bed dips slightly to the west in the eastern part of the lease area and is relatively flat throughout the rest of the area, with the altitude of the base of the coal between 4,350 and 4,400 ft (area C, pl. 1). Overburden thickness in the area to be mined generally is less than 150 ft.

The local ground-water flow system in the Thunderbird coal-lease area is controlled by the local topography. Koch and others (1982, p. V-55, 56) determined that ground water less than 500 ft deep generally flows from east to west through the lease area toward the Powder River. Analysis of available water-level data on file with the U.S. Geological Survey and the Wyoming State Engineer also indicates local ground-water flow to the west, with ground water following surface drainages toward the valley of the Powder River (area C, pl. 1). Ground water greater than 500 ft deep generally moves to the north in intermediate and regional flow systems; however, the interaction between these flow systems and the shallower local flow system may be limited by relatively impermeable shale layers that occur in the Wasatch Formation.

Little is known about recharge to the local ground-water flow system in the vicinity of the Thunderbird coal-lease area. Information on outcrops of coal and clinker is lacking, as this area was not included in any of the early coal-field studies. Recharge to the local ground-water system likely occurs from ephemeral streamflow on the alluvium of the major drainages. The local flow system also may be recharged by upward leakage of ground water from intermediate and regional flow systems; however, the limited extent of subirrigated areas (Rusmore and others, 1985, pl. 7) indicates that upward leakage of deeper ground water is not a major source of recharge.

The presence of numerous flowing wells in and around the Thunderbird coal-lease area indicates that the lease area is in a region of ground-water discharge (Freeze and Cherry, 1979, p. 200). Several flowing wells less than 215 ft deep in the southeastern part of the lease area discharge ground water from the local flow system. Local ground-water flow also is discharged by evapotranspiration from the subirrigated alluvium of Fortification Creek, Barber Creek, Dead Horse Creek, and the Powder River (Rusmore and others, 1985, pl. 7).

Ground water is withdrawn from local, intermediate, and regional flow systems by livestock and domestic wells in and around the coal-lease area. Records of the U.S. Geological Survey and the Wyoming State Engineer indicate eight wells are within the lease area, not including several abandoned dry holes that were used to construct the geologic section for area C on plate 1. In addition, many nearby wells outside the lease area obtain water from the alluvium of Fortification Creek, Barber Creek, Dead Horse Creek, and the Powder River (area C, pl. 1). Most other nearby wells outside the lease area are completed well below the Ulm coal bed.

The quality of ground water in and around the Thunderbird coal-lease area varies with the formation from which it is withdrawn. Chemical analyses of two water samples from wells completed in the alluvium of the Powder River indicated calcium sulfate and calcium sodium sulfate type water, with dissolved-solids concentrations between 1,000 and 2,500 mg/L (Larson and Daddow, 1984, p. 12, 14). Water of this quality is suitable for livestock watering but unsuitable for domestic consumption. Chemical analyses of four water samples from wells less than 500 ft deep completed in the Wasatch Formation indicated relatively uniform water chemistry. All the water samples were a sodium bicarbonate type, and dissolved-solids concentrations ranged from 250 to 400 mg/L (Larson and Daddow, 1984, p. 12, 14). Water of this quality is suitable for livestock watering and domestic consumption.

Mining the Thunderbird coal-lease area may alter the local ground-water flow system. Analysis of limited information on coal depths and water levels in the lease area indicates that mining in the southeastern part of the lease area may be below the local water table, whereas mining in the rest of the lease area likely will be above the water table. Where mining is below the water table, aquifers intercepted by the mine will discharge to the pit, and ground-water levels will decline in the vicinity of the mine. Maximum water-level decline should not go below an altitude of about 4,350 ft, the altitude of the base of the Ulm coal bed. Water-level declines should not extend as far north as Fortification Creek or as far south as Dead Horse Creek, as water levels along these streams are already well below the base of the Ulm coal bed.

Replacement of spoil material into the mined area may leave permanent changes in the local ground-water flow system. Initially ground water will move into the mined area until an equilibrium water table develops in the backfilled spoil. Because dragline-laid spoil is more permeable than undisturbed overburden (Rahn, 1976, p. 31), recharge in the reclaimed area may be greater than before mining. If recharge to the spoil is great enough to raise the water table above that in the surrounding undisturbed overburden, the spoil will become a recharge area for the local flow system. Subirrigation of the alluvium along Barber Creek may be increased, and springs may develop near the contact between the spoil and the undisturbed overburden.

Mining likely will destroy the eight wells within the coal-lease area. Water-level declines in nearby wells outside the lease area are unlikely because almost all offsite wells are completed well below the base of the Ulm coal bed. A possible exception is the well in section 21 of T. 50 N., R. 75 W. This well may be completed in the coal updip from the mine, and water-level declines in the coal may draw down water levels in this well.

The quality of water that will develop in the spoil aquifer is difficult to predict. Assuming that water in the spoil aquifer will be two to three times more mineralized than water in the undisturbed aquifers (U.S. Department of the Interior, 1981, p. 54-55; U.S. Bureau of Land Management, 1984, p. 94), dissolved-solids concentrations in the spoil water would range from 800 to 1,200 mg/L. Such water would be suitable for livestock use but unsuitable for domestic consumption. Mineralized water from the spoil aquifer may move into the alluvium along the upstream reaches of Barber Creek, causing an increase of salts in the soils of the alluvium and a possible increase in the salinity of streamflow.

### Thunderbird-2 Coal-Lease Area

The Thunderbird-2 coal-lease area (site 4, fig. 1) is in the central part of the Wyoming Powder River structural basin, just west and south of the Thunderbird coal-lease area in western Campbell and eastern Johnson Counties. Coal-lease applications for this area have proposed mining two coal beds in the Wasatch Formation and six coal beds in the Fort Union Formation by a combination of surface and underground mining and in-situ coal gasification. Depths of the coal beds range from near the land surface to about 2,500 ft (area A, pl. 2).

Because of the depths of the coal beds proposed for development, the Thunderbird-2 lease area includes local, intermediate, and regional ground-water flow systems. The local ground-water flow system for the Thunderbird-2 coal-lease area is similar to that described for the Thunderbird lease area. Local ground-water movement in aquifers less than about 500 ft deep generally is to the west (Koch and others, 1982, p. V-55, 56), with ground water following surface drainages toward the valley of the Powder River (area A, pl. 2). At depths greater than 500 ft, intermediate and regional flow systems begin to affect ground-water movement until, at a depth of about 2,500 ft, the direction of ground-water movement generally is from south to north (Hotchkiss and Levings, 1986, p. 26). Also, many of the deeper wells near the Powder River flow at the land surface, indicating an upward component of flow in intermediate and regional systems (Hagmaier, 1971, p. 48, 53). Some of these wells may flow because of gas in the formation; many of the flowing wells also produce gas.

The local, intermediate, and regional flow systems are recharged in different areas. The local flow system is recharged by precipitation and ephemeral streamflow on the alluvium of channels tributary to Barber Creek, Dead Horse Creek, and the Powder River. A limited quantity of recharge to the local flow system also comes from upward leakage of ground water from intermediate and regional flow systems. Recharge areas for the intermediate and regional flow systems are more distant from the coal-lease area. Most recharge of the regional flow system likely takes place at higher altitudes around basin margins.

The presence of numerous flowing wells in and around the Thunderbird-2 lease area and along the Powder River indicates that the lease area is in a region of ground-water discharge. The range of depths associated with these flowing wells indicates the discharge may be coming from intermediate and regional flow systems as well as the local flow system. If discharge from intermediate and regional flow systems is substantial, one would expect streamflow gains in the Powder River, and perennial streamflow and springs in other parts of the area. The absence of measureable gains in Powder River streamflow (Rankl and Lowry, 1990), perennial streams, and springs indicates that ground-water discharge from intermediate and regional flow systems is not substantial, and that discharge mainly occurs where almost impermeable confining layers have been penetrated by wells. Ground-water discharge also occurs as evapotranspiration from subirrigated alluvium along Barber Creek, Dead Horse Creek, and the Powder River (area A, pl. 2).

In addition to many flowing wells, several other livestock and domestic wells are located in and around the lease area. Records of the U.S. Geological Survey and the Wyoming State Engineer indicate 20 wells are within lease area boundaries (area A, pl. 2). Analysis of available information indicates that almost all of the nearby wells outside the lease area are less than 2,500 ft deep.

The quality of ground water in the vicinity of the Thunderbird-2 coal-lease area depends upon the source of the water and the depth from which it is pumped. Water throughout the area generally is suitable for livestock watering, but shallow water in the Wasatch Formation may be the only water suitable for domestic supply. Analysis of data on file with the U.S. Geological Survey indicates that water from wells completed in the alluvium along the Powder River generally is a calcium sulfate or calcium sodium sulfate type, with dissolved-solids concentrations ranging from about 1,000 to 2,500 mg/L. Water from wells completed in bedrock aquifers in the Wasatch and Fort Union Formations is consistently a sodium bicarbonate type, with dissolved-solids concentrations ranging from about 300 mg/L in a well less than 200 ft deep to about 2,000 mg/L in a well more than 6,000 ft deep (Larson and Daddow, 1984, p. 12, 14).

Mining the Thunderbird-2 coal-lease area will affect local, intermediate, and regional ground-water flow systems. Surface mining proposed for some parts of the lease area will produce effects on local ground-water flow similar to those described for the Thunderbird lease area. Because of the depth of the proposed coal development, underground mining and coal gasification likely will affect flow in intermediate and regional flow systems. Underground mining and in-situ gasification will require extensive dewatering as mining progresses in several different coal seams. If the entire stratigraphic section is dewatered from the land surface to a depth of 2,500 ft, a large cone of depression will develop in the aquifers. Water-level declines in these aquifers may decrease ground-water discharge to flowing wells in the area.

Subsidence from underground mining and coal gasification could produce permanent changes in local, intermediate, and regional flow. Studies of the roof rock over the Big George coal seam near the Thunderbird-2 lease area indicate weak rock strength and a high probability of subsidence in this area (Hladysz, 1983). Subsidence-induced fractures may result in interconnection of previously isolated aquifers, and perched aquifers may be drained. Ground water under pressure at depth may move up through the fractures and discharge at the land surface. Depressions in the land surface caused by subsidence may collect surface runoff and increase recharge through fractures in the overburden.

Many wells in and around the Thunderbird-2 lease area could be affected by the proposed coal development. The 20 wells in the lease area likely will be destroyed by mining. In addition, water levels in most wells in the surrounding area likely will decline because of the large-scale dewatering anticipated with the Thunderbird-2 proposal. Subsidence of overburden roof materials also could affect water levels in nearby wells; many wells that flow because of gas pressure in the coal may stop flowing if mining or gasification processes relieve that pressure.

Underground coal gasification also will affect the quality of ground water in the Thunderbird-2 lease area. The processes of underground burning and steam injection create substantial pressures in the coal seam that will force chemical contaminants into the surrounding formation. The extent of this phenomenon will depend on the temperature and operating pressure inside the gasification chamber or "georeactor." Potential chemical species that may be transported into the surrounding formation by the pressurized gases include sulfur and nitrogen compounds, and possibly potassium, sodium, lithium, fluorine, and chlorine (Saulnier and others, 1983, p. 498). Underground coal gasification by-products that also may enter the ground water include coal tars (benzenes, nitrogen bases, phenols, and condensed aromatics), ammonia, and cyanide. Of these, phenols are the dominant organic contaminants because of their concentration and solubility in water (Ahner and Bloomstran, 1983, p. 482).

After the burn and gas-recovery process is completed, leaching of the residual ash is the principal process affecting water quality. Increases in dissolved solids and changes in pH are likely as formation water reacts with ash products such as calcium and magnesium oxides, calcium sulfate, calcium hydroxide, and reduced iron forms. Overburden material that collapses into the cavity is another source of potential leachate (Saulnier and others, 1983, p. 498). Collapse of the overburden roof materials also may allow mixing of waters from different aquifers and associated changes in water quality.

## Caballo and East Black Thunder Coal-Lease Areas

The Caballo coal-lease area (site 5, fig. 1) and the East Black Thunder coal-lease area (site 6, fig. 1) are discussed together because of their similar situations. Both lease areas are small (less than 1 $mi^2$), and both areas are adjacent to large existing mines. Surface mining of the Wyodak-Anderson coal bed is proposed for both areas. The Caballo coal-lease area consists of one 160-acre tract and one 320-acre tract adjacent to the existing Caballo Mine (area B, pl. 2), about 13 mi southeast of Gillette in eastern Campbell County. The East Black Thunder coal-lease area is an 80-acre tract adjacent to the existing Black Thunder Mine (area C, pl. 2), about 14 mi southeast of Reno Junction in the southeastern corner of Campbell County.

Local ground-water flow in the two coal-lease areas generally is toward the major stream channels draining the areas. King (1974) identified ground-water movement to the south toward Caballo Creek in and around the Caballo lease area (area B, pl. 2). Analysis of water-level monitoring data from the Caballo Mine also indicates ground-water flow toward Caballo Creek, especially in the overburden (Gillette Area Groundwater Monitoring Organization, 1985). Water in the coal aquifers also is moving toward Caballo Creek, but it is moving in a southwesterly direction and likely is affected somewhat by the dip of the coal. Water-level information is not available for the thin overburden at the East Black Thunder coal-lease area, but analysis of water levels in the coal seam near the Black Thunder Mine indicate ground water in this area is moving to the north toward Little Thunder Creek (area C, pl. 2) (Gillette Area Groundwater Monitoring Organization, 1985).

Both lease areas are in recharge areas for the local flow systems. Both areas contain extensive outcrops of permeable clinker that allow recharge by precipitation and ephemeral streamflow (areas B and C, pl. 2). The permeability of the clinker outcrops is several times greater than that of the other overburden units or coal beds (Rahn, 1976, p. 46).

Local ground-water flow discharges to the main stream channels draining the two coal-lease areas and to the existing mines. Ground-water flow toward Caballo Creek contributes to the base flow of this perennial stream and also contributes to the subirrigation of the alluvium along Gold Mine Draw and Tisdale and Caballo Creeks (area B, pl. 2) (Rusmore and others, 1985, pl. 8). Water in the coal seam also may move downdip to the west and discharge to the pit of the Caballo Mine. Ground water in the East Black Thunder coal-lease area discharges to the alluvium of Little Thunder Creek. The alluvium along Little Thunder Creek is subirrigated (area C, pl. 2) (Rusmore and others, 1985, pl. 9); however, Little Thunder Creek is not perennial in the vicinity of the lease area, so most ground water in the area is discharged by evapotranspiration. Water in the coal bed also may enter the Black Thunder Mine and be pumped into sedimentation ponds.

Most of the wells in the vicinity of the two lease areas are monitoring or supply wells associated with existing coal-mining operations; however, ground water also is used for livestock watering and domestic supply, particularly near the Caballo lease area. Four wells are in the Caballo lease area (area B, pl. 2); there are no wells in the East Black Thunder lease area (area C, pl. 2). Limited use of ground water for irrigation also may occur near the Caballo lease area.

The quality of ground water in the coal-lease areas is expected to be similar to the quality of ground water in the undisturbed parts of the existing mines. Concentrations of dissolved solids in water from undisturbed coal aquifers at the Caballo Mine ranged from 846 to 4,170 mg/L, with calcium and sulfate as the dominant ions. Concentrations of dissolved solids in undisturbed coal aquifers at the Black Thunder Mine ranged from 662 to 3,190 mg/L, with sodium, calcium, and sulfate as the dominant ions. The quality of water in these areas is suitable for livestock watering, but generally is unsuitable for use for irrigation or domestic supply.

Mining of the two new lease areas will have little effect on the local ground-water system beyond that already anticipated for the existing Caballo and Black Thunder Mines. Water-level monitoring data from the Gillette Area Groundwater Monitoring Organization (1985) indicate virtually no change in water levels in coal and overburden aquifers near the Caballo Mine. Water-level declines in the coal aquifers have been recorded near the Black Thunder Mine. Water levels in the coal aquifers have declined nearly 110 ft in one well 1 mi south of the mine and nearly 50 ft in a well almost 3 mi south of the mine. Water levels in the overburden near the Black Thunder Mine remain virtually unchanged (Gillette Area Groundwater Monitoring Organization, 1985).

After mining, the clinker overburden of the coal-lease areas will be replaced with spoil material. Recharge to the local ground-water system likely will be decreased because the permeability of reclaimed spoil will be less than the permeability of clinker (Rahn, 1976, p. 48). Ground-water flow toward Caballo and Little Thunder Creeks likely will be decreased during mining; however, it is unlikely that the effects of mining the new lease areas will be distinguishable from the effects of the existing mines. After a new water table develops in the spoil, ground-water flow toward Caballo and Little Thunder Creeks may be reestablished.

The existing wells in the Caballo lease area will be destroyed by mining; however, the effects of mining the new lease areas on offsite wells will be similar to those anticipated from the mining at the existing mine. Wells north and west of the Caballo lease area will be destroyed by the Caballo Mine. One well in the southwest quarter of section 13, T. 48 N., R. 71 W., may obtain water from the coal seam, and the water level in this well likely will decline because of mining at the existing mine and in the new lease areas. Water levels in shallow wells along Tisdale and Caballo Creeks also may decline during mining. Wells south of Caballo Creek are much less likely to be affected. Wells to the west of the East Black Thunder coal-lease area will be destroyed by the Black Thunder Mine. Offsite wells north of Little Thunder Creek are not likely to be affected by mining the new lease area if they are not affected by the existing mine.

After mining, the quality of water that will be present in the spoil aquifers in the coal-lease areas is expected to be similar to the quality of water in the spoil aquifers of the existing mines. Concentrations of dissolved solids in water from spoil aquifers at the Caballo Mine ranged from 888 to 7,380 mg/L, with calcium, magnesium, and sulfate as the dominant ions. Concentrations of dissolved solids in spoil aquifers at the Black Thunder Mine ranged from 1,470 to 3,730 mg/L, with calcium, sodium, sulfate, and bicarbonate as the dominant ions. Water of this quality would be suitable only for livestock watering. Analyses of water from the spoil aquifers at the Caballo Mine indicated large selenium concentrations (as much as 0.75 mg/L) and large nitrate concentrations (as much as 250 mg/L). Water with selenium concentrations greater than 0.05 mg/L does not meet State standards for domestic use, irrigation, or livestock watering, and water with nitrate concentrations greater than 10 mg/L is considered unsafe for human consumption.

### Rochelle Coal-Lease Area

The Rochelle coal-lease area (site 7, fig. 1) is in the southeastern part of the Wyoming Powder River structural basin, about 20 mi southeast of Reno Junction in the southeastern corner of Campbell County. Coal-lease applications for this area have proposed mining the Wyodak-Anderson coal bed by surface-mining methods. The Wyodak-Anderson coal bed dips slightly to the west in this area with about 100 ft of clinker overburden throughout most of the lease area (area D, pl. 2). The base of the coal is at an altitude of about 4,700 ft near the southwest corner of the largest tract in the lease area. This corner of the lease area is contiguous with the existing Rochelle Mine.

Local ground-water flow in and around the Rochelle coal-lease area likely follows the local topography. There are very few wells in the vicinity of the lease area, and there is little water-level information available to define the ground-water flow system. The largest tract in the lease area occupies a high topographic position that forms a watershed divide. Surface drainage of most of the lease area is to the northwest toward School Creek; however, parts of the east side of the lease area drain to the north toward Hansen Draw, to the east toward Piney Creek, and to the south toward Beckwith Creek. Local ground-water flow likely moves toward these same drainages (area D, pl. 2). Some water entering the shallow ground-water system also likely moves down through the clinker to the coal bed, where it may flow downdip to the west.

Recharge to and discharge from local ground-water flow occur in the Rochelle coal-lease area. The entire lease area is covered with clinker outcrops that are a recharge area for the local ground-water system (area D, pl. 2). Ground-water discharge occurs in several places along the major stream channels draining the lease area. Ground water discharges as springs in the upstream end of School Creek, Hansen Draw, Beckwith Creek, and West Fork Creek (area D, pl. 2). In addition, information on alluvial valley floors (Rusmore and others, 1985, pl. 9) indicates the alluvium along parts of School, Piney, Beckwith, and West Fork Creeks is subirrigated (area D, pl. 2). However, none of these streams are perennial, so most ground water discharged to the alluvium of these streams is lost by evapotranspiration. Ground water that moves into the coal bed will move downdip to the west (Daddow, 1986) and will discharge to the existing Rochelle Mine west of the lease tracts.

Ground water in the vicinity of the Rochelle coal-lease area primarily is used for livestock watering and, to a lesser extent, for domestic supply. Records of the U.S. Geological Survey and the Wyoming State Engineer indicate one livestock well is in the lease area. Several other stock and domestic wells are located within about 5 mi of the coal-lease area.

Only one chemical analysis is available for evaluating the quality of ground water in the vicinity of the lease area. Water from a 120-ft deep domestic well completed in the Fort Union Formation 2 mi north of the lease area contained 613 mg/L dissolved solids, with sodium and bicarbonate as the major ions (Larson and Daddow, 1984, p. 8-9). Generally water of this quality would be considered marginal for domestic use.

Surface mining of the Rochelle coal-lease area will alter the local ground-water system. Mining will remove the clinker overburden and the coal bed, and water levels will decline in the vicinity of the mine. Water-level declines from mining the coal in the lease area will not go below an altitude of about 4,700 ft, the base of the coal at the west boundary of the lease. However, mining of the same coal bed at the existing Rochelle Mine west of the lease area will lower water levels in the coal below 4,700 ft, because the coal continues to dip to the west. Mining of the Rochelle coal-lease area will destroy the spring in the upstream end of School Creek, and water-level declines associated with the new lease and the existing mine may decrease spring discharge in the upstream ends of Hansen Draw, Beckwith Creek, and West Fork Creek. Water that would recharge the local ground-water system through the clinker in the lease area will be intercepted by the proposed new mine, and ground-water flow toward the subirrigated areas along School, Piney, West Fork, and Beckwith Creeks will be decreased.

Permanent changes in the ground-water system will remain after mining and reclamation are complete. Depending on the level of the water table that develops in the spoil, the lease area may once again be a recharge area for local flow; however, the quantity of flow likely will be decreased because the permeability of reclaimed spoil will be less than the permeability of clinker (Rahn, 1976, p. 48). Subirrigation of alluvium along the major streams draining the lease area likely will be decreased. The destruction of the spring in the upstream end of School Creek will be a permanent loss. Decreased spring discharge along other streams draining the lease area may not be permanent, depending on the level of the water table in the spoil.

Mining of the lease area will destroy a spring and a livestock well within the area. Wells and springs outside the lease area may be affected by declines in ground-water levels caused by mine dewatering; however, it likely will not be possible to distinguish the effects of mining the new lease area from the effects of the existing Rochelle Mine.

Only one water-quality analysis is available from which to estimate the quality of water that might be present in the spoil after mining. Assuming that water in the spoil aquifer will be two to three times more mineralized than water in the undisturbed aquifers (U.S. Department of the Interior, 1981, p. 54-55; U.S. Bureau of Land Management, 1984, p. 94), concentrations of dissolved solids in the spoil water might range from about 1,200 to 1,800 mg/L. Although more data on the quality of water in the area might result in larger estimates, it is unlikely the suitability of the water for livestock watering will be affected.

## North Antelope and South Antelope Coal-Lease Areas

The North Antelope and South Antelope coal-lease areas (sites 8 and 9, fig. 1) are in the southeastern part of the Wyoming Powder River structural basin. The North Antelope lease area is north of Antelope Creek in the southeastern corner of Campbell County and the northeastern corner of Converse County; the South Antelope lease area is south of Antelope Creek in the northeastern corner of Converse County (area A, pl. 3). Coal-lease applications for both areas propose mining the Wyodak-Anderson coal bed by surface-mining methods. The Wyodak-Anderson coal ranges from flat to gently westward dipping and is within 100 to 150 ft of the land surface in these lease areas (area A, pl. 3). The North Antelope coal-lease area is near several existing mines: the Rochelle Mine to the northeast, the North Antelope Mine to the north, and the Antelope Mine to the southwest.

The North Antelope and South Antelope coal-lease areas are discussed together because these two lease areas are part of the same local flow system. Water-level information from the Gillette Area Groundwater Monitoring Organization (1985) indicates shallow ground-water movement toward Antelope Creek from both the north and south sides of the stream and toward Porcupine

Creek (area A, pl. 3). Ground water moves toward the streams through the overburden and the coal beds. North of Antelope Creek, water in the coal beds also moves toward the existing mines.

Recharge to the local ground-water flow system occurs in both North and South Antelope coal-lease areas. Both lease areas contain extensive clinker outcrops that are recharge areas for local ground-water flow (area A, pl. 3). Ephemeral streamflow in Porcupine Creek (North Antelope coal-lease area) also may recharge the local flow system as it seeps through the clinker or alluvium into the coal beds.

Discharge from the local ground-water flow system also occurs in both North and South Antelope coal-lease areas. Ground water discharges from a spring near the center of the South Antelope coal-lease area (area A, pl. 3). Ground water discharges to the alluvium of Antelope Creek between the two lease areas and to the alluvium of Porcupine Creek between the tracts of the North Antelope lease area (area A, pl. 3). Information on alluvial valley floors in this area (Rusmore and others, 1985, pl. 9, 10) indicates the alluvium of Antelope and Porcupine Creeks is subirrigated; however, neither stream is perennial, so most ground-water discharge to the alluvium is lost by evapotranspiration. Some ground water also may discharge to existing mines.

The primary use of ground water in the vicinity of the North and South Antelope coal-lease areas is livestock watering and, to a lesser extent, domestic supply; however, there are no wells within either coal-lease area. Several off-site wells are located along Antelope Creek and its tributaries, but most of these wells are more than 500 ft deep and are completed well below the base of the coal beds.

The quality of ground water in the two coal-lease areas is expected to be similar to the quality of ground water in the undisturbed areas of the adjacent North Antelope and Antelope Mines. Information from surface-mining permit applications for these two mines indicates that ground-water quality generally improves with depth. Ground water in the alluvium has the highest concentrations of dissolved solids (generally greater than 2,000 mg/L) and dissolved sulfate (generally greater than 1,000 mg/L). Water quality in the overburden is extremely variable. Concentrations of dissolved solids range from less than 600 to more than 3,000 mg/L and the water generally is either a sodium bicarbonate or a calcium sodium sulfate type. Water in the coal generally is the least mineralized ground water in the area; however, the quality of water in the coal also varies with depth. Water in the upper coal generally is a sodium sulfate or sodium calcium sulfate type, with concentrations of dissolved solids commonly exceeding 2,000 mg/L, whereas water in the lower coal generally is a sodium bicarbonate type, with concentrations of dissolved solids less than about 1,600 mg/L. Ground water throughout the area generally is suitable only for livestock watering.

Mining the North Antelope and South Antelope coal-lease areas will alter the local ground-water hydrology; however, north of Antelope Creek, the effects of mining the new lease areas will be difficult to distinguish from the effects of the existing mines. Aquifers interrupted by the new mine north of Antelope Creek, including the Wyodak-Anderson coal bed, will discharge to the pit, and ground-water levels will decline in the vicinity of the mine.

Water-level declines to the east will be limited by the nearness of the clinker recharge area; water-level declines to the west will be affected more by the large existing mines. Extensive water-level declines generally have not been recorded yet at the existing mines, because mining has begun only recently. A decline in water level of 38 ft has been recorded in one well along Porcupine Creek in the North Antelope Mine permit area; however, water levels in other monitoring wells in the North Antelope and Antelope Mines have declined less than 5 ft. Declines in water levels north and south of the lease area could extend to the alluvium along Porcupine and Antelope Creeks, decreasing subirrigation of the alluvium along these streams. Mining of the South Antelope coal-lease area may decrease discharge from seeps and springs south of Antelope Creek that otherwise might be unaffected by the existing mines.

After mining, the clinker overburden of the coal-lease areas will be replaced with spoil material. Recharge to the local ground-water system likely will be decreased because the permeability of reclaimed spoil will be less than the permeability of clinker (Rahn, 1976, p. 48). After a new water table develops in the spoil, the direction of ground-water flow toward Antelope and Porcupine Creeks may be reestablished; however, the quantity of ground-water flow likely will be decreased because of the lesser permeability of the spoil.

There are no wells in the North Antelope or South Antelope coal-lease areas to be destroyed by the proposed mining. One spring in the South Antelope lease area would be destroyed. Most of the offsite wells along Antelope Creek and tributaries are more than 500 ft deep and likely will not be affected by surface mining of the Wyodak-Anderson coal. Wells that could be affected by mine dewatering include one well in the southwest quarter of section 9, T. 41 N., R. 70 W., and one well in the southwest quarter of section 25, T. 41 N., R. 70 W.

The quality of water that will be present in the spoil aquifers of the lease areas is difficult to predict. Analyses of the quality of water in the spoil aquifers at the Antelope and North Antelope Mines are not yet available. The variability in the quality of water in the alluvium, overburden, and coal beds precludes an accurate prediction of post-mining water quality. An initial estimate might be that post-mining water will be no more mineralized than the most mineralized water in the area before mining. The water likely will be a calcium sulfate or sodium calcium sulfate type, and the concentration of dissolved solids likely will exceed 2,000 mg/L. Post-mining ground-water quality likely will be such that the water is only suitable for livestock watering.

## Stevens North Coal-Lease Area

The Stevens North coal-lease area (site 10, fig. 1) is in the southwestern part of the Wyoming Powder River structural basin, about 25 mi west of Bill in northwestern Converse County. Coal-lease applications for this area have proposed mining the Badger coal bed by surface-mining methods. The Badger coal bed dips gently to the east in the lease area, with the base of the coal at an altitude of about 5,200 ft near the eastern boundary of the lease (area B, pl. 3). The coal does not crop out extensively in the lease area, and the thickness of the overburden is as much as 150 ft.

Little information is available about the shallow ground-water system in the vicinity of the Stevens North coal-lease area. Hagmaier (1971, p. 47) identified ground-water movement to the east toward the Dry Fork Cheyenne River in local and intermediate flow systems less than 500 to 1,000 ft deep. Surface drainage in the northern one-half of the lease area is toward North Fork and South Fork Bear Creek; surface drainage in the southern one-half of the lease area is toward the Dry Fork Cheyenne River. Analysis of available water-level information indicates local ground-water flow within the lease area generally follows surface drainages toward South Fork Bear Creek and Dry Fork Cheyenne River. Ground water outside the lease area generally is moving from southwest to northeast, with a significant component of flow toward the Dry Fork Cheyenne River (area B, pl. 3).

Recharge to the local ground-water flow system mostly occurs outside the coal-lease area. Recharge within the lease area is limited by a lack of coal and clinker outcrops. Recharge likely occurs where the Badger coal bed crops out near Pine Ridge west and southwest of the lease area (area B, pl. 3). The local flow system also may be recharged by ephemeral streamflow in Sand Creek and in the headwaters of the North Fork Dry Fork Cheyenne River.

Ground water in the local flow system is discharged to the alluvium of the major stream channels in and near the lease area (area B, pl. 3). Available information (Rusmore and others, 1985, pl. 10) indicates the alluvium of the Stinking Water Creek, North and South Forks Bear Creek, and Dry Fork Cheyenne River is subirrigated. However, none of the streams near the lease area are perennial; thus, most ground water in the local flow system is discharged by evapotranspiration from the alluvium of these streams.

Ground water primarily is used for livestock watering and domestic purposes in and around the Stevens North coal-lease area. Records of the U.S. Geological Survey and the Wyoming State Engineer indicate six wells are within the lease area (area B, pl. 3). An analysis of the records indicates several nearby wells outside the lease area are completed in or above the Badger coal bed.

No analyses of water quality are available for wells within the coal-lease area; chemical analyses of water from wells outside the lease area indicate that water of suitable quality for domestic use generally is available in the vicinity of the lease. Dissolved-solids concentrations in water from five wells completed in the Wasatch Formation ranged from 242 to 377 mg/L, with sodium, calcium, and bicarbonate as the major ions (Larson and Daddow, 1984, p. 22-23). More mineralized water also is present in places. Water from one well completed in the Wasatch Formation near South Fork Bear Creek contained 2,100 mg/L of dissolved solids; however, the quality of water in this well may have been affected by the quality of water in the alluvium along South Fork Bear Creek.

Mining the Badger coal bed in the Stevens North coal-lease area will alter the local ground-water system. All of the aquifers down to and including the Badger coal bed will be removed, and water levels will decline in the vicinity of the mine. Water levels will not decline below an altitude of about 5,200 ft, the altitude of the base of the Badger coal. Based on analyses of water-level changes at existing mines in the eastern part of the basin (Gillette Area Groundwater Monitoring Organization, 1985; Hasfurther and others, 1982), water-level declines will not extend more than about 5 mi from the mine to the north, west, and south. Water-level declines to the east and northeast will not extend more than 2 or 3 mi from the mine, as pre-mining water levels beyond that distance are below the altitude of the base of the coal. Water moving from recharge areas west and southwest of the lease to discharge areas east of the lease will be intercepted by the pit, causing decreased ground-water discharge to the alluvium of both forks of Bear Creek and the Dry Fork Cheyenne River.

Replacement of spoil material into the mined area may result in permanent changes in the local ground-water flow system. Initially ground water will move toward the mined area until a new equilibrium water table develops in the spoil. Recharge to the reclaimed lease area likely will be greater than before mining because the permeability of dragline-laid spoil will be greater than the permeability of undisturbed overburden (Rahn, 1976, p. 31). Within the lease area, subirrigation of the alluvium along North Fork and South Fork Bear Creek will depend on the altitude of the reconstructed stream channels and the altitude of the water table that develops in the spoil. The altitude of the water table in the spoil also may affect subirrigation of the alluvium along the South Fork Bear Creek and Dry Fork Cheyenne River outside the lease area.

Mining will destroy the six wells in the coal-lease area, and it may affect water levels in nearby wells outside the lease area. Most of the off-site wells within 2 or 3 mi of the lease area are completed in or above the coal bed, and water levels could decline because of mine dewatering. The magnitude of water-level decline will depend on the proximity of the well to the mine and on the hydraulic connection between the mine pit and the aquifer supplying the well. After mining, recovery of water levels in wells affected by mine dewatering will depend on the level of the water table that develops in the spoil.

The quality of water that will develop in the spoil aquifer is difficult to predict. At the Dave Johnston Mine south of the lease area, concentrations of dissolved solids in spoil water generally ranged from 1,500 to 4,500 mg/L and were three to six times greater than concentrations of dissolved solids in water from overburden and undisturbed coal aquifers. Assuming similar increases for the Stevens North lease area, concentrations of dissolved solids in the spoil water would range from about 700 to 2,300 mg/L. From this estimate it appears that spoil-aquifer water quality will be unsuitable for domestic consumption, but it will be suitable for livestock watering.

## Stevens South Coal-Lease Area

The Stevens South coal-lease area (site 11, fig. 1) is in the southwestern part of the Wyoming Powder River structural basin, about 18 mi north-northeast of Glenrock in northwestern Converse County. Coal-lease applications for this area have proposed mining the School coal bed by underground-mining methods. The School coal bed dips gently to the east in this area, with overburden thickness ranging from about 150 ft in the western part of the lease area to more than 300 ft in the eastern part (area B, pl. 3). The base of the School coal is at an altitude of about 5,300 ft near the eastern boundary of the lease area. The Stevens South lease area is bounded on the north and west by the existing Dave Johnston Mine.

Little information is available about the shallow ground-water system in the vicinity of the Stevens South coal-lease area. Surface drainage in the vicinity of the lease is away from the Sage Creek Divide, with water north of the divide flowing into the Dry Fork Cheyenne River, and Phillips and Brown Springs Creeks, and water south of the divide flowing into Sage Creek. Analysis of limited water-level information indicates that local ground-water flow in the vicinity of the lease generally follows the surface drainage. Within the lease-area boundaries, local ground-water flow generally is to the northeast toward Brown Springs Creek (area B, pl. 3).

Recharge to the local ground-water flow system mostly occurs outside the coal-lease area. Recharge within the lease area is limited because there are no extensive outcrops of coal or clinker in the area. The School coal bed crops out west of the Stevens South lease area in the vicinity of the Dave Johnston Mine (area B, pl. 3). Recharge to the local ground-water system likely occurs west of the lease area where streams cross coal outcrops in and around the existing mine. Reclaimed spoil material at the mine also may be a recharge area for the local flow system.

Ground water in the local flow system is discharged by springs and flowing wells and by evapotranspiration from the alluvium of the major streams near the lease (area B, pl. 3). Available information (Rusmore and others, 1985, pl. 10) indicates the alluvium of the Dry Fork Cheyenne River and Sage, Brown Springs, and Phillips Creeks is subirrigated with ground water. However, none of these streams are perennial near the lease area, so most ground-water discharge along the streams is by evapotranspiration from the alluvium. Ground water also is discharged from several springs and flowing wells along Brown Springs Creek east and northeast of the lease area.

Ground water is used for livestock watering and domestic supply in and around the Stevens South coal-lease area. Records of the U.S. Geological Survey and the Wyoming State Engineer indicate three wells are within the lease area (area B, pl. 3). Wells north and west of the lease area are within the permitted boundaries of the existing Dave Johnston Mine. Most wells south and east of the lease area are completed in or above the School coal.

No analyses of water quality are available for wells within the coal-lease area. Chemical analyses of water from wells outside the lease area indicate ground water in the vicinity of the lease generally is suitable for livestock watering, and some water is marginal for domestic use. Water-quality analyses are available for six wells completed in the Wasatch Formation, ranging in depth from 35 to 474 ft, and one spring issuing from the Wasatch within about 5 mi of the lease area. Concentrations of dissolved solids in these analyses ranged from 228 to 768 mg/L, and the dominant ions were calcium and bicarbonate. An analysis of water from one 360-ft deep well completed in the Fort Union Formation indicated a dissolved-solids concentration of 227 mg/L, and the dominant ions were calcium, bicarbonate, and sulfate (Larson and Daddow, 1984, p. 22-23).

Underground mining of the Stevens South coal-lease area could alter the local ground-water system. Mine dewatering will lower the water levels in the coal and in other aquifers hydraulically connected with the mine or the coal. Subsidence and associated fractures in the overburden also could drain perched aquifers above the coal. Because of the location between the recharge area at the existing Dave Johnston Mine and the discharge areas east of the lease, dewatering of the proposed underground mine likely will intercept local ground-water flow before it reaches natural discharge areas. Discharge from springs along Brown Springs Creek will be decreased if aquifers supplying the springs are disrupted by mining, and subirrigation of the alluvium will be decreased. A possible permanent change to the flow system after mining would be interconnection of previously isolated aquifers if subsidence of the overburden occurs.

Underground mining in the Stevens South coal-lease area could affect wells both inside and outside the lease area. Mining could destroy the three wells in the lease area if they are completed in or below the coal bed, or if they are obstructions to needed surface facilities. Subsidence from the mining operation also could destroy the wells in the lease area, even if they are completed above the coal. Mine dewatering associated with the underground operation could affect water levels in nearby off-site wells completed in the dewatered units. Again, subsidence could extend these effects to wells completed above the coal as well. Many off-site wells north, south, and west of the lease area will be destroyed or affected by the existing Dave Johnston Mine. In addition, most of the wells within 3 or 4 mi east of the lease area are completed in or above the coal and could be affected by the mining operation. Wells completed above the coal are most likely to be affected if substantial subsidence occurs in the lease area.

The quality of ground water that will occur in the lease area after mining is difficult to predict. The most likely effect on water quality of the proposed underground mining is mixing of waters from previously isolated aquifers if subsidence causes fractures in the overburden. However, available information indicates that present water quality in aquifers less than 500 ft deep in this area is fairly uniform, with concentrations of dissolved solids ranging between about 200 and 1,000 mg/L and calcium and bicarbonate as the dominant ions. Mixing of these waters should have no negative effect on the suitability of the water for livestock watering; however, water suitable for domestic consumption could be rendered unsuitable if mixed with more mineralized water.

### South Powder River Coal-Lease Area

The South Powder River coal-lease area (site 12, fig. 1) is in the southwestern part of the Wyoming Powder River structural basin, about 11 mi northeast of Glenrock in west-central Converse County. Coal-lease applications for this lease area have proposed mining the Badger and School coal beds by a combination of surface and underground mining methods. The School coal dips gently to the east in the lease area, and overburden thickness is as much as 300 ft (area C, pl. 3). The majority of the South Powder River coal-lease area is about 1 mi east of the existing Dave Johnston Mine.

Analysis of limited water-level information indicates that local ground-water flow in and around the South Powder River lease area generally follows the surface drainage toward Sage Creek (area C, pl. 3). The local flow system likely is recharged where the School coal crops out near the west boundary of the Dave Johnston Mine and in the south end of the lease area. Numerous other coal beds, including the Badger coal bed, crop out in and around the lease area and also may be recharge areas. Reclaimed spoil material at the Dave Johnston Mine also may be a recharge area for the local flow system. Discharge from the local ground-water flow system mainly occurs along Sage Creek. Available information on alluvial valley floors (Rusmore and others, 1985, pl. 10) indicates the alluvium along Sage Creek and parts of Frank Draw is subirrigated with ground water. However, Sage Creek is not perennial; thus, most ground-water discharge in the area is by evapotranspiration from the alluvium along the stream.

Ground water primarily is used for livestock watering in and around the South Powder River coal-lease area. Records of the U.S. Geological Survey and the Wyoming State Engineer indicate three wells are within lease-area boundaries. In addition, most wells east of the lease area are completed in or above the School coal bed.

No analyses of water quality are available for wells within the coal-lease area. Analysis of the quality of water from wells outside the lease area indicate that ground water in the vicinity of the South Powder River lease area is similar in quality to ground water around the Stevens South lease area. Water from three wells completed in the Wasatch Formation and a spring issuing from the Wasatch within about 5 mi of the lease area contained concentrations of dissolved solids ranging from 228 to 564 mg/L, with calcium and bicarbonate as the dominant ions. Water from a well completed in the Fort Union Formation about 3 mi from the lease area contained 227 mg/L dissolved solids, and the dominant ions were calcium, bicarbonate, and sulfate (Larson and Daddow, 1984, p. 22-23). Water in the vicinity of the lease area generally is suitable for livestock watering and domestic supply.

Surface mining in the South Powder River coal-lease area could affect the local ground-water system in much the same way as that described for the Stevens North lease area, and underground mining in the South Powder River lease area could have effects on ground water similar to those described for the Stevens South lease area. Surface mining will remove all aquifers down to and including the School coal bed, and water levels in the interrupted aquifers will decline in the vicinity of the pit. Where mining is underground, mine dewatering will lower water levels in the coal and in other aquifers hydraulically connected to the mine. Subsidence of the overburden could extend these effects to overlying aquifers, and perched aquifers could be drained. Water-level declines could extend 3 or 4 mi north of the lease area; however, water-level declines south and west of the lease area would be limited by the short distance to the coal outcrop and the existing mine. Water-level declines east of the lease area are not likely to extend more than 3 or 4 mi from the mine, as pre-mining water levels beyond that distance are below the altitude of the base of the coal in the lease area. The coal-lease area is between the recharge area to the west and the discharge area along Sage Creek, and mining the new lease will intercept some of the flow between these areas. Subirrigation of the alluvium along Sage Creek likely will be decreased.

Permanent changes in the local ground-water system will be related to the condition of the spoil and the overburden after mining. Initially ground water will move toward the mined area until a new equilibrium water table develops in the reclaimed lease area. Recharge to the lease area may be greater than before mining because the permeability of dragline-laid spoil will be greater than the permeability of undisturbed overburden (Rahn, 1976, p. 31), and because of subsidence-induced fractures in the overburden above the underground parts of the mine. Subirrigation of the alluvium along Sage Creek may return to pre-mining levels, depending on the level of the water table that develops in the reclaimed lease area. A possible permanent change in the flow system would be the interconnection of previously isolated aquifers if subsidence of the overburden occurs.

Surface and underground mining in the South Powder River coal-lease area probably will destroy the wells in the lease area and may affect water levels in nearby wells outside the lease area. Underground mining may not destroy the wells in the area if the wells are completed above the coal beds and are not obstructions to surface facilities; however, subsidence of the overburden above the underground mine could destroy the wells, even if they are completed above the coal. Mine dewatering could draw down water levels in wells outside the lease area. Most of the wells east of the lease area are completed above the School coal bed. The decline of water levels in these wells will depend on the method of mining, the distance from the mine to the well, and the hydraulic connection between the mine and the well. In areas of underground mining, water-level declines in off-site wells also may depend on the degree of subsidence in the overburden. After mining, recovery of water levels will depend on the level of the water table that develops in the reclaimed lease area.

The quality of ground water that will be present in the lease area after mining is difficult to predict. The most likely effect on water quality of underground mining is mixing of waters from previously isolated aquifers if subsidence causes fractures in the overburden; however, existing water quality in aquifers less than 500 ft deep in this area is fairly uniform, and mixing of waters should have no effect on the suitability of the water for livestock use. The quality of water in the spoil aquifer in surface-mined areas likely will be more mineralized. Concentrations of dissolved solids in spoil water at the Dave Johnston mine generally are three to six times greater than in water from undisturbed overburden and coal aquifers. Assuming similar increases in the South Powder River coal-lease area, concentrations of dissolved solids in the spoil water would range from about 700 to 3,400 mg/L. This water would be suitable for livestock use.

# SUMMARY

The geohydrology of 12 coal-lease areas in the Powder River structural basin is described in relation to the mining proposed for each area. The description of the hydrology includes identification of recharge and discharge areas, directions of ground-water movement, and possible effects of mining. Understanding the ground-water hydrology of the 12 coal-lease areas will improve the understanding of the shallow ground-water system in the basin.

The Paleocene Fort Union Formation, Eocene Wasatch Formation, and Quaternary alluvium comprise most of the surface geology of the Powder River structural basin. The most productive aquifers in the shallow ground-water system are alluvial deposits, sandstone beds, and fractured coal beds. Well yields range from less than 10 gal/min in many parts of the basin up to 1,000 gal/min from clean, coarse-grained material along some of the rivers. Water in the northern part of the basin tends to be more mineralized than water in the southern part of the basin. Median dissolved-solids concentrations for water from wells in Campbell County (northern part of the basin) were more than 1,200 mg/L compared to a median value of about 400 mg/L for water from wells in Converse County (southern part of the basin).

Local ground-water flow systems are most likely to be affected by coal mining in the lease areas. Local flow systems develop where ground water flows from a topographic high to an adjacent low and have flow paths that range in length from a few thousand to several thousand feet. Ground-water recharge generally occurs in topographically high areas, especially where these areas are capped by permeable clinker outcrops. Ground-water discharge generally occurs in topographically low areas, especially where these areas contain springs, perennial streamflow, or evidence of subirrigation.

The potential effects of coal mining in the 12 coal-lease areas include alteration of ground-water flow systems and changes in water quality. Alteration of ground-water flow systems includes disruption of recharge and discharge areas and decreased flow to wells and springs. Changes in water quality will result from chemical reactions occurring in backfill material, from hydraulic connection between previously isolated aquifers, and from coal gasification. Surface mining, proposed for 11 of the 12 lease areas, generally will affect only local ground-water flow systems. Underground mining, proposed for 3 of the 12 lease areas, and in-situ coal gasification, proposed for 1 of the 12 lease areas, also could affect intermediate and regional flow systems.

The aquifers that would be affected by mining include the alluvium and water-yielding coals and sandstones in the Wasatch and Fort Union Formations. Aquifers in formations below the Fort Union would be affected only if they are developed for water supplies for increased population or mining operations. This report considered only the hydrologic effects of the mining operation itself. Water-level declines in the coal aquifers generally will extend less than 4 or 5 mi from the mines, and water-level declines in the overburden aquifers generally will extend less than 2 or 3 mi from the mines.

Mining of lease areas that contain extensive outcrops of permeable clinker will decrease recharge to the local ground-water flow system. Some recharge will still occur because of seepage from the pit; however, most ground-water inflow will be pumped into sedimentation ponds or used for mining operations or both. Recharge in the reclaimed lease areas that contained clinker will be less than before mining because the permeability of clinker is an order of magnitude greater than the permeability of the reclaimed spoil. Lease areas that contain extensive clinker outcrops are Ulm, Wildcat Creek, Caballo, East Black Thunder, Rochelle, North Antelope, and South Antelope.

Mining of lease areas that do not contain extensive outcrops of clinker likely will increase recharge to the local ground-water flow system. The lease areas that lack substantial amounts of clinker in the overburden are Thunderbird, Thunderbird-2, Stevens North, Stevens South, and South Powder River. After reclamation, recharge to these lease areas may be greater than before mining because the permeability of dragline-laid spoil will be greater than the permeability of the undisturbed overburden.

Mining of lease areas in or near locations of ground-water discharge may decrease ground-water discharge to nearby streams, springs, and flowing wells. Ground-water discharges to perennial streams near the Ulm and Caballo coal-lease areas. Ground water discharges from springs in or near the Ulm, Wildcat Creek, Rochelle, South Antelope, and Stevens South coal-lease areas. Ground water discharges through flowing wells in or near the Thunderbird, Thunderbird-2, and Stevens South coal-lease areas. Ground water also is discharged by evapotranspiration from the alluvium along all the major streams draining the lease areas.

Surface mining will destroy the wells in the coal-lease areas and may affect water levels in nearby wells outside the lease areas. The number of wells within the lease areas ranges from no wells in three lease areas (East Black Thunder, North Antelope, and South Antelope) to 20 wells in two lease areas (Wildcat Creek and Thunderbird-2). In nearby wells outside the lease areas, water-level declines will depend on the proximity of the well to the mine and the hydraulic connection between the mine and the well. At the small coal-lease areas adjacent to large existing mines (Caballo, East Black Thunder, and North Antelope), the effects of mining the new lease areas on offsite wells will be similar to those anticipated from mining of the existing mines.

Underground mining and in-situ coal gasification also will destroy wells in the coal-lease areas and may affect water levels in nearby offsite wells. Subsidence of overburden materials above the mine cavities causes fractures in the overburden and results in interconnection of previously isolated aquifers. Perched aquifers may be drained, and associated springs and wells may go dry. Subsidence also creates depressions in the land surface that can collect water and increase recharge through the fractures.

Mining also will affect the quality of ground water available in the lease areas. Concentrations of dissolved solids in water from spoil aquifers generally are two to three times greater than in water from undisturbed coal aquifers. Increases in dissolved sulfate and calcium comprise most of the increase in dissolved solids in the spoil water. Large concentrations of dissolved solids (greater than 5,000 mg/L) or dissolved sulfate (greater than 3,000 mg/L) or both in spoil water occasionally may render the water unsuitable for livestock watering. Water suitable for domestic use generally is available only in the southern part of the basin, and mining of lease areas in this part of the basin (Stevens North, Stevens South, and South Powder River) likely will leave spoil water unsuitable for domestic use. Large selenium (greater than 0.10 mg/L) and nitrate (greater than 100 mg/L) concentrations, such as those measured in spoil water near the Caballo lease area, could render spoil water unsuitable for livestock or domestic use.

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