CUMULATIVE POTENTIAL HYDROLOGIC IMPACTS OF SURFACE COAL MINING IN THE EASTERN POWDER RIVER STRUCTURAL BASIN, NORTHEASTERN WYOMING

By Lawrence J. Martin, David L. Naftz, H.W. Lowham, and J.G. Rankl

---

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 88-4046

Prepared in cooperation with the

WYOMING DEPARTMENT OF ENVIRONMENTAL QUALITY and the

U.S. OFFICE OF SURFACE MINING

Cheyenne, Wyoming

1988

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
2120 Capitol Avenue
P.O. Box 1125
Cheyenne, WY 82003

Copies of this report can
be purchased from:

U.S. Geological Survey
Books and Open-File Reports
Federal Center, Building 810
P.O. Box 25425
Denver, CO 80225

CONTENTS

PLATES

FIGURES

TABLES

Page

CONVERSION FACTORS

For use of readers who prefer to use metric (International System) units, rather than the inch-pound units used in this report, the following conversion factors may be used:

Multiply inch-pound unit	By	To obtain metric unit
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per square mile	3,195	cubic meter per square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per foot (ft/ft)	1.0	meter per meter
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per day (gal/d)	0.003785	cubic meter per day
gallon per day per square foot [$(gal/d)/ft^2$]	0.352	liter per day per square meter
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	2.540	centimeter
inch per hour (in./h)	2.540	centimeter per hour
mile (mi)	1.609	kilometer
mile per hour (mi/h)	1.609	kilometer per hour
mile per square mile	0.62	kilometer per square kilometer
square mile (mi^2)	2.590	square kilometer
ton (short, 2,000 pounds)	0.9072	megagram
ton per square mile	0.35	megagram per square kilometer

Temperature in degrees Fahrenheit (°F) and degrees Celsius (°C) can be converted by the following equations:

$$°F = 9/5\ (°C) + 32$$

and

$$°C = 5/9\ (°F - 32).$$

CUMULATIVE POTENTIAL HYDROLOGIC IMPACTS OF SURFACE COAL MINING IN THE EASTERN POWDER RIVER STRUCTURAL BASIN, NORTHEASTERN WYOMING

By Lawrence J. Martin, David L. Naftz, H.W. Lowham, and J.G. Rankl

ABSTRACT

There are 16 existing and 6 proposed surface coal mines in the eastern Powder River structural basin of northeastern Wyoming. In addition to the areas already developed for surface coal mines or being considered for mining, there are large tracts remaining that have thick deposits of coal suitable for extraction by surface-mining methods. Coal-mining companies predict water-level declines of 5 feet or more in the Wasatch aquifer to extend from about 1,000 to about 2,000 feet beyond the mine pits. The predicted 5-foot water-level decline in the Wyodak coal aquifer generally extends 4 to 8 miles beyond the lease areas.

About 3,000 wells are in the area of potential cumulative water-level declines resulting from all anticipated mining. Of these 3,000 wells, about 1,200 are outside the areas of anticipated mining: about 1,000 wells supply water for domestic or livestock uses, and about 200 wells supply water for municipal, industrial, irrigation, and miscellaneous uses. The 1,800 remaining wells are used by coal-mining companies. According to well logs and completion reports for these wells, about 580 wells are completed in the Wasatch aquifer, about 100 in the Wyodak coal aquifer, and about 280 in aquifers below the Wyodak coal bed. Stratigraphic location of the completion interval could not be determined for about 260 wells because of lack of information on the well-completion report. Alternative sources of water that could replace the wells significantly impacted by mining operations are the Tongue River-Lebo aquifer (Fort Union Formation) for domestic and livestock supplies, and either the Tullock (Fort Union Formation) or Lance-Fox Hills (Upper Cretaceous) aquifers for uses requiring a larger yield. Although the quality of water from these alternative sources does not always meet the standard for domestic water supplies prescribed by the Wyoming Department of Environmental Quality, the quality of water approximates the quality of water currently (1987) being used for domestic supplies.

On the basis of the compiled premining (Wasatch aquifer and Wyodak coal aquifer) and postmining (spoil aquifers) water-quality data, the majority of current and future postmining water will be of suitable quality to meet the State standard for livestock watering. Future surface coal mining probably will result in postmining ground water of similar quality to that currently present in the study area. Column-leaching-test results compiled from three mines in the study area are variable depending on the type of water used in the columns (deionized versus actual ground

water) and the chemical composition of the overburden. Decreases in the concentrations of dissolved solids, nitrate, and selenium in future postmining water are predicted based on the column-leaching-test results.

Geochemical data collected at the Cordero and Dave Johnston Mines were used to predict future ground-water-quality changes and to identify reclamation methods that could minimize future postmining water-quality degradation. Isolation of overburden material with large soluble-salt contents to areas above the postmining ground-water table in conjunction with decreasing the rates of surface-water infiltration in the spoil aquifer could minimize increases in dissolved-solids concentrations in future reclaimed areas. Furthermore, isolation of spoil material with large soluble-salt contents from clay-rich and organic-rich strata during backfilling also could minimize increases in dissolved-solids concentrations in postmining ground water.

By use of geochemical-modeling techniques, the results of a hypothetical reaction-path exercise indicate the potential for marked improvements in postmining water quality because of chemical reactions as a postmining ground water with a large dissolved-solids concentration (3,540 milligrams per liter) moves into a coal aquifer with relatively small dissolved-solids concentrations (910 milligrams per liter). Results of the modeling exercise also indicate geochemical conditions that are most ideal for large decreases in dissolved-solids concentrations in coal aquifers receiving recharge from a spoil aquifer.

Infiltrometer studies indicate that reclaimed soils have, on the average, a 29-percent slower infiltration rate than that of undisturbed soils. In addition, the data indicate a trend for the infiltration rates to return to premining rates. For the purpose of computing the effective change in infiltration, it was assumed that runoff had an inverse corresponding rate. The computation of runoff using disturbed areas for all anticipated mining is a worst-case condition and indicates a maximum increase in runoff of 7.6 percent for Coal Creek and 5.3 percent for Little Thunder Creek. The remainder of the drainage basins analyzed for the worst-case condition had increases in runoff of less than 5 percent.

Analyses of changes in sediment yield are limited due to a lack of data; therefore, predictions of cumulative changes in sediment yield are subjective. The larger sediment yield from reclaimed soils probably will not be conveyed to the streams in the basins due to sediment deposition as a result of flatter slopes on re-constructed hillsides and sediment entrainment by sediment-settling ponds.

Postmining drainage networks and stream channels have been and are being designed with attention to existing geomorphic conditions and accepted engineering principles. In general, re-constructed stream and valley slopes are and will be consistent with natural conditions for the area; however, re-constructed drainage basins have and will have fewer streams than natural basins. Although additional first-order channels likely will form in the reclaimed basins, the practice of re-constructing only higher-order major channels is believed to have advantages of: (1) Allowing flatter hillslopes with resulting greater re-vegetation success, and (2) providing smaller sediment yields than if drainage networks were fully re-constructed to premining densities.

INTRODUCTION

The Wyoming Department of Environmental Quality, Land Quality Division, in cooperation with the U.S. Office of Surface Mining, Department of the Interior, is required to assess the probable cumulative impacts of current and anticipated mining on the ground- and surface-water systems each time a mine-permit application is made. The assessment is required by the Surface Mining Control and Reclamation Act of 1977 (Public Law 95-87) and Wyoming Department of Environmental Quality, Land Quality Division, Rules and Regulations (Wyoming Department of Environmental Quality, 1986).

The Wyoming Deoartment of Environmental Quality is assessing the potential cumulative impacts of surface coal mining in the eastern Powder River structural basin (hereinafter referred to as the eastern Powder River basin). In order to provide the hydrologic information needed to assess the cumulative impacts of all anticipated mining in sufficient detail, the U.S. Geological Survey, in cooperation with the Wyoming Department of Environmental Quality and the U.S. Office of Surface Mining, conducted a study of the hydrology of the eastern Powder River basin.

Purpose and Scope

The purpose of this report is to describe the cumulative effects of all current (1987) and anticipated surface coal mining on the hydrologic system in the eastern Powder River basin, Wyoming (fig. 1). Specific objectives of the study, which was conducted during 1986-87, included the following:

1. Determine the potential, cumulative ground-water-level declines in the overburden (Wasatch aquifer) and the coal (Wyodak aquifer) as a result of surface coal mining at existing (1987) and proposed mines and the effects of declines on ground-water use.

2. Determine the availability and quality of alternative ground-water supplies not disturbed by surface coal mining.

3. By use of existing data from surface coal mines in the study area, define the current premining (Wasatch aquifer and Wyodak coal aquifer) and postmining (spoil aquifer) ground-water quality, identify chemical constituents that exceed water-use criteria, and evaluate future ground-water-quality monitoring needs.

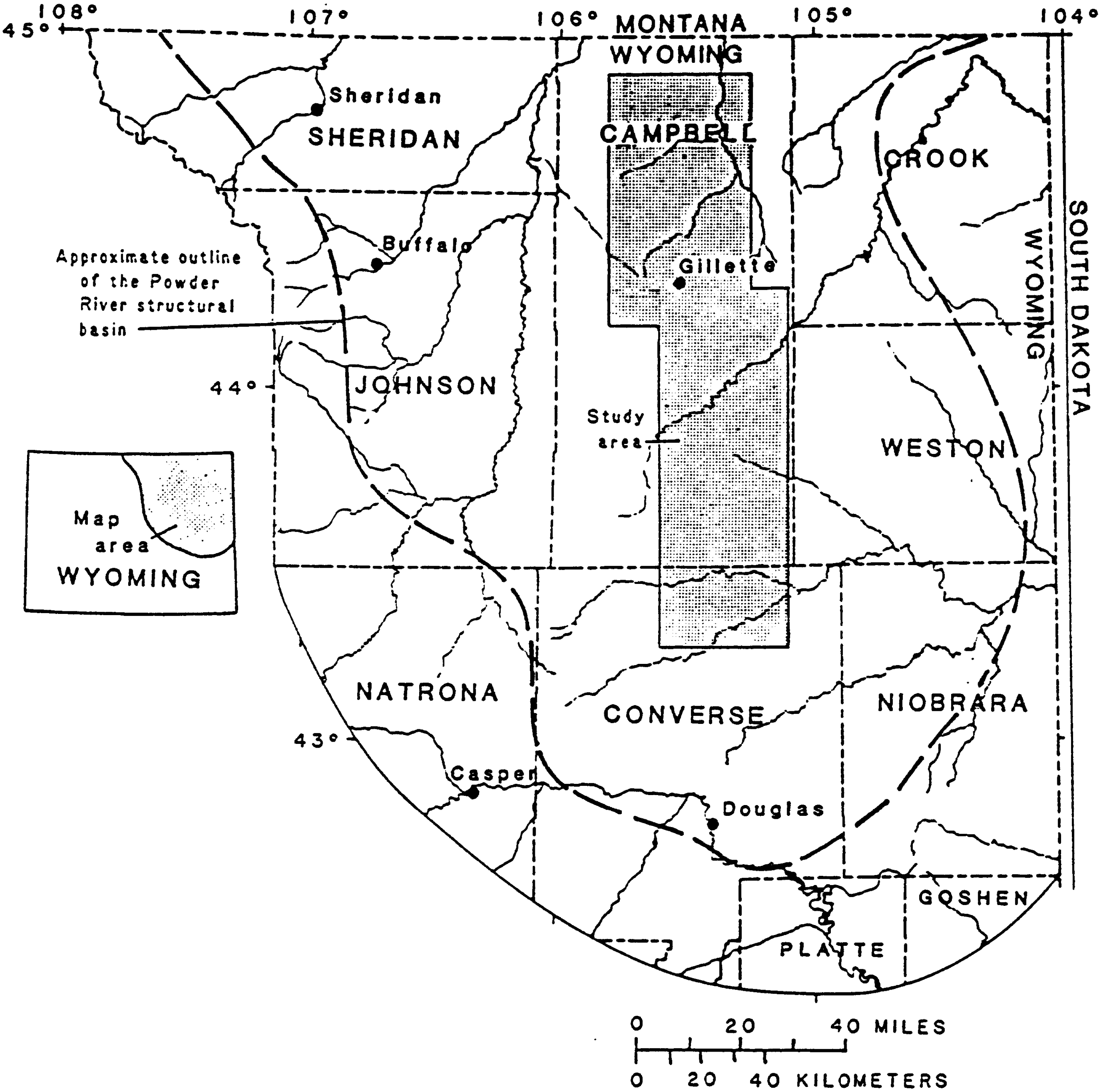


Figure 1.--Location of the study area and the Powder River structural basin in Wyoming.

4. By use of existing data from batch-mixing and column-leaching experiments, evaluate their predictive capabilities for selected chemical constituents.

5. By use of detailed and site-specific geochemical data from two surface coal mines, define the possible geochemical reactions that control the postmining water quality in the coal and spoil aquifers, investigate possible future ground-water-quality changes in coal and spoil aquifers, and identify reclamation methods that could minimize future postmining water-quality degradation in the spoil aquifer.

6. By use of geochemical-modeling techniques to determine hypothetical reaction paths, estimate possible water-quality changes that might occur in the coal aquifer as a result of offsite movement of postmining ground water from a spoil aquifer.

7. Determine if a significant change in runoff will occur in the Little Powder, Belle Fourche, and Cheyenne River drainage basins as a result of surface coal mining.

8. Determine whether surface coal mining will cause either an increase or decrease in sediment yield.

9. Determine if postmining drainage networks and stream channels will be stable by evaluating the stability of reclaimed drainages.

Previous Investigations

A narration about the eastern Powder River basin is published in the Wyoming Geological Association 13th Annual Field Conference Guidebook (Wyoming Geological Association Guidebook Committee, 1958). The guidebook contains the geologic history of the area, the stratigraphy of the underlying rocks, the economic importance of the mineral resources, and a general bibliography.

A hydrologic study of the area by Hodson and others (1973) describes the general geology, availability of ground water, chemical quality of the ground water, and streamflow characteristics. Breckenridge and others (1974) provide a synoptic view of the geology, hydrology, land use, and mineral resources of the area.

Koch and others (1982) investigated the regional effects of surface mining on the ground-water system in the eastern Powder River basin. This investigation, funded by the U.S. Bureau of Mines, used computer-based models to simulate ground-water flow, surface-water flow, and water quality.

A comprehensive report by Lowry, Wilson, and others (1986) summarizes the hydrology of the entire Powder River drainage basin and parts of adjacent drainage basins. It is one of a series of reports by the U.S. Geological Survey that resulted from a nationwide program to summarize the hydrology of areas within the major coal provinces of the United States.

Bloyd and others (1986) investigated the effects of surface coal mining on the surface- and ground-water systems in the eastern Powder River basin. A computer model of surface-water flow in the Belle Fourche River drainage basin was developed and physical characteristics of 102 drainage subbasins in the area were determined. Premining and postmining ground-water quality data also were compiled from selected mines in the basin.

A map of the premining potentiometric surface for the Wyodak-Anderson coal bed in Campbell County was constructed by Daddow (1986). The potentiometric surface indicates ground-water movement is from the coal outcrops toward the north and northwest and that the coal bed is recharged along its outcrop.

Rankl and Lowry (in press) looked for evidence of regional ground-water discharge to streams in the area. 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.

Fogg and others (in press) identified recharge and discharge areas, directions of ground-water movement, and possible effects of mining for 12 coal-lease areas in the Powder River structural basin. Their study concluded that surface coal mining would affect only local ground-water flow systems. Potential effects include alteration of ground-water flow systems and changes in water quality.

Acknowledgments

The authors express their gratitude to the hydrology staff of the Wyoming Department of Environmental Quality, Land Quality Division, for their assistance with data retrieval and knowledge of mining activities in the study area. Assistance from the Gillette Area Groundwater Monitoring Organization (GAGMO) and company hydrologists at the coal mines in the study area was invaluable and is much appreciated.

This study was funded by the U.S. Geological Survey, the Wyoming Department of Environmental Quality, and the U.S. Office of Surface Mining. This report does not necessarily reflect the views of the Wyoming Department of Environmental Quality, or the U.S. Office of Surface Mining.

GEOGRAPHIC AND GEOLOGIC SETTING

Climate

The climate of the study area is temperate and semiarid, with considerable variations in temperature and precipitation between winter and summer seasons. The growing season is short, averaging about 120 days between the last spring and first fall freezes.

During the winter, average daily minimum temperatures range between 5 °F and 40 °F. However, nighttime temperatures commonly may be less than 0 °F and daytime temperatures may be as much as 50 °F. Summers generally are mild with short periods of temperatures exceeding 100 °F. The mean maximum daily temperature for July is 90 °F. Nights usually are cool despite high daytime temperatures.

Average annual precipitation ranges from 11 in. in the southern part of the study area to 18 in. in the north. More than two-thirds of the annual precipitation occurs as rainfall between March and August of the average year. About one-third of the annual precipitation is snowfall. The average annual snowfall of 50 in. is well distributed through the winter but is greatest during December.

Prevailing winds in the study area are from the northwest. Maximum wind velocities commonly occur in the spring. Wind velocity averages about 14 mi/h annually, ranging from an average of 10 mi/h during July and August to an average of 16 mi/h during November through April.

Topography and Drainage

The eastern Powder River basin lies within the unglaciated part of the Missouri Plateau of the Northern Great Plains. The entire study area is within the drainage basin of the Missouri River. The Little Powder River flowing northward, and the Belle Fourche and Cheyenne Rivers flowing eastward are the main tributaries draining the study area. Elevations in the Little Powder drainage basin range from 3,600 ft above sea level along the Little Powder River to about 4,800 ft on the ridges, from 4,400 ft along the Belle Fourche River to 5,000 ft on the prairie, and from 4,400 ft along the Cheyenne River to 4,800 ft on the uplands. The larger stream valleys are deeply eroded and have wide, flat floors and broad floodplains. The landscape is dominated by plains and low-lying hills and tablelands, interrupted by entrenched river valleys and isolated, flat-topped buttes and mesas, and long narrow divides and ridges that are from 100 to 500 ft above valley floors.

The streams draining the study area are described by Rankl (1986a):

> The channel bottom of the Little Powder River consists of clay, silt, and some clinker gravel. The stream is perennial. The Belle Fourche and the Cheyenne Rivers originate in and drain an area underlain by continental deposits of shale, sandstone, and coal. The channel of the Belle Fourche River is relatively narrow, has a silt and clay bottom, and in places is grass covered. The ground-water table is intercepted by the channel in many reaches, thus forming pools, but very little ground water is contributed to streamflow. The channel of the Cheyenne River and its major tributaries have wide sand channels and flow is ephemeral.

Most of the tributaries to the Little Powder, Belle Fourche, and the Cheyenne Rivers are ephemeral, and streamflow results from rainstorms and melting snow.

Soil Characteristics and Vegetation

Soils in the study area have developed under the short-grass vegetative cover common to the semiarid Great Plains. Due to prevailing climatic and vegetative conditions, organic matter accumulates slowly, and soils have developed with light-colored surfaces. Subsoil colors are normally light brown or reddish brown, and substratum colors are commonly affected by white, powdery, limey carbonate accumulations caused by minimal precipitation and insufficient leaching. Soils are mostly residual (developed in place) and formed from weathered sedimentary bedrock, which is commonly sandstone and shale.

On gently rolling uplands, slightly altered bedrock usually is not more than 36 in. below the land surface. On more rolling lands, the depth to bedrock is about 20 to 30 in. On steep slopes, only a few inches of soil or soil material overlies the partly weathered bedrock. Rock outcrops are common on the steep slopes.

Developed soils have characteristics similar to the bedrock. Areas of sandy and medium-textured friable soils are underlain by sandstone and sandy shale. Dense clay soils are underlain by clay shale.

The natural vegetation in the study area is a mixture of grasses and shrubs. Common plants include prairie sandreed grass, needleandthread grass, western wheatgrass, blue gramma grass, little bluestem grass, big sagebrush, and greasewood (Peterson, 1986, p. 20). Cottonwood trees commonly grow along the streams.

Geology

The geologic units of interest in this study are the relatively shallow units stratigraphically above the Pierre Shale of Cretaceous age. These geologic units, in ascending order, are the Fox Hills Sandstone and Lance Formation of Late Cretaceous age, the Fort Union Formation of Paleocene age, the Wasatch Formation of Eocene age, and alluvium of Pleistocene and Holocene age. The outcrop areas of these units are shown in figure 2.

The Fox Hills Sandstone and Lance Formation consist of fine- to medium-grained sandstone interbedded with sandy shale. The Fort Union Formation consists of the Tullock, Lebo, and Tongue River Members in ascending order. The Tullock Member consists principally of interbedded medium- to light-gray shale and light-gray, fine-grained sandstone and siltstone. Thin coal beds in the Tullock Member grade upward into light-gray sandy or silty shale and locally resistant sandstone. The Lebo Member is predominantly dark shale and concretionary sandstone with siltstone, and locally thin coal beds. The Tongue River Member consists of light-yellow to light-gray, fine- to medium-grained, thick-bedded to locally massive cross-bedded and lenticular sandstone and siltstone interbedded with gray and black shale. South of the Belle Fourche River, the Lebo Member is equivalent to the Lebo and Tongue River Members of the Fort Union Formation in the northern part of the eastern Powder River basin (Denson and others, 1978).

Many thick and laterally persistent coal beds are present in the Tongue River Member. However, the only major coal bed that is presently (1987) mined is the Wyodak coal bed. The Wyodak coal bed has been correlated in many parts of the eastern Powder River 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. Because of correlation problems, the Wyodak coal bed was erroneously called the Roland-Smith coal bed in some reports. North of Gillette, the Wyodak coal bed separates into an upper Wyodak and lower Wyodak (Glass, 1986a, p. 26). 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, sheet 1). The Wyodak also separates into the Anderson and Canyon coal beds south and west of Gillette (Glass, 1986a, p. 26-27). Clinker, which consists of fractured shale, siltstone, and sandstone that have been baked by the burning of underlying coal beds, is present near the coal outcrops (Lewis and Hotchkiss, 1981; Love and Christiansen, 1985).

The Wasatch Formation consists of brownish-gray, fine- to coarse-grained lenticular sandstone interbedded with shale and coal. Coal beds occur in the lower part of the Wasatch Formation. Clinker also occurs near the coal outcrops (Lewis and Hotchkiss, 1981; Love and Christiansen, 1985).

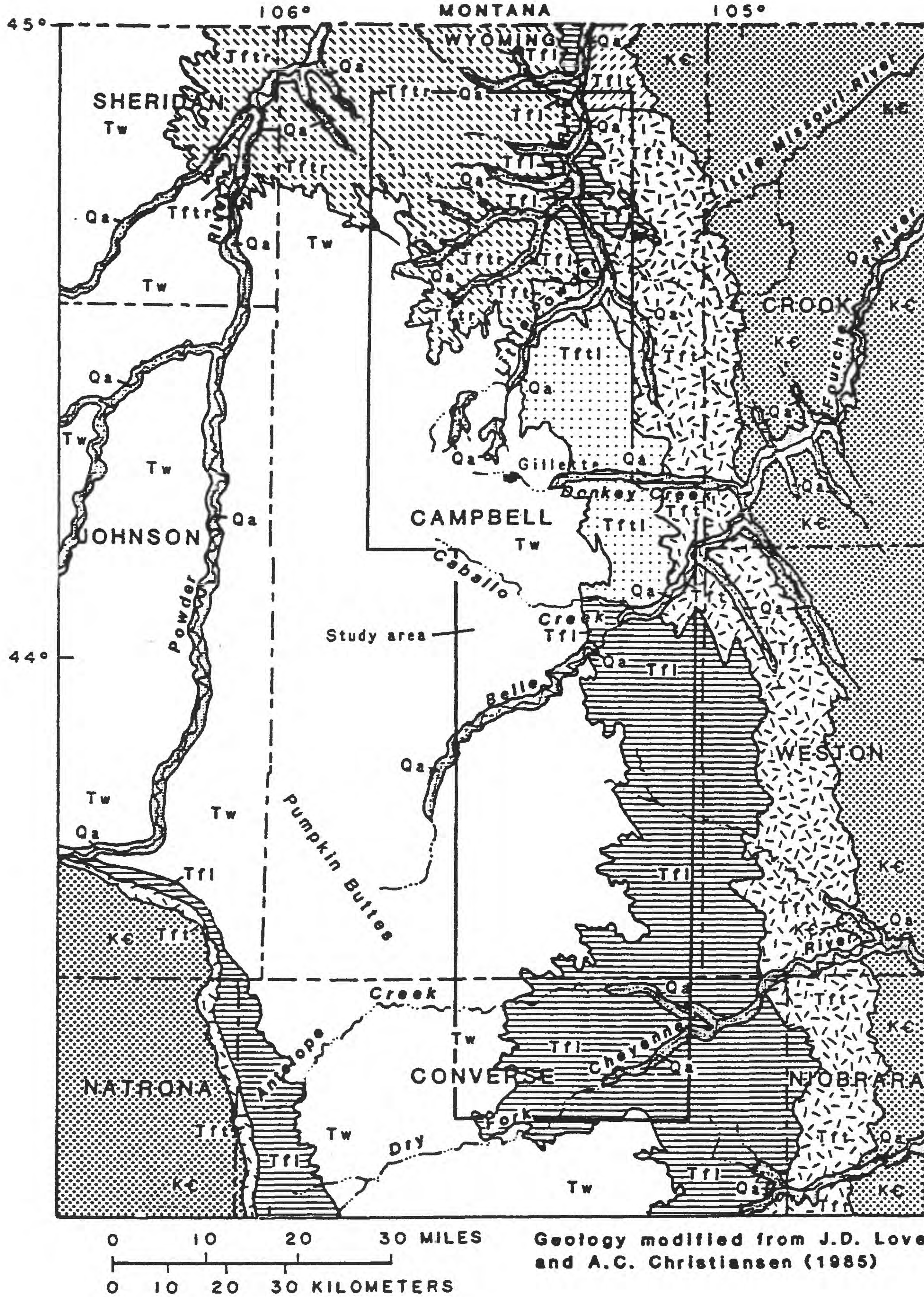


Figure 2.--Surficial geology within and adjacent to the study area.

The Fort Union and Wasatch Formations consist of continental-type sediments deposited in fluvial, lacustrine, and swampy environments. Consequently, the strata of these formations are alternating sandstone, siltstone, and mudstone, with occasional coal. The strata are lenticular and seldom correlate for more than short distances in any direction. The Fort Union Formation is less variable lithologically than the Wasatch Formation; lenses and channels of sandstone are common in the Wasatch. Coal beds are thicker and more numerous in the Fort Union than in the Wasatch. Local custom among the coal-mining companies has been to consider the top of the thick Wyodak coal bed as being equivalent to the top of the Fort Union Formation. For this report, the top of the Wyodak coal bed is assumed to be the contact between the Fort Union and Wasatch Formations.

The alluvium consists of unconsolidated deposits of silt, sand, and gravel. Generally fine to medium grained, the alluvial deposits may be coarser grained in the valleys of the Belle Fourche and Little Powder Rivers (Hodson and others, 1973).

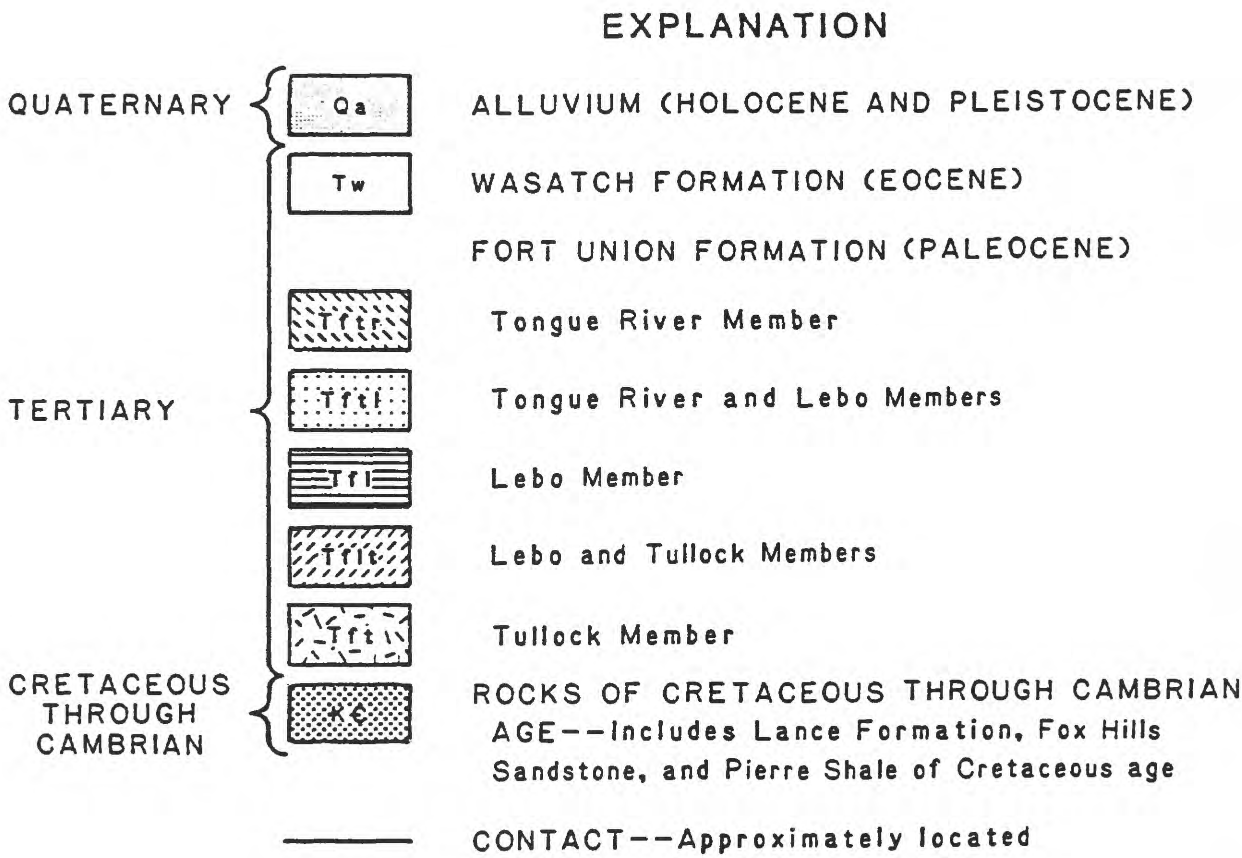


Figure 2.--Continued.

SURFACE COAL MINING

Coal in the eastern Powder River basin is extracted by surface-mining methods. Topsoil is removed from areas in advance of overburden removal and stockpiled for later use in reclamation. After removal of the topsoil, overburden is excavated down to the coal. After being excavated, the overburden is referred to as spoil. Thickness of the overburden at existing and proposed mines generally ranges from as little as several feet to as much as 300 ft. During the initial stages of pit excavation, the overburden is placed in spoil piles near the perimeter of the mine. After the overburden has been removed, the coal is blasted and hauled by truck or conveyors to railroad-loading facilities. After completion of mining, the overburden spoil piles are used to fill in the final pit. As mining progresses, reclamation takes place where mining has been completed. Mined areas are backfilled with overburden material from areas being mined and are then re-contoured and re-vegetated. A typical mining and reclamation process is illustrated in figure 3.

Even though the volume of the overburden increases as it is broken and disturbed during mining, the increase in volume of the overburden used as backfill generally is not sufficient to compensate for the removal of the thick coal beds. The final result generally is a lowering and flattening of the land surface after mining and reclamation are completed.

Existing Mines

Currently (1987), 16 surface coal mines are operating in the eastern Powder River basin (table 1). The mines are aligned along a northerly trend approximately coincident with the coal outcrop. The lease areas for the existing mines are shown on plate 1. Mining at the Wyodak Mine began in 1922. The remainder of the mines started operations during the 1970's and 1980's. The projected completion dates of existing surface mines range from 1996 (Buckskin Mine) to 2026 (Caballo Mine). Projected completion dates may change due to fluctuations in market conditions and the demand for low-sulfur, subbituminous coal. The projected maximum areas to be disturbed by existing surface coal mines range from 959 to 13,217 acres. The projected completion dates and maximum areas to be disturbed are from mine-permit applications on file with the Wyoming Department of Environmental Quality.

Proposed Mines

Six additional surface coal mines in the eastern Powder River basin are proposed (table 2). Permits have been issued by the Wyoming Department of Environmental Quality for five of these mines. The other proposed mine has a mine-permit application pending with the Wyoming Department of Environmental Quality. The lease areas for these proposed mines are shown on plate 1. There is one other lease area (Peabody) listed in table 2 and shown on plate 1 for which a mine-permit application for surface coal mining has not been made.

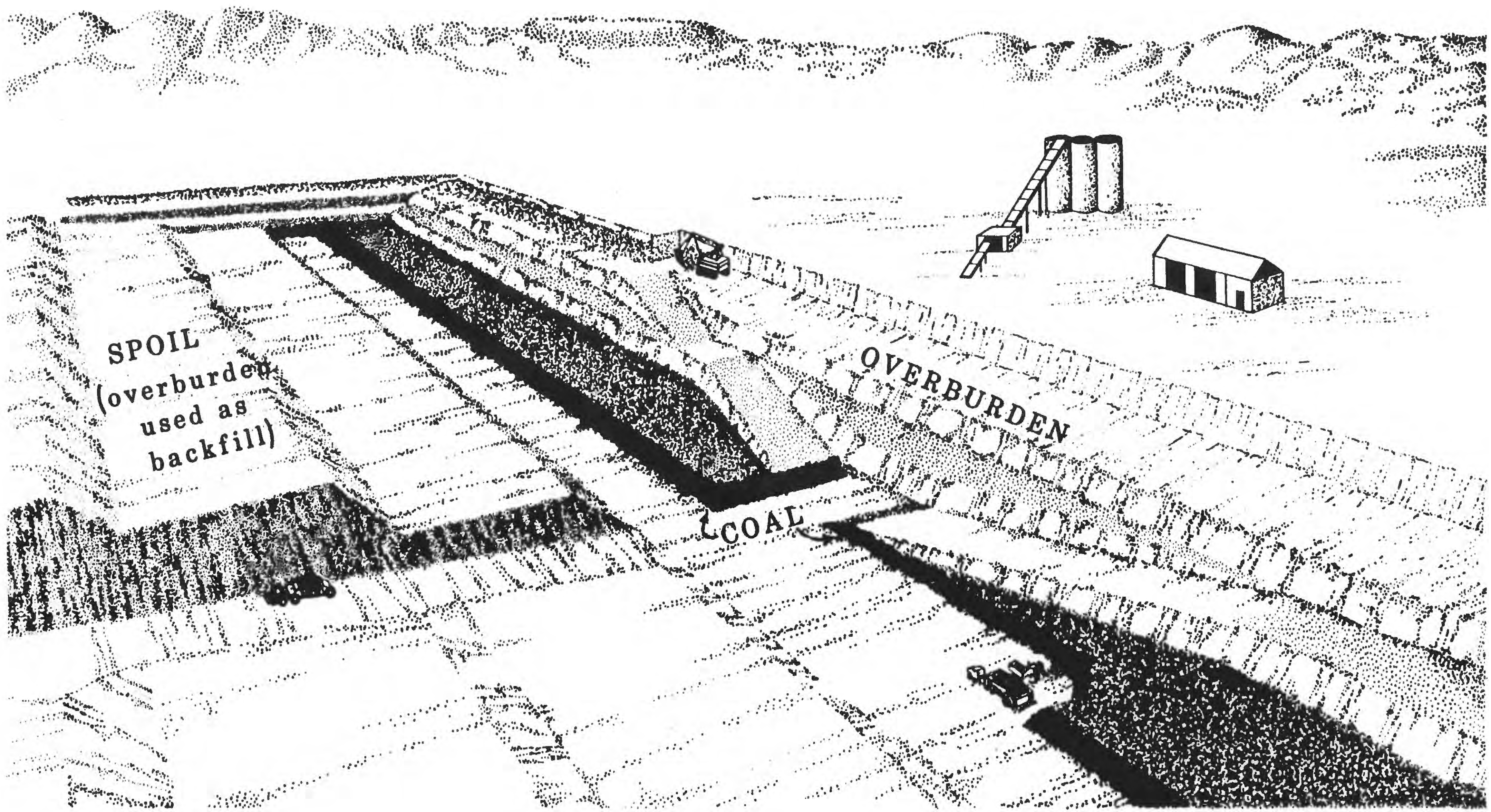


Figure 3.--Typical mining and reclamation operations.

Table 1.--Existing surface coal mines[1]

Mine name	Permit number	Start-up date	Projected completion date	Area disturbed by mining (acres)	
				End of 1986	Projected maximum
Antelope	525	1982	2011	338	4,896
Belle Ayr	214	1973	2016	2,495	4,250
Black Thunder	233	1974	2018	2,817	13,217
Buckskin	500	1980	1996	760	959
Caballo	433	1977	2026	1,199	9,104
Caballo Rojo	511	1981	2007	815	4,922
Clovis Point	447	1977	2000	672	1,067
Coal Creek	483	1979	2011	1,047	8,310
Cordero	237	1974	2006	1,631	7,102
Eagle Butte	428	1976	2019	1,337	4,759
Fort Union	486	1979	2019	217	2,454
Jacobs Ranch	271	1975	2005	2,253	4,687
North Antelope	532	1982	2019	667	2,792
Rawhide	240	1974	2004	1,296	4,921
Rochelle	569	1984	2017	196	5,285
Wyodak	232	1922	2014	572	1,720

[1] Data from mine-permit applications, Wyoming Department of Environmental Quality.

Table 2.--Proposed surface coal mines including mines that have been granted permits, but that have not been constructed[1]

[--, not applicable]

Mine name	Permit number	Start-up date	Projected completion date	Area disturbed by mining (acres)	
				End of 1986	Projected maximum
Dry Fork	599	--	2020	--	2,905
East Gillette	581	--	2011	--	2,603
Keeline	602	--	2009	--	4,692
North Rochelle	550	1985	2011	4	3,271
Peabody Lease[2]	--	--	--	--	4,000
Rocky Butte	--	--	2002	--	1,054
Wymo	540	--	1995	--	750

[1] Data from mine-permit applications, Wyoming Department of Environmental Quality.

[2] The Peabody Lease is an area that has been leased for coal mining; however, a mine-permit application has not been filed with the Wyoming Department of Environmental Quality. Therefore, it is not counted as a proposed mine in the text of this report.

Other Areas Considered for Mining

Additional areas being considered for surface coal mines in the eastern Powder River basin can be grouped in two categories: Selected Coal Tracts and areas with Preference Right Lease Applications (table 3). A Selected Coal Tract is an area that has been evaluated by the U.S. Bureau of Land Management for inclusion in future competitive leasing. Generally, each Selected Coal Tract would constitute an individual mine. Areas with Preference Right Lease Applications were claimed by specific companies prior to the beginning of the competitive-leasing system now used. Generally, Preference Right Lease Applications are small areas that would be appended to existing mines. Locations of Selected Coal Tracts and Preference Right Lease Applications are shown on plate 1.

Table 3.--Selected Coal Tracts and Preference Right Lease Applications

Name	Area[1] (acres)
Selected Coal Tracts	
Calf Creek	7,050
Donkey Creek	3,270
Hay Creek	5,370
Kintz Creek	4,200
Mount Logan	6,805
Porcupine	720
Ridgerunner	5,396
Rochelle Hills	6,625
Rockpile	5,585
Roundup	5,890
Thundercloud	4,525
Timber Creek	3,750
Wildcat	4,085
Preference Right Lease Applications	
Caballo	480
East Black Thunder	90
Rochelle	2,250
South Antelope	820
Wildcat Creek	10,450

[1] Data from U.S. Bureau of Land Management, Casper office.

In addition to the areas already being mined or being considered for development, large tracts remain that have thick deposits of coal suitable for extraction by surface-mining methods. These large tracts probably will not be developed in the near future unless there is a substantial increase in the demand for coal. It should be recognized, however, that these tracts do exist and may be developed as the existing mines are mined to completion. Additional tracts may be added to existing lease areas by noncompetitive lease modifications. Because the size, location, and time of acquisition can not be predicted, these tracts are generically referred to in this report as areas of possible future mining.

Definition of "All Anticipated Mining"

One of the requirements of the Surface Mining Control and Reclamation Act of 1977 (SMCRA) is that the regulatory agency assess the probable cumulative impacts of "all anticipated mining" in the region to assure that proposed mining operations have been designed to prevent material damage to the hydrologic balance outside the permit area of the proposed mine.

In its broadest context, "all anticipated mining" could include all surface mining in a north-trending strip bounded on the east by the coal outcrop and on the west by an arbitrary economic limit (for example, 300 ft of overburden). Analysis of impacts from mining such a large area would require many assumptions and generalizations by the investigators. The result would be a nebulous report of limited use to the regulatory agencies.

For the purposes of this study, "all anticipated mining" is defined as the existing (1987) and potential surface coal mining in the lease areas, Selected Coal Tracts, and areas with Preference Right Lease Applications. The quantity of detailed hydrologic data varies considerably for each of the types of areas. Lease areas have large amounts of data readily available in mine-permit applications submitted to the Wyoming Department of Environmental Quality. Site-specific data for Selected Coal Tracts are almost never available. Limited data are available for areas with Preference Right Lease Applications.

In order to maintain the level of detail needed in this report, the study was conducted using data primarily from existing lease areas and mine plans. Hydrologic conditions for Selected Coal Tracts and areas with Preference Right Lease Applications, by default, are addressed with less certainty. Because they are in the same general area as lease areas, hydrologic conditions are assumed to be the same as in lease areas. The level of analysis in each area varies with the availability of hydrologic data. Estimations and assumptions need to be made for areas where site-specific hydrologic data are not available.

HYDROGEOLOGY

The ground-water system occurs predominantly in a matrix of lenticular sandstone and siltstone beds interbedded with shale and coal, which results in discontinuous aquifers of limited areal extent. For this report, the hydrogeologic units of interest are the aquifers in stratigraphic units overlying the Pierre Shale. In descending order, these aquifers are the Wasatch aquifer, Wyodak coal aquifer, Tongue River-Lebo aquifer, Tullock aquifer, and the Lance-Fox Hills aquifer. The relation between stratigraphic units and hydrogeologic units is shown in figure 4.

The Wasatch aquifer consists primarily of discontinuous lenticular sandstone beds and sand channels surrounded by siltstone and shale. The siltstone and shale may be saturated and static water levels may be at the same elevation as in the adjacent sand deposits. However, wells completed in the siltstone and shale generally will not yield sufficient quantities of water to consider the material as an aquifer. Transmissivity of the Wasatch aquifer is typically less than 13 ft^2/d and commonly is less than 1.3 ft^2/d. Wells completed in the sandstone beds and sand channels may yield from 10 to 50 gal/min in the northern part of the basin and as much as 500 gal/min in the southern part of the basin (Hodson and others, 1973, pl. 3). Quaternary alluvium is present in most stream valleys in the study area. In this study, the aquifers in alluvial deposits are defined as being part of the Wasatch aquifer.

The Wyodak coal bed is the most continuous hydrogeologic unit in the study area. Water in the Wyodak coal bed is confined between a shale forming the basal sequence of the overlying Wasatch Formation and a thick shale sequence directly underlying the coal. The Wyodak coal aquifer consists of the Wyodak coal bed and associated coal beds where the Wyodak splits and separates into multiple beds, interbedded sandstone beds, and clinker beds along the coal outcrop. Flow of water in the coal is affected in places where the coal bed separates to form two or more coal beds with interbedded claystone, shale, or sandstone. Flow in the coal also may be affected by differences in aquifer properties caused by differences in the distribution and density of fractures in the coal. Solid coal is virtually impermeable. Permeability is imparted to the coal as a result of fracturing and is dependent on the degree of fracturing. The Wyodak coal bed is an anisotropic aquifer with flow occurring through fractures in the coal bed. Transmissivity of the Wyodak coal aquifer is typically less than 134 ft^2/d. Wells completed in the Wyodak coal aquifer generally yield from 10 to 50 gal/min (Hadley and Keefer, 1975, sheet 1).

The Tongue River-Lebo aquifer consists of sandstone lenses in a predominantly shale and siltstone matrix. Transmissivity of sandstone lenses comprising the Tongue River-Lebo aquifer generally ranges from 10 to 75 ft^2/d. Wells completed in the Tongue River-Lebo aquifer will yield adequate quantities of water for domestic and livestock use if a sufficient thickness of saturated sandstone lenses is penetrated. The thick shale sequence underlying the Wyodak coal hydrologically isolates the Tongue River-Lebo aquifer from impacts due to dewatering of mine pits in the Wyodak coal aquifers.

Erathem	System	Series	Stratigraphic Unit		Hydrogeologic Unit
Cenozoic	Quaternary	Holocene and Pleistocene	Alluvium		Wasatch aquifer
	Tertiary	Pliocene			
		Miocene			
		Oligocene			
		Eocene	Wasatch Formation		
					Confining unit
		Paleocene	Fort Union Formation	Wyodak coal bed	Wyodak coal aquifer
					Confining unit
				Tongue River Member	Tongue River-Lebo aquifer
				Lebo Member	
				Tullock Member	Tullock aquifer
Mesozoic	Cretaceous	Upper	Lance Formation		Lance-Fox Hills aquifer
			Fox Hills Sandstone		
			Pierre Shale		Confining unit

Figure 4.--Relation of stratigraphic units to hydrogeologic units.

The Tullock aquifer consists of fine-to-medium grained sandstone beds and thin coal beds interbedded with siltstone, shale, and carbonaceous shale. Sandstone beds in the Tullock tend to be coarser and more massive than those in the overlying Tongue River-Lebo aquifer. Transmissivity of the Tullock aquifer generally ranges from 200 to 400 ft^2/d. Yields of 200 to 300 gal/min are available from wells completed in the Tullock. Most of the wells for facilities at coal mines are completed in the Tullock.

The Lance-Fox Hills aquifer consists of numerous lenticular beds of massive sandstone isolated by interbedded shale and siltstone. Transmissivity generally ranges from about 10 to 250 ft^2/d. Wells completed in the Lance-Fox Hills aquifer generally yield several hundred gallons per minute. However, few wells in the study area are completed in the Lance-Fox Hills because it lies 2,500 to 3,000 ft below the land surface. This aquifer is utilized for water supplies in waterflood operations at oil fields in Campbell County and for municipal supplies at Gillette.

Hydraulic Conductivity

Site-specific determinations of hydraulic conductivity have been made by coal-mining companies. These data have been reported to the Wyoming Department of Environmental Quality as part of the mine-permit applications. Data for hydraulic conductivity of the Wasatch aquifer and the Wyodak coal aquifer were obtained from these applications. Results of aquifer tests were available for 203 tests using wells completed in the Wasatch aquifer and 357 tests using wells completed in the Wyodak coal aquifer. Values of hydraulic conductivity were determined by several aquifer-test methods including multiple- and single-well drawdown and recovery tests, and slug tests.

In order to check the validity of aquifer-test results reported in the mine-permit applications, a representative sample of aquifer tests was selected for re-analysis. Data from 39 aquifer tests of the Wyodak coal aquifer involving 63 wells were re-analyzed to ascertain the reliability of the reported aquifer-test results. Results of the re-analysis of aquifer-test data were not substantially different from those originally reported by the coal-mining companies.

The logs of hydraulic-conductivity values from aquifer tests using wells completed in the Wasatch aquifer and Wyodak coal aquifer are plotted as histograms in figures 5 and 6. The log values of hydraulic conductivity were used to normalize the hydraulic-conductivity data from markedly skewed arithmetic distributions. The hydraulic conductivity of the Wasatch aquifer has a log normal distribution with a geometric mean of -0.685 (0.2 ft/d). The frequency distribution of hydraulic conductivity in the Wyodak coal aquifer approximates a log normal distribution with a geometric mean of -0.09 (0.8 ft/d). Rehm and others (1980, p. 554) report a geometric mean from 70 aquifer tests using wells completed in sandstone (overburden) as 0.35 ft/d and from 63 aquifer tests using wells completed in siltstone and claystone (also in overburden) as 0.007 ft/d. They also report a geometric mean of hydraulic conductivity from 193 coal-aquifer tests conducted in Wyoming, North Dakota, and Montana as 0.9 ft/d.

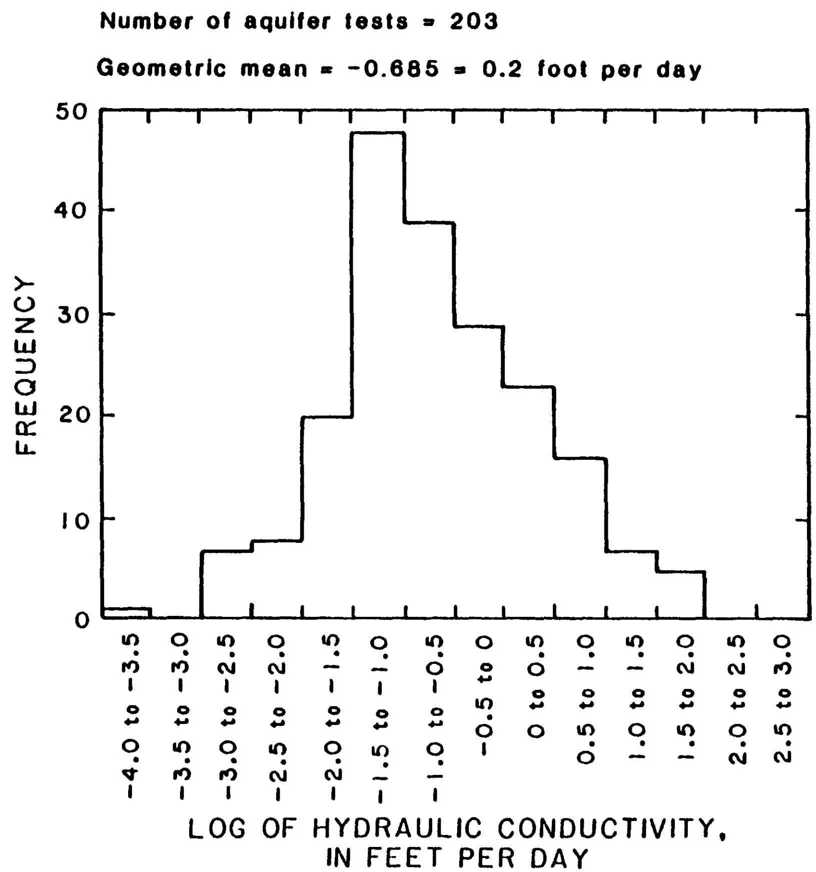


Figure 5.--Frequency distribution of the logs of hydraulic-conductivity values from aquifer tests of the Wasatch aquifer.

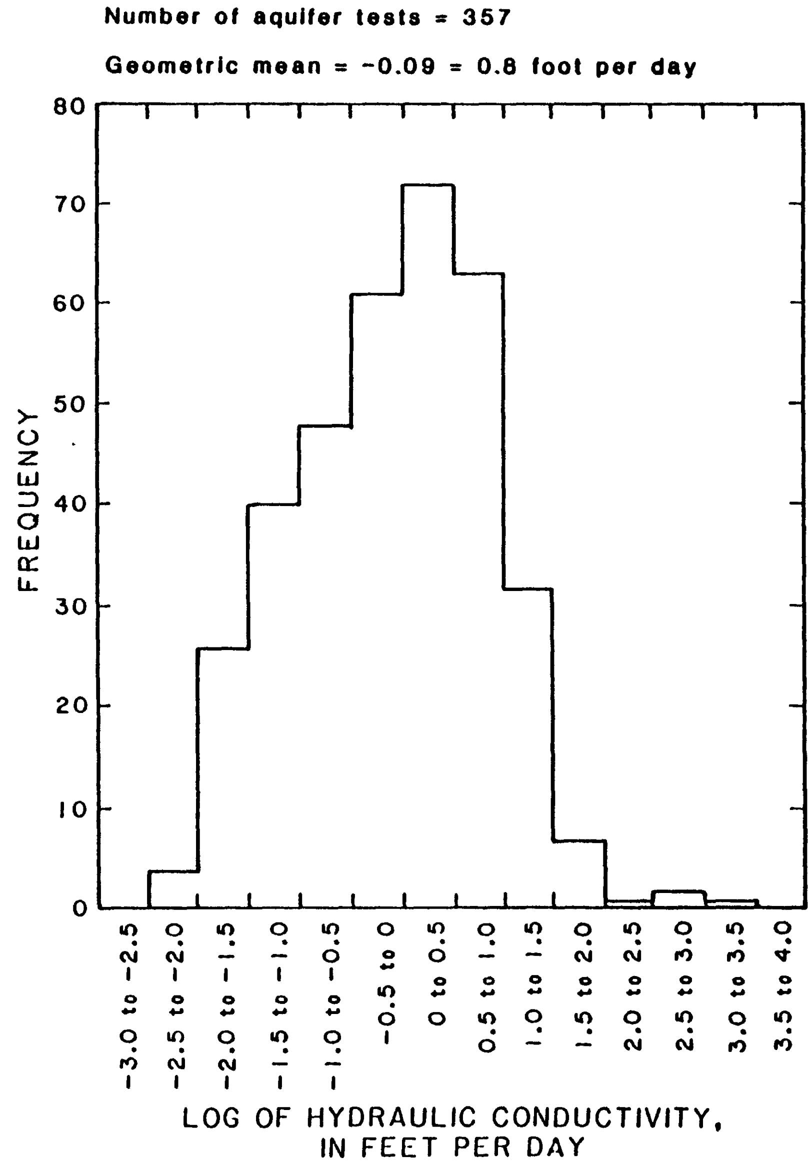


Figure 6.--Frequency distribution of the logs of hydraulic-conductivity values from aquifer tests of the Wyodak coal aquifer.

Areal variation of hydraulic conductivity in the Wyodak coal aquifer was investigated by dividing the study area into three subareas: north, central, and south. Comparison was made of the probability distribution of the hydraulic conductivity between each of the three subareas. The north subarea included all mines north of and including the Wyodak Mine (T. 50-52 N.). The central subarea included all mines from Rocky Butte on the north to Keeline on the south (T. 45-49 N.). The south subarea included all mines from Jacobs Ranch on the north to Antelope on the south (T. 40-43 N.). These three subareas were chosen because mines are close together in each subarea and because subareas are separated by gaps of several miles. The probability distribution of the logs of hydraulic-conductivity values for each of the three subareas and for the total study area is shown on figure 7. There is no significant difference in the distribution of hydraulic conductivity for the three subareas.

Recharge, Movement, and Discharge

Recharge to the Wasatch aquifer is from infiltration of precipitation and lateral movement of water from adjacent clinker. Water is discharged by small springs and seeps along stream drainages, by evaporation and transpiration, and by pumping of wells. Local flow systems are predominant, with discharge occurring along creeks and minor tributaries adjacent to recharge areas. Regional ground-water movement is toward the north, however, the quantity of water is small and the rate of movement is slow because the fine-grained rocks in the Wasatch Formation impede the flow of water.

Recharge to the Wyodak coal aquifer occurs primarily along the outcrop areas of associated clinker. Regional flow is toward the northwest as indicated by the configuration of the potentiometric surface prepared by Daddow (1986). Local flow may differ from regional flow. Coal-aquifer recharge and discharge occurs locally where the coal subcrops under the floor of alluvium-filled valleys. In the southern part of the study area, water in the coal is not moving north, but is moving toward local discharge areas where Antelope and Porcupine Creeks cross the coal subcrop.

Recharge to aquifers underlying the Wyodak coal bed is primarily from the infiltration of precipitation on outcrop areas. General movement of water in the aquifers is northward toward the Powder River and Little Powder River. However, discharge to these streams is too small to measure (Rankl and Lowry, in press). Other possible discharge mechanisms include evapotranspiration along stream drainages and pumping by wells. Some water leaks downward through the Fort Union Formation into the underlying strata.

Maps showing areas of ground-water recharge and discharge at each mine are included in the mine-permit applications. Many of these maps depict local flow systems rather than regional flow systems.

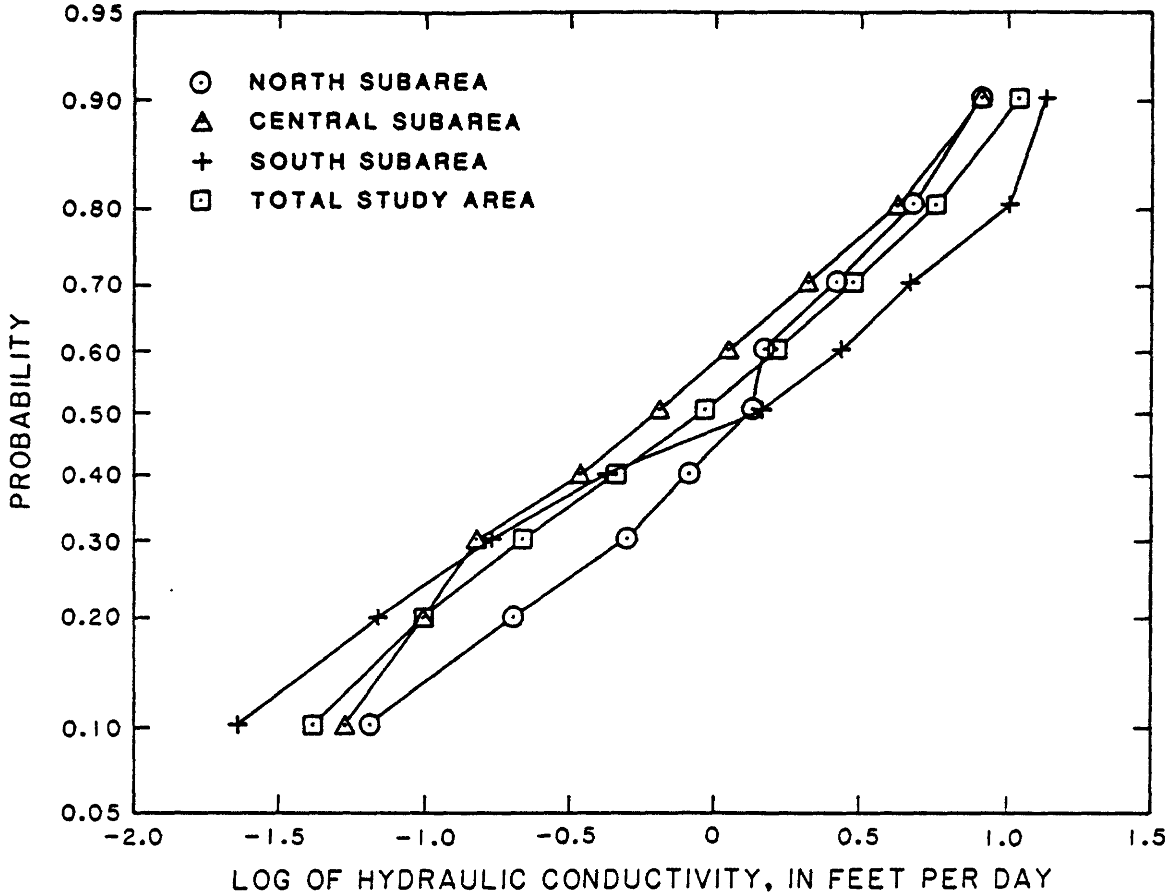


Figure 7.--Comparison of probability distribution of the logs of hydraulic-conductivity values for the Wyodak coal aquifer for three subareas and the total study area.

Impacts of Mining on Hydrogeology

Hydraulic Conductivity

Mining and reclamation will result in the replacement of the Wasatch aquifer in the overburden and the Wyodak coal aquifer with unconsolidated backfilled overburden materials referred to as spoil. The spoil aquifer is developed as the spoil materials become saturated. Although the lithologic materials in the spoil aquifer will be the same as previously described for the overburden, the bedding and arrangement of materials will be different.

The spoil aquifer will be created by physically moving overburden to areas being backfilled, either by dragline or shovel-and-truck methods. Most of the spoil will consist of unconsolidated clay, silt, and sand mixed with fragments of consolidated claystone, shale, and sandstone. It is anticipated that the zone closest to the base of the pit, or the base of each layer in areas backfilled by multiple layers, will be the most permeable horizon within the reclaimed spoil (Rahn, 1976; Van Voast and others, 1976; Groenewold, 1979). The more permeable zone is formed by the tendency for the coarser overburden material to roll to the bottom of the pit floor or to the base of the layer as the material is dumped.

Research in other coal-mining areas in the northern Great Plains indicates that hydraulic conductivity in the reclaimed spoil will be large enough to consider the material an aquifer. Rehm and others (1980) reported hydraulic-conductivity values of spoil aquifers, ranging from 0.02 to 2.9 ft/d with a geometric mean of 0.23 ft/d. Van Voast and others (1976) reported hydraulic-conductivity values of spoil aquifers ranging from 0.004 to 9.8 ft/d with an average from 0.2 to 1.0 ft/d. Thompson and Van Voast (1983) reported an average hydraulic conductivity for spoil aquifers of 0.5 ft/d.

Values of hydraulic conductivity determined from aquifer tests using wells completed in spoil aquifers within the study area generally ranged from 0.07 to 2.0 ft/d with the arithmetic average skewed to the low end of the range. Some settling and compaction of the spoil material is anticipated, causing the hydraulic conductivity to decrease. However, the final hydraulic conductivity of the spoil aquifer probably will approximate the geometric mean values of hydraulic conductivity for the undisturbed Wasatch aquifer (0.2 ft/d) and the Wyodak coal aquifer (0.8 ft/d).

Mining and reclamation will result in the replacement of the Wasatch aquifer and Wyodak coal aquifer with unconsolidated backfilled spoil materials. The resulting spoil aquifer is predicted to have approximately the same hydraulic conductivity as did the Wasatch aquifer and Wyodak coal aquifer.

Recharge, Movement, and Discharge

The potential for recharge to the backfilled spoil will be greater than in areas not disturbed by mining. The natural bedding will be destroyed, creating a more isotropic condition in the spoil, resulting in generally greater vertical permeability than exists in undisturbed areas. The infiltration capacity of the backfilled and reclaimed spoil will be greater than that of the undisturbed Wasatch aquifer and Wyodak coal aquifer. However, the infiltration rate for reclaimed soils is less than that for natural soils due to the lack of root structure and other paths for vertical movement of water. After several years, infiltration rates for reclaimed soils will increase to approximately the same rates as for undisturbed soils. As infiltration rates increase to approximate premining conditions, ground-water recharge rates also will increase to approximate premining conditions.

Although the recharge potential of the reclaimed mine areas will increase, the actual recharge rate after reclamation probably will approximate or be somewhat greater than premining recharge. Actual recharge will depend on how well vegetation is re-established and maintained, and how well the surface contours are restored. A flatter average slope of the reclaimed land would increase the potential recharge by decreasing the rate of runoff from reclaimed areas. Recharge will increase locally where water is allowed to pond in surface impoundments. Also, some increase in recharge along re-constructed channels probably will occur during the infrequent periods of surface runoff.

Postmining recharge rates and mechanisms will not change in areas where lateral movement of ground water from adjacent clinker is a major source of recharge. This is because, in general, the clinker will not be disturbed by mining operations. After mining and reclamation have been completed, water will move laterally from clinker to the spoil aquifer.

Recharge to the spoil aquifer will be from infiltration of precipitation, lateral flow from the undisturbed clinker and the Wasatch aquifer and Wyodak coal aquifer, and leakage from surface-water impoundments and stream channels. Estimates of the time required for the ground-water system to re-establish equilibrium varies from a few tens of years to hundreds of years. The anticipated potentiometric surface of the spoil aquifer will resemble a composite of the premining potentiometric surfaces in the Wasatch aquifer and Wyodak coal aquifer. After equilibrium is re-established, ground-water flow patterns will approximate premining conditions. Discharge from the spoil aquifer will flow into the undisturbed Wasatch aquifer and Wyodak coal aquifer to the west (regional flow) or to reclaimed stream channels (local flow). The quantity and quality of ground water that may be discharged from the spoil aquifer is not known, and so impacts of surface coal mining cannot be fully addressed in this area.

Postmining recharge, movement, and discharge of ground water in the Wasatch aquifer and Wyodak coal aquifer will probably not be substantially different from premining conditions. Recharge rates and mechanisms will not change substantially. Hydraulic conductivity of the spoil aquifer will be approximately the same as in the Wasatch aquifer and Wyodak coal aquifer allowing ground water to move from recharge areas where clinker is present east of mine areas through the spoil aquifer to the undisturbed Wasatch aquifer and Wyodak coal aquifer to the west.

Ground-Water Levels

Measured Declines

Water levels in the Wasatch aquifer and Wyodak coal aquifer are measured annually, on or about October 1, by members of the Gillette Area Groundwater Monitoring Organization (GAGMO). Water levels in about 1,200 monitoring wells at 20 mine sites were measured in 1986. Well location, aquifers in which wells are completed, and water levels are tabulated and published annually by GAGMO. Also included in the annual reports are potentiometric-surface maps and water-level-change maps for both the Wasatch aquifer and Wyodak coal aquifer.

The water-level-change maps for the Wasatch aquifer indicate that water-level declines from 1980 through 1986 resulting from mining activities are limited to areas near mine pits (Gillette Area Groundwater Monitoring Organization, 1987). Measured water-level declines are generally less than 5 ft at distances greater than 0.5 mi from mine pits. Water-level measurements in wells more than 0.5 mi from mine pits indicate approximately an equal number of occurrences of water-level rises and water level-declines. Water-level fluctuations in these wells probably are due to naturally occurring events, such as climatic variations, rather than mining operations. Water-level declines in the Wasatch aquifer near the Wyodak Mine have been limited to an area within 1,500 to 2,000 ft of the pit (Everett, 1979, p. 157) even though the mine has been in operation for 65 years.

The water-level-change maps for the Wyodak coal aquifer indicate that water-level declines from 1980 through 1986 resulting from mining activities generally are less than 10 ft at distances greater than 1 mi from the mine pits (Gillette Area Groundwater Monitoring Organization, 1987). Water levels in wells completed in the Wyodak coal aquifer and located near mine pits have declined as much as 80 ft during 1980-86. Water levels in wells more than 2 to 3 mi from mine pits have not been affected by mining operations. In the vicinity of active mine pits, the water-level-change maps indicate cones of depression.

Predicted Areal Extent of Declines Resulting from Individual Existing and Proposed Mines

Each coal-mining company has predicted the areal extent of 5-ft or more water-level declines in the Wasatch aquifer and Wyodak coal aquifer resulting from mining operations at their existing and proposed mines. Predictions are based on the results of numerical-flow models and analytical methods. Site-specific data used in the models and analytical methods were obtained from aquifer tests and test drilling at the mine sites.

The small hydraulic conductivity of the interbedded claystone, shale, and siltstone, and the discontinuous, lenticular nature of the sandstone beds comprising the Wasatch aquifer in the overburden will restrict the effects of mining on water levels in the Wasatch aquifer to areas near active mine pits. Coal-mining companies predict water-level declines of 5 ft or more in the Wasatch aquifer to extend from about 1,000 to about 2,000 ft beyond individual mine pits.

The predicted 5-ft or more water-level decline in the Wyodak coal aquifer resulting from an individual existing or proposed mine generally extends 4 to 8 mi beyond the lease areas (pl. 2). Variations in the predicted areal extent of the 5-ft or more water-level decline are dependent on local hydraulic properties, length of time a pit will be mined, and professional judgement of hydrologists making the predictions.

The most notable exception is the Eagle Butte lease area north of Gillette where the areal extent of the predicted 5-ft or more water-level decline is shown to be farther than 12 mi from the lease area. Use of large values of transmissivity to estimate the extent of water-level declines may be the reason that a larger area is predicted for this lease area than for other lease areas in the study area. Because there is no evidence to support the use of large values of transmissivity for the Wyodak coal aquifer outside the Eagle Butte lease area, it was assumed, in order to be consistent with predictions for other lease areas, that the areal extent of predicted 5-ft or more water-level decline will be about 8 mi.

The areal extent of water-level declines depicted on plate 2 generally is the result of worst-case analyses using the projected maximum duration of mining operations at each lease area, which were required by the Wyoming Department of Environmental Quality, and, therefore usually does not reflect actual drawdowns. Water-level data available from Gillette Area Groundwater Monitoring Organization (1987) indicate that actual effects will be less than the worst-case predictions. The worst-case analyses were necessary in the early days of mine permitting, before most mines had been constructed. Predicted water-level changes will become more accurate with time as measurements of water levels become available for calibrating the numerical-flow models.

The extent of the predicted 5-ft or more water-level decline resulting from anticipated mining in areas with Selected Coal Tracts and Preference Right Lease Applications is not shown on plate 2 because site-specific data necessary to make reasonable predictions are not available. The extent and configuration of water-level decline associated with Selected Coal Tracts will be approximately the same as for lease areas, assuming that mine plans and hydrologic conditions are similar to those at existing lease areas. The addition of Preference Right Lease Applications areas to existing coal leases will not have a significant effect on the areal extent of predicted water-level declines in the coal aquifer because of the small size of the Preference Right Lease Application areas and their location adjacent to large lease areas.

Predicted Areal Extent of Cumulative Declines Resulting from All Existing and Proposed Mines

Cumulative water-level declines are not expected to be substantial in the Wasatch aquifer because water-level declines due to individual mining operations generally will not extend more than 2,000 ft beyond the mine pits. The areal extent of water-level declines in the Wasatch aquifer will be restricted because the ground-water system consists of discontinuous sandstone beds that have limited hydraulic connection. Therefore, there will be few areas where water-level declines from individual mines will overlap to create cumulative impacts. In areas where a cumulative impact may occur, the impacts will be localized because of the discontinuous, lenticular nature of the sandstone beds comprising the Wasatch aquifer.

Water-level declines in the Wyodak coal aquifer are predicted to extend beyond the area affected by individual existing and proposed mines because of the cumulative effect of adjacent mining operations. The probable areal extent of the cumulative impacts was determined for each mine as part of the mine-permit applications submitted to the Wyoming Department of Environmental Quality. The areal extent of cumulative water-level declines generally is determined by superposition of predicted water-level declines resulting from individual existing and proposed mines. In its most sophisticated form, the determination is made by including several adjacent mining operations in a numerical model of ground-water flow. The area of cumulative impacts for existing and proposed mines was determined by compositing information from mine-permit applications for the entire study area.

The predicted areal extent of cumulative water-level declines of 5 ft or more shown on plate 2 is considered a worst-case prediction because it is based on worst-case predictions of water-level declines resulting from individual mining operations at existing and proposed mines. Within the area of cumulative water-level declines, water-level declines are predicted to range from 5 to 80 ft depending on the proximity to mining operations. Hydrologic conditions, such as permeable fracture zones or zones of small permeability, may affect the predicted effects locally.

North and west of Gillette, the areal extent of cumulative water-level declines is shown to be as much as 15 mi from the lease areas. This large extent is due primarily to the large areal extent of water-level decline from the Eagle Butte lease area. In this study, it was assumed that the areal extent of 5-ft water-level decline in the Wyodak coal aquifer would be about 8 mi from the Eagle Butte lease area. This assumption also will decrease the areal extent of predicted cumulative water-level decline to less than that shown on plate 2.

Predicted Areal Extent of Cumulative Declines Resulting from All Anticipated Mining

In order to determine which water-supply wells may be affected by water-level declines resulting from all anticipated mining, the area of the potential cumulative 5-ft or more water-level decline in the Wyodak coal aquifer resulting from all anticipated mining was approximated and is shown on plate 2. The extent of this area was approximated on the basis of the predicted cumulative 5-ft water-level decline (pl. 2) resulting from the existing and proposed mining, the location and potential effects of the Selected Coal Tracts and areas with Preference Right Lease Applications, and the extent of the Wyodak coal bed. In general, predicted cumulative water-level declines resulting from existing and proposed mining extend about 8 mi from lease areas. Therefore, the area of potential cumulative water-level declines from all anticipated mining is defined, in this report, as extending from the outcrop of the Wyodak coal bed to about 8 mi from areas of all anticipated mining.

Addition of areas for possible future mining to existing lease areas may or may not affect the predicted extent of water-level declines from all anticipated mining shown on plate 2. The areal extent of water-level declines may be substantially changed if large areas are leased for mining where there are now (1987) no leases, Selected Coal Tracts, or Preference Right Lease Applications. The impacts of future mining in areas not included in the definition of all anticipated mining will depend on the size, location, timing of mining with respect to adjacent mines, and local hydrogeologic conditions. Generally, the probable maximum extent of 5-ft or more water-level decline in the Wyodak coal aquifer will be about 8 mi from mined areas. If additional areas are leased for surface coal mining in the future, the 8-mi criterium can be applied to determine if the areal extent of water-level decline in the Wyodak coal aquifer will be substantially different from that shown on plate 2.

GROUND-WATER USE

About 4,800 wells with valid ground-water rights are in the study area. The number of wells is estimated on the basis of a computer retrieval of water-well completion data for the entire study area by the Wyoming State Engineer's Office. Wells not registered with the State Engineer do not have valid water rights and are not included in the retrieval of well-completion data.

Of the 4,800 wells in the study area, about 2,700 wells are used as sources of water supply: about 2,000 wells are used for domestic or livestock supplies, and about 700 wells are used for municipal, industrial, irrigation, or miscellaneous supplies. Miscellaneous uses include domestic supply for subdivisions, trailer parks, and potable supplies at coal mines and commercial establishments. The remaining 2,100 wells in the study area are used by coal-mining companies for monitoring or dewatering purposes.

About 3,000 wells are in the area of potential cumulative water-level declines resulting from all anticipated mining. Of these 3,000 wells, about 1,200 are outside the areas of anticipated mining: about 1,000 wells supply water for domestic or livestock uses, and about 200 wells supply water for municipal, industrial, irrigation, and miscellaneous uses. The remaining 1,800 wells are used by coal-mining companies: about 1,700 wells are used for monitoring ground-water levels and quality, and about 100 wells are used for water supply and dewatering at mine sites.

Impacts of Water-Level Declines on Ground-Water Use

The impacts of water-level declines are of primary concern for the 1,200 wells outside the areas of anticipated mining and not for the 1,800 wells used by the coal-mining companies. Water-level declines in monitoring wells are not detrimental in that they do not affect the use of the well for its intended purpose. Water-level declines in water-supply wells and dewatering wells owned by coal-mining companies were not investigated because water-level declines in these wells will be caused primarily by mining operations of the companies owning the wells rather than by cumulative impacts of all anticipated mining operations.

In order to determine the impacts of water-level declines on the 1,200 water-supply wells outside the areas of anticipated mining, the aquifer in which the well is completed had to be determined. According to well logs and completion reports for these wells, about 580 wells are completed in the Wasatch aquifer, about 100 in the Wyodak coal aquifer, and about 280 in aquifers stratigraphically below the Wyodak coal bed. Stratigraphic location of the completion interval could not be determined for about 260 wells because of lack of information on the well-completion report. Well-completion data for the 1,200 water-supply wells outside the areas of anticipated mining are given in table 32 (Supplemental Data section at back of report).

The impacts of water-level declines on wells outside mining areas will depend on the magnitude of decline that occurs in the individual wells, which in turn, is related to the proximity of a well to mining operations. Other factors important in determining the impacts on individual wells include the depth of the well, the depth and number of perforated intervals, depth to water, and the yield required from the well to maintain it as a useable source of water.

The most important factor in determining if the water level in a well will be affected by mining operations is the stratigraphic location of the perforated interval of the well and, consequently, the aquifer in which the well is completed. In wells completed in the Wasatch aquifer in the area of anticipated water-level declines, water levels will decline only if the wells are about 2,000 ft or less from a mine pit. Water-supply wells completed in the Wasatch aquifer are shown on plate 3. However, wells completed in the Wyodak coal aquifer may be affected as far away as 8 mi from mine pits. Wells completed in the underlying aquifers will not be affected by dewatering of the mine pits, but may be affected by withdrawals from wells supplying facilities at mines.

Wells completed in the Wyodak coal aquifer also are shown on plate 3. Water-level declines in these wells are predicted to range from less than 5 ft in wells far away from mining operations to more than 80 ft in wells near mining operations. Most wells completed in the coal aquifer are small-yield (less than 25 gal/min) domestic and livestock water-supply wells. If the water level in any of the wells declines such that the yield is markedly decreased, the well can be deepened or replaced with a well completed in the underlying aquifers.

Most mines in the Gillette area have wells completed in the lower part of the Fort Union Formation (Tongue River-Lebo aquifer and Tullock aquifer). Water from these wells is used for potable supply, dust control, equipment washing, and so forth. In addition to the wells at the mines, many of the subdivisions and trailer parks near Gillette obtain their water supply from wells completed in the lower part of the Fort Union Formation. The city of Gillette has 12 public-supply wells completed in this same stratigraphic interval.

Water-level declines in the lower part of the Fort Union Formation have been documented in the Gillette area. However, these declines are most likely attributable to withdrawals at subdivisions and trailer parks in and near Gillette (M.A. Crist, U.S. Geological Survey, written commun., 1987). Wells supplying facilities at mines are scattered throughout a large area. Because there is no major center of pumping, most of the water-level decline due to withdrawal from these wells occurs within 1 mi of the pumped well. Static water levels measured in wells completed in the lower part of the Fort Union Formation generally are 500 ft or more above the top of the perforated interval. Water-level declines of 100 to 200 ft in the vicinity of a pumped well will not dewater the aquifer. However, the yields of wells located near wells supplying facilities at mines may be affected by water-level declines in the vicinity of the pumped wells.

Alternative Sources of Supply

Although surface-water supplies are limited in the study area, alternative sources of ground-water supplies are available to replace existing supplies that may be interrupted or depleted by water-level declines resulting from mining operations. Shallow ground water is the principal source of domestic and livestock supplies. Affected wells completed in the Wasatch aquifer or Wyodak coal aquifer could be replaced by wells completed in either the Tongue River-Lebo aquifer or Tullock aquifer. Wells completed in the Tongue River-Lebo aquifer or Tullock aquifer probably will not be affected by water-level declines; if they are affected, replacement wells could be completed in the underlying Lance-Fox Hills aquifer. Relocation of existing water-supply wells, deepening of wells, and construction of new wells require analysis and approval by the Wyoming State Engineer.

The Tongue River-Lebo aquifer consists of 800 to 1,000 ft of lenticular beds of fine-grained claystone, shale, and sandstone. Well yields generally are sufficient for domestic and livestock supplies. The Tullock aquifer is composed of numerous lenticular sandstone beds isolated by interbedded shale and siltstone. Yields of 200 to 300 gal/min are available from wells completed in the Tullock aquifer. The Lance-Fox Hills aquifer consists of lenticular beds of massive sandstone isolated by interbedded shale and siltstone. Well yields as much as 380 gal/min are available from wells perforated through the entire stratigraphic interval of the Lance-Fox Hills aquifer.

The main alternative sources of water supplies for wells significantly impacted by mining operations will be the Tongue River-Lebo aquifer for domestic and livestock supplies and the Tullock aquifer or Lance-Fox Hills aquifer for uses requiring a larger yield. Withdrawals from large-capacity wells completed in the Tullock aquifer or Lance-Fox Hills aquifer should not affect water supplies of wells completed in the Tongue River-Lebo aquifer because they are hydrologically separated by a thick shale zone.

Quality of Alternative Supplies

Water quality in aquifers in the Fort Union Formation is variable and appears to correlate with the permeability of the water-yielding sands and proximity to the recharge area. Dissolved-solids concentrations range from about 200 to about 3,000 mg/L (milligrams per liter), but commonly range between 500 and 1,500 mg/L (Hodson and others, 1973). Larson (1984) summarized dissolved-solids concentration data for 60 water samples from aquifers in the Fort Union Formation in Campbell County; the median concentration was 1,230 mg/L, and the average concentration was 1,480 mg/L.

Selected water-quality data for samples from wells completed in aquifers in Upper Cretaceous formations, stratigraphically below the Fort Union Formation, were compiled for areas within and adjacent to the study area (fig. 8). Sources of data for this compilation include the Water Data Storage and Retrieval System (WATSTORE) water-quality file of the U.S. Geological Survey and geochemical studies done by Chatham and others (1981) and Henderson (1984). It was assumed that the data compiled from those sources were representative of water quality in the Lance-Fox Hills aquifer. Additional summaries of water-quality data that pertain to the study area have been done by Larson (1984) and Larson and Daddow (1984).

In order to provide a brief overview of the water quality from aquifers of Late Cretaceous age, the concentration ranges of dissolved solids, fluoride, and selenium in these ground waters are illustrated in figure 9. Dissolved-solids concentrations in 130 ground-water samples ranged from 240 to 2,800 mg/L (fig. 9). About 13 percent of the samples had dissolved-solids concentrations less than the 500-mg/L standard for domestic use (Wyoming Department of Environmental Quality, 1980a).

Dissolved fluoride concentrations in 124 ground-water samples ranged from less than 0.1 to 6.0 mg/L (fig. 9). Assuming a maximum daily air temperature of 54 to 58 °F, the maximum acceptable fluoride concentration in a public water supply is 2.2 mg/L (Wyoming Department of Environmental Quality, 1980a). About 10 percent of the ground-water samples had fluoride concentrations that exceeded this maximum concentration.

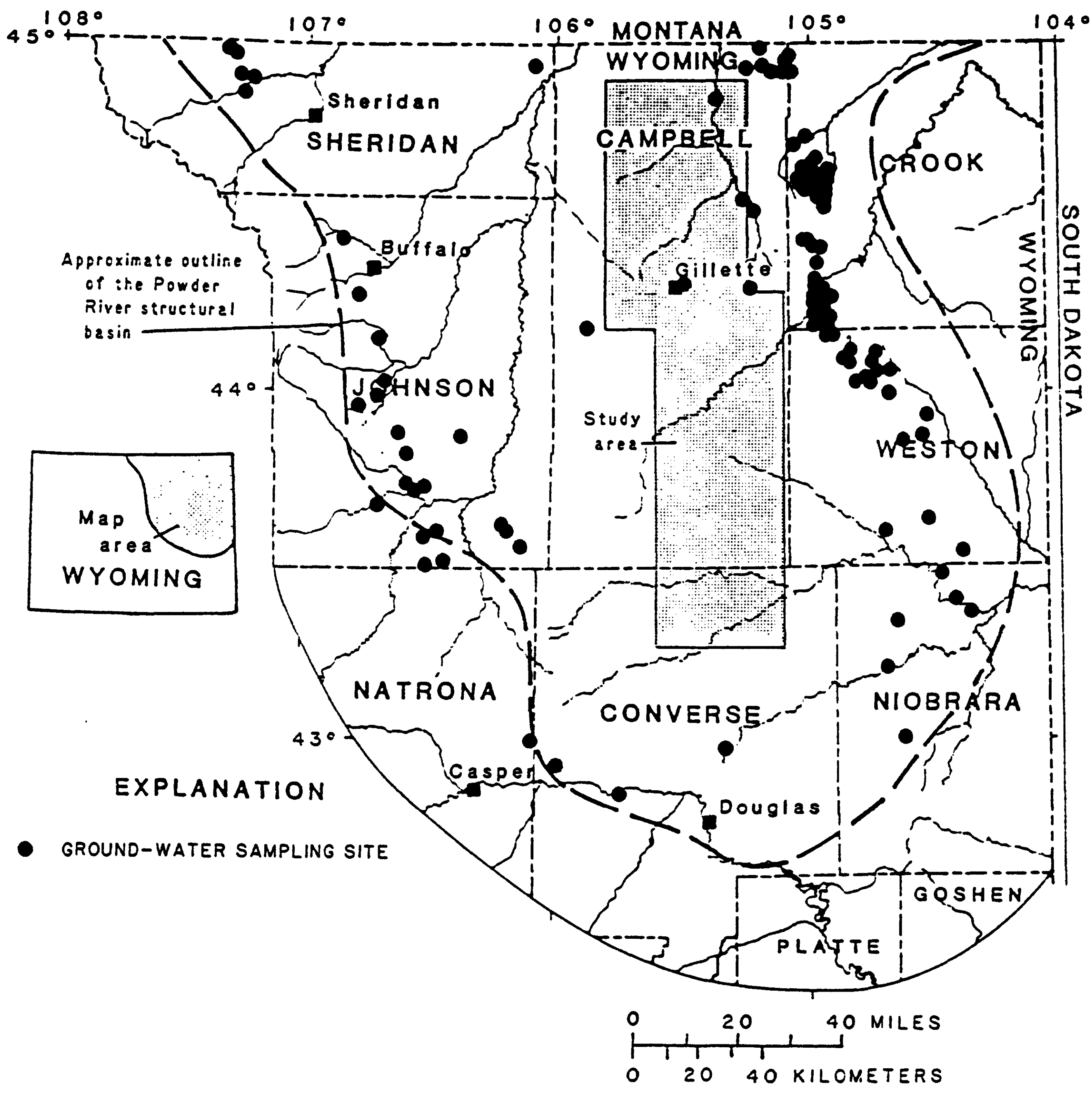


Figure 8.--Location of sampling sites for which water-quality data is available for water samples from aquifers in Upper Cretaceous formations.

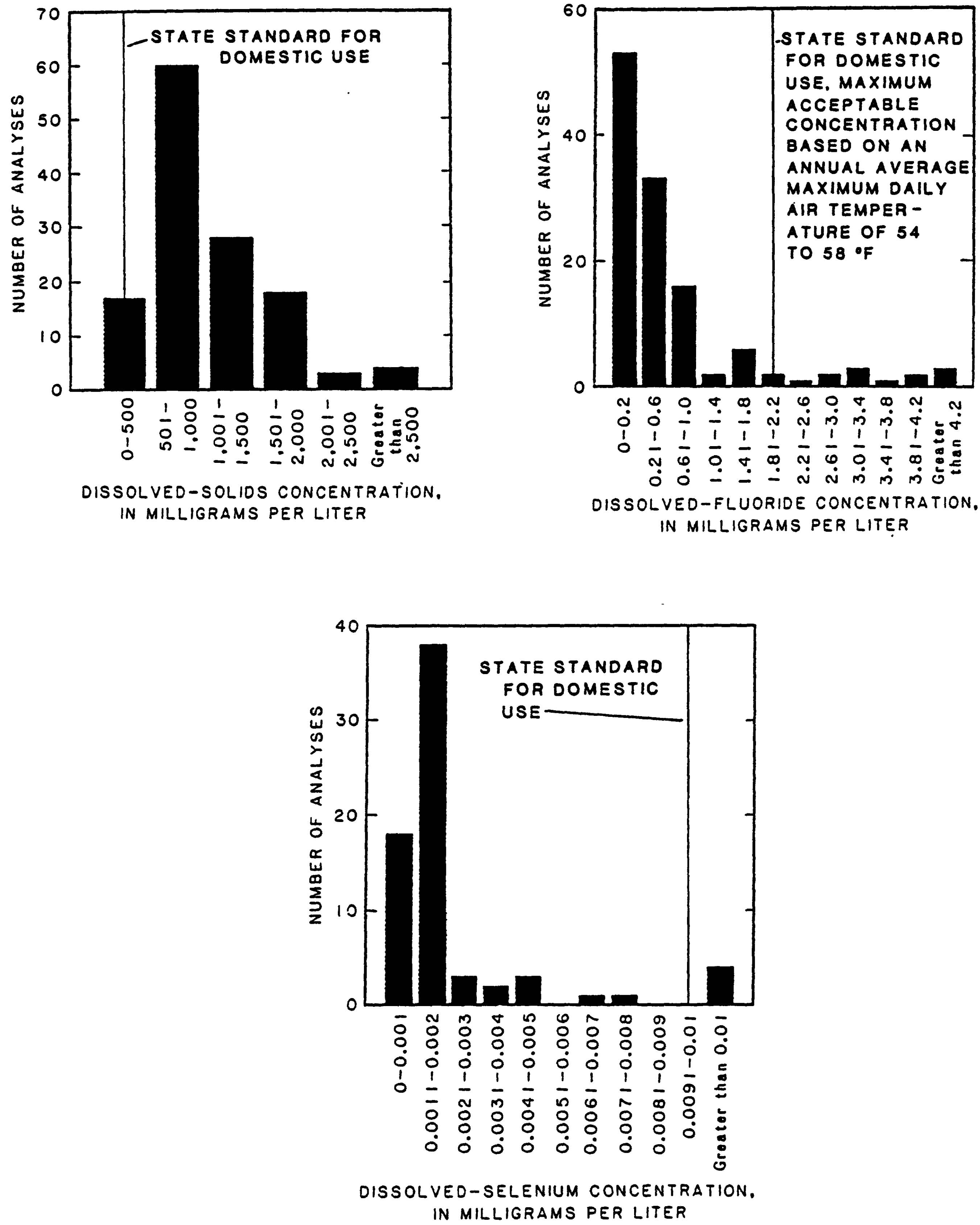


Figure 9.--Histograms of selected water-quality constituents in water samples from aquifers in Upper Cretaceous formations.

Dissolved-selenium concentrations in 70 ground-water samples ranged from less than 0.001 to greater than 0.01 mg/L (fig. 9). About 6 percent of the ground-water samples had dissolved-selenium concentrations exceeding the standard of 0.01 mg/L for domestic use as prescribed by the Wyoming Department of Environmental Quality (1980a).

Alternative sources of ground-water supplies are available to replace existing supplies that are interrupted or depleted by water-level declines resulting from mining operations. Alternative sources are the Tongue River-Lebo aquifer and the Lance-Fox Hills aquifer. Although, the quality of water from these alternative sources does not always meet the State domestic standard, it is approximately the same as the quality of water currently being used.

GROUND-WATER QUALITY

Surface coal mining in the study area has the potential to affect the ground-water quality in near-surface aquifers. The removal of coal from mines in the study area modifies near-surface aquifers by replacing the Wasatch aquifer and Wyodak coal aquifer with rubblized overburden material which becomes saturated as the postmining water table equilibrates after mining. In general, the Wasatch aquifer and spoil aquifers are of limited regional extent, whereas the Wyodak coal aquifer is more regional.

Existing Water-Quality Data

Chemical data from premining (Wasatch aquifer in the overburden and Wyodak coal aquifer) and postmining (spoil aquifers) ground-water samples were compiled from existing information collected from selected coal mines in the study area (fig. 10). Water samples were collected by the coal-mining companies and the chemical analyses were compiled from files of the Wyoming Department of Environmental Quality. Premining water-quality data were compiled from 174 chemical analyses of samples collected from 50 wells completed in the Wasatch aquifer and from 379 chemical analyses of samples collected from 88 wells completed in the Wyodak coal aquifer at 7 existing mines. Postmining water-quality data were compiled from 336 chemical analyses of samples collected from 45 wells completed in spoil aquifers at 10 existing mines. The premining water-quality data were compiled for samples collected from 1977 through 1986; the postmining water-quality data were compiled for samples collected from 1981 through 1986. Because all existing chemical analyses were utilized in this data compilation, the postmining (spoil aquifer) data set is biased toward large concentrations of constituents. Because at present (1987), spoil aquifers are not fully saturated, relatively few areas of backfilled spoil are saturated, and more mining and resulting spoil areas are anticipated, the biased water-quality data represents a worst-case statistical summary of the existing water quality. For example, a spoil aquifer with water containing constituents that exceeded a particular water-quality standard commonly has more water-quality sampling wells and chemical analyses than does a spoil aquifer with water containing constituents that do not exceed any water-quality standards.

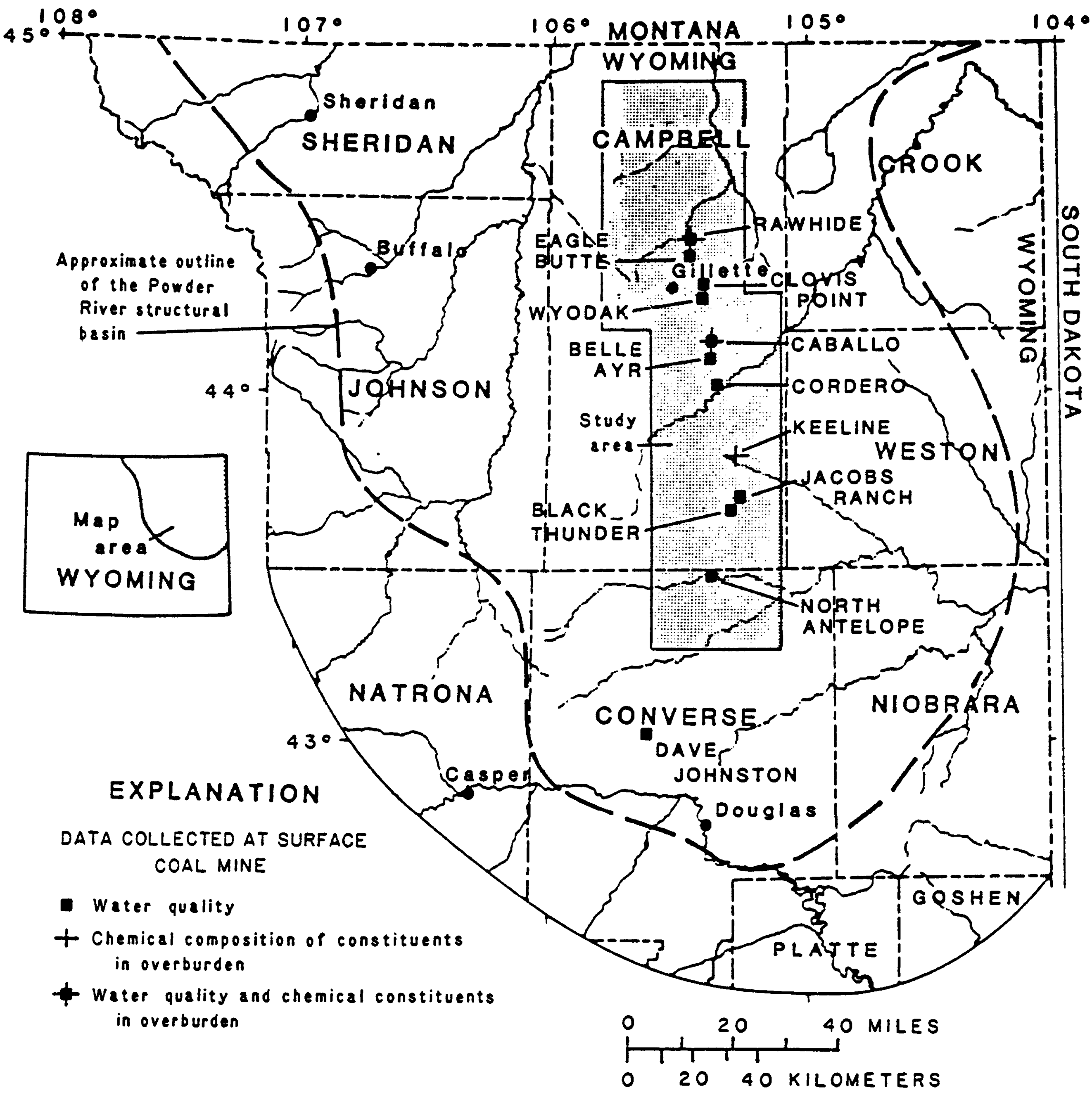


Figure 10.--Location of surface coal mines where data for determining the water quality in aquifers and the chemical composition of constituents in overburden were collected.

Water-quality samples were analyzed by numerous laboratories and, therefore, are not subject to consistent quality-control checks. Analyses with a cation-anion charge balance differing by greater than 7 percent were eliminated from the data set. The sample-preservation and analytical methods used may not be consistent within the compiled data set, especially with respect to the minor- and trace-element analyses. However, within the limits of these qualifications, the compiled water-quality data are useful for summarizing premining water quality in the Wasatch aquifer and the Wyodak coal aquifer, and postmining water quality in spoil aquifers.

The compiled water-quality data were compared to the Quality Standards for Wyoming Groundwaters published by the Wyoming Department of Environmental Quality (1980a). Hereafter in the report, these water-quality standards will be referred to as the State standard for each chemical constituent of interest.

The median concentrations of dissolved solids and sulfate were larger in water from spoil aquifers compared to water from either the Wasatch aquifer or Wyodak coal aquifer (table 4). The median dissolved-solids and sulfate concentrations in water samples from the spoil aquifers were less than the State standard for livestock (see table 4). Dissolved-solids concentrations in 27 percent of the water samples from the spoil aquifers exceeded the State standard for livestock, compared to 0 percent for water samples from the Wyodak coal aquifer. Dissolved-sulfate concentrations in 16 percent of the water samples from the spoil aquifers exceeded the State standard for livestock, compared to 0 percent for water samples from the Wyodak coal aquifer. The maximum dissolved-solids concentration in water samples from the spoil aquifers was about 25,000 mg/L, and the maximum dissolved-sulfate concentration was about 17,000 mg/L.

Data from 7 of the 10 individual mines listed in table 5 indicate that median dissolved-solids concentrations were smaller in water from the Wyodak coal aquifer compared to water from the Wasatch aquifer and spoil aquifers (table 5). The increase in the median concentration of dissolved solids in water from the spoil aquifers compared to water from the Wyodak coal aquifer is because of material redistribution during mining. As noted by Groenewold and others (1983, p. 138-139), redistribution of overburden materials (Wasatch Formation) creates the potential for substantial changes in the chemical reactivity of the spoil-pile landscape. For example, emplacement of sediments from the unsaturated zone (premining) to depths below the postmining water table could cause increases in the dissolved-solids concentration resulting from dissolution of gypsum and other efflorescent salts accumulated in these spoil materials.

The median concentration of fluoride in water from the spoil aquifers (0.34 mg/L) was smaller than in water from the Wyodak coal aquifer (0.52 mg/L) (table 4). A possible reason for the smaller median fluoride concentration in water from the spoil aquifers could be the increased calcium concentrations in water from the spoil aquifers resulting in precipitation of fluorite. The median concentration of calcium in water from the Wyodak coal aquifer was 105 mg/L; the median concentration of calcium in water from the spoil aquifers was 478 mg/L.

Table 4.--Percentage of samples with concentrations exceeding State standards and statistical summary of selected constituents in water samples from the Wasatch aquifer, Wyodak coal aquifer, and spoil aquifers from selected coal mines

[Constituents are dissolved; concentrations and standards are in milligrams per liter. Samples collected by coal-mining companies; analyses from the files of the Wyoming Department of Environmental Quality. Total number of samples equals total number of samples that were chemically analyzed. Percentage of samples with concentrations less than detection limit(s) was computed from the total number of samples with concentrations less than the detection limit(s) divided by the total number of samples for each constituent; there may be more than one detection limit due to the various laboratories and methods used to produce the data. State standard refers to ground-water quality standards of Wyoming Department of Environmental Quality (1980a). (--), no State standard; l.d., less than analytical detection limit(s); --, no data]

Chemical constituent and aquifer	Total number of samples[1]	Percentage of samples with concentrations less than detection limit(s)	Median concentration	Percentage of samples with concentrations exceeding State standards (standards in parentheses): Domestic	Livestock	Maximum concentration
Dissolved solids				(500)	(5,000)	
Wasatch aquifer	174	0	2,215	98	5	9,470
Wyodak coal aquifer	379	0	1,310	100	0	5,180
Spoil aquifers	336	0	3,680	100	27	25,320
Sulfate				(250)	(3,000)	
Wasatch aquifer	174	0	1,215	83	7	5,800
Wyodak coal aquifer	379	2	565	100	0	3,030
Spoil aquifers	336	0	2,080	87	16	17,170
Fluoride				[2](1.4-2.4)	(--)	
Wasatch aquifer	173	4	0.430	0	--	1.8
Wyodak coal aquifer	374	0	.515	0	--	2.92
Spoil aquifers	336	0	.34	0	--	2.15

Table 4.--Percentage of samples with concentrations exceeding State standards and statistical summary of selected constituents in water samples from the Wasatch aquifer, Wyodak coal aquifer, and spoil aquifers from selected coal mines--Continued

Chemical constituent and aquifer	Total number of samples[1]	Percentage of samples with concentrations less than detection limit(s)	Median concentration	Percentage of samples with concentrations exceeding State standards (standards in parentheses) Domestic	Livestock	Maximum concentration
Ammonia (as nitrogen)				(0.50)	(--)	
Wasatch aquifer	138	3	1.52	88	--	5.36
Wyodak coal aquifer	337	2	1.81	89	--	20.2
Spoil aquifers	335	1	1.53	85	--	29
Nitrate (as nitrogen)				(10.0)	[3](--)	
Wasatch aquifer	139	23	.120	4	--	36.4
Wyodak coal aquifer	324	30	.09	1	--	21.3
Spoil aquifers	323	25	.130	19	--	305
Aluminum				(--)	(5.0)	
Wasatch aquifer	167	72	l.d.	--	0	.9
Wyodak coal aquifer	366	80	l.d.	--	0	1.5
Spoil aquifers	336	61	l.d.	--	0	8.4
Arsenic[4]				(0.050)	(0.020)	
Wasatch aquifer	170	92	l.d.	0	0	.021
Wyodak coal aquifer	369	100	l.d.	0	0	.006
Spoil aquifers	336	66	l.d.	0	0	.049
Barium				(1.0)	(--)	
Wasatch aquifer	156	81	l.d.	0	--	.59
Wyodak coal aquifer	348	77	l.d.	1	--	2.4
Spoil aquifers	320	81	l.d.	1	--	2.2

Table 4.--Percentage of samples with concentrations exceeding State standards and statistical summary of selected constituents in water samples from the Wasatch aquifer, Wyodak coal aquifer, and spoil aquifers from selected coal mines--Continued

Chemical constituent and aquifer	Total number of samples[1]	Percentage of samples with concentrations less than detection limit(s)	Median concentration	Percentage of samples with concentrations exceeding State standards (standards in parentheses) Domestic	Livestock	Maximum concentration
Boron[4]				(0.75)	(5.00)	
Wasatch aquifer	163	31	0.07	0	0	0.71
Wyodak coal aquifer	356	18	.10	2	0	2.9
Spoil aquifers	336	5	.15	5	0	1.5
Cadmium[4]				(0.01)	(0.05)	
Wasatch aquifer	172	84	l.d.	1	0	.02
Wyodak coal aquifer	373	96	l.d.	0	0	.03
Spoil aquifers	336	57	l.d.	3	0	.029
Chromium[4]				(0.05)	(0.05)	
Wasatch aquifer	173	82	l.d.	1	1	.06
Wyodak coal aquifer	324	91	l.d.	1	1	.09
Spoil aquifers	336	78	l.d.	7	7	.75
Copper[4]				(1.0)	(0.05)	
Wasatch aquifer	170	64	l.d.	1	0	1.61
Wyodak coal aquifer	368	72	l.d.	0	0	1.21
Spoil aquifers	336	64	l.d.	0	0	.2
Iron[4]				(0.30)	(--)	
Wasatch aquifer	139	43	.06	28	--	98.1
Wyodak coal aquifer	305	34	.08	24	--	7.53
Spoil aquifers	334	13	.18	42	--	114

Table 4.--Percentage of samples with concentrations exceeding State standards and statistical summary of selected constituents in water samples from the Wasatch aquifer, Wyodak coal aquifer, and spoil aquifers from selected coal mines--Continued

Chemical constituent and aquifer	Total number of samples[1]	Percentage of samples with concentrations less than detection limit(s)	Median concentration	Percentage of samples with concentrations exceeding State standards (standards in parentheses) Domestic	Livestock	Maximum concentration
Lead[4]				(0.05)	(0.10)	
Wasatch aquifer	169	89	l.d.	5	4	.83
Wyodak coal aquifer	368	95	l.d.	1	0	.13
Spoil aquifers	334	73	l.d.	2	0	1.36
Manganese[4]				(0.05)	(--)	
Wasatch aquifer	172	7	.25	86	--	9.80
Wyodak coal aquifer	373	18	.06	52	--	2.90
Spoil aquifers	335	2	.58	93	--	8.52
Mercury[4]				(0.0002)	[5](0.00005)	
Wasatch aquifer	164	98	l.d.	2	2	0.3
Wyodak coal aquifer	355	96	l.d.	2	4	.016
Spoil aquifers	335	97	l.d.	1	3	.004
Molybdenum				(--)	(--)	
Wasatch aquifer	112	97	l.d.	--	--	.02
Wyodak coal aquifer	245	99	l.d.	--	--	.03
Spoil aquifers	334	94	l.d.	--	--	.12
Nickel[4]				(--)	(--)	
Wasatch aquifer	173	66	l.d.	--	--	.13
Wyodak coal aquifer	372	71	l.d.	--	--	1.1
Spoil aquifers	291	55	l.d.	--	--	.650

Table 4.--Percentage of samples with concentrations exceeding State standards and statistical summary of selected constituents in water samples from the Wasatch aquifer, Wyodak coal aquifer, and spoil aquifers from selected coal mines--Continued

Chemical constituent and aquifer	Total number of samples[1]	Percentage of samples with concentrations less than detection limit(s)	Median concentration	Percentage of samples with concentrations exceeding State standards (standards in parentheses): Domestic	Livestock	Maximum concentration
Selenium[4]				(0.01)	(0.05)	
Wasatch aquifer	164	96	l.d.	0	0	.007
Wyodak coal aquifer	355	100	l.d.	0	0	.005
Spoil aquifers	335	60	l.d.	26	18	3.388
Zinc				(5.0)	(25.0)	
Wasatch aquifer	173	29	0.02	0	0	2.83
Wyodak coal aquifer	372	29	0.02	0	0	3.22
Spoil aquifers	336	17	.05	0	0	5.09

[1] For Wasatch aquifer and the Wyodak coal aquifer, number refers to water samples collected at seven existing mines, and for the spoil aquifers, number refers to water samples collected at the Eagle Butte, North Antelope, and Rawhide Mines in addition to the same seven existing mines.

[2] Depends on the annual average of the maximum daily air temperature. The limit of 2.4 milligrams per liter corresponds to a temperature of 12.0 °Celsius and less.

[3] State nitrite plus nitrate standard for livestock is 100 milligrams per liter as nitrogen.

[4] Concentrations are reported in milligrams per liter rather than micrograms per liter to conform with units used in State standards by Wyoming Department of Environmental Quality.

[5] State mercury standard for livestock (0.00005 milligram per liter) is less than the analytical detection limit of procedures used by the laboratories doing the analyses. Therefore, all water samples with a detectable mercury concentration exceed the livestock standard.

Table 5.--Summary of dissolved-solids concentrations in water from the Wasatch aquifer, Wyodak coal aquifer, and spoil aquifers by coal mine

[+, median dissolved-solids concentration, in milligrams per liter; [ ], 25th and 75th quartiles of the data; -----, range of the data values outside the 25th and 75th quartiles]

```
                           Number of          Range of dissolved-solids concentrations
Mine and aquifer           analyses                  (milligrams per liter)

Belle Ayr Mine

                                              ----[            +  ]---
  Wasatch aquifer             35    ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                          [+   ]--------
  Wyodak coal aquifer         49    ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                          ---[    +          ]-------------------------------
  Spoil aquifer               57    ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^
                                    0       1,000     2,000     3,000     4,000     5,000     6,000     7,000     8,000     9,000
Black Thunder Mine

                                               -----------[  +            ]--------
  Wasatch aquifer             22    ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                           --[    +        ]---
  Wyodak coal aquifer         70    ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                                   --------[      +     ]--------------------------
  Spoil aquifer               30    ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^
                                    0       1,000     2,000     3,000     4,000     5,000     6,000     7,000     8,000     9,000
Caballo Mine

                                       -------------------[     +             ]--------------------------
  Wasatch aquifer             36    ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                            ------[    +       ]---------------
  Wyodak coal aquifer         27    ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                             -----------------------[       +               ]------------------
  Spoil aquifer              135    ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^
                                    0       1,000     2,000     3,000     4,000     5,000     6,000     7,000     8,000     9,000
Clovis Point Mine

                                                [+ ]-------
  Wasatch aquifer              6    ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                            --[ +  ]----------------
  Wyodak coal aquifer         24    ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                                                   --[ +]----------------
  Spoil aquifer               14    ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^
                                    0       1,000     2,000     3,000     4,000     5,000     6,000     7,000     8,000     9,000
```

Table 5.--Summary of dissolved-solids concentrations in water from the Wasatch aquifer, Wyodak coal aquifer, and spoil aquifers by coal mine--Continued

```
                            Number of
Mine and aquifer            analyses    Range of dissolved-solids concentrations
                                        (milligrams per liter)

Cordero Mine

                                       ---[            +                        ]----------------------------------------------
  Wasatch aquifer           17      ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                       -----[  +          ]---------------
  Wyodak coal aquifer       98      ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                                                                          -----[+]---
  Spoil aquifer             22      ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^
                                    0        1,000     2,000     3,000     4,000     5,000     6,000     7,000     8,000     9,000
Jacobs Ranch Mine

                                             ------[      +      ]--
  Wasatch aquifer           23      ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                            --[     +        ]---------------------------
  Wyodak coal aquifer       35      ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                                  --[+   ]------------------------
  Spoil aquifer             14      ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^
                                    0        1,000     2,000     3,000     4,000     5,000     6,000     7,000     8,000     9,000
Wyodak Mine

                                         -[  +           ]----
  Wasatch aquifer           35      ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                       -----------[      +      ]---------------
  Wyodak coal aquifer       76      ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^

                                              -------------------[             +    ]---------------
  Spoil aquifer             32      ^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^+++++++++^
                                    0        1,000     2,000     3,000     4,000     5,000     6,000     7,000     8,000     9,000
```

The median concentration of nitrate (as nitrogen) was slightly larger in water from the spoil aquifers compared to the median concentration in water from the Wasatch aquifer and the Wyodak coal aquifer (table 4). Nitrite plus nitrate in 10 percent of the water samples from the spoil aquifers exceeded the State standard for livestock compared to zero percent of the water samples from the Wasatch aquifer and Wyodak coal aquifer. All of the water samples exceeding the State standard for livestock were from five closely spaced wells at the Caballo Mine. (The maximum nitrate concentration in water samples from the spoil aquifers exceeded 300 mg/L as nitrogen.)

Although the median concentrations of chromium and selenium in water samples from the spoil aquifers were less than the analytical detection limits, 7 percent of the water samples analyzed for chromium and 18 percent of the water samples analyzed for selenium exceeded the State standard for livestock (table 4). Based on the water samples from the Wasatch aquifer and the Wyodak coal aquifer, 1 percent analyzed for chromium and zero percent analyzed for selenium exceeded the State standard for livestock. Of the 10 mines where water samples from the spoil aquifers were collected, five mines had at least one sample in which chromium exceeded the State standard for livestock and three mines had at least one sample in which selenium exceeded the State standard for livestock. Except for four samples from the North Antelope Mine and one sample from the Belle Ayr Mine, all the selenium analyses exceeding the State standard for livestock were from six closely spaced wells at the Caballo Mine. In the water samples from the spoil aquifers, the maximum concentration of chromium was 0.750 mg/L and the maximum concentration of selenium was 3.388 mg/L.

Changes with time in dissolved-solids, sulfate, nitrate, chromium, and selenium concentrations, in water samples from selected wells illustrate that water quality in spoil aquifers may change with time in the same well and may differ between mines (figs. 11 and 12). Part of this variation possibly is due to sources and magnitude of recharge to the spoil aquifers and the chemical composition of the spoil materials. For example, a distinct increase in dissolved-solids and sulfate concentrations during nearly 4 years of record is indicated in well EG16-1R (Clovis Point Mine) (fig. 11). A distinct decrease in dissolved-solids and sulfate concentrations from 1983 to 1985, followed by a distinct increase in the concentrations of both constituents from 1985 to 1987 is documented for well MB26-1P (Cordero Mine) (fig. 11). Dissolved nitrate concentrations for all three wells shown in figure 11 indicate decreasing trends in concentration with time.

Chromium and selenium concentrations in water samples from different wells indicate varying trends with time. For example, a marked increase in chromium concentration during the 1 year of record is documented for well SP4NA (North Antelope Mine) (fig. 12). An overall decrease in chromium concentration from a large concentration exceeding 0.35 mg/L to less than the detection limit of 0.02 mg/L during the 3-year period is recorded for well RW2801 (Belle Ayr Mine) (fig. 12). Selenium concentrations in wells CA723 and CA724 (Caballo Mine), and in well SP4NA (North Antelope Mine) (fig. 12) generally decreased with time. None of the selenium concentrations in samples from these three wells in figure 12 were less than the State standard for livestock of 0.05 mg/L.

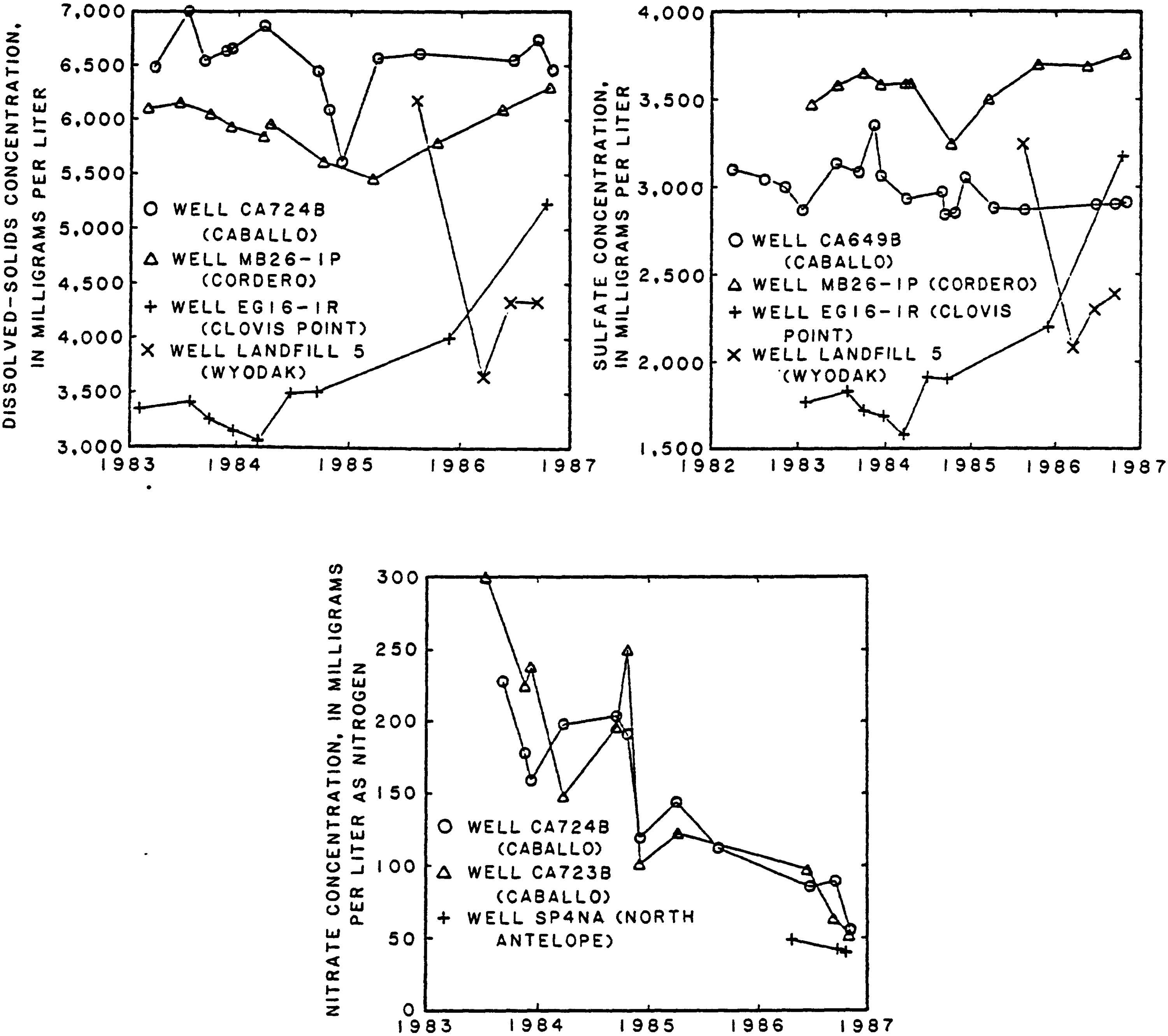


Figure 11.--Changes in the dissolved-solids, sulfate, and nitrate concentrations, as a function of time, in water samples from wells completed in the spoil aquifers at selected mines.

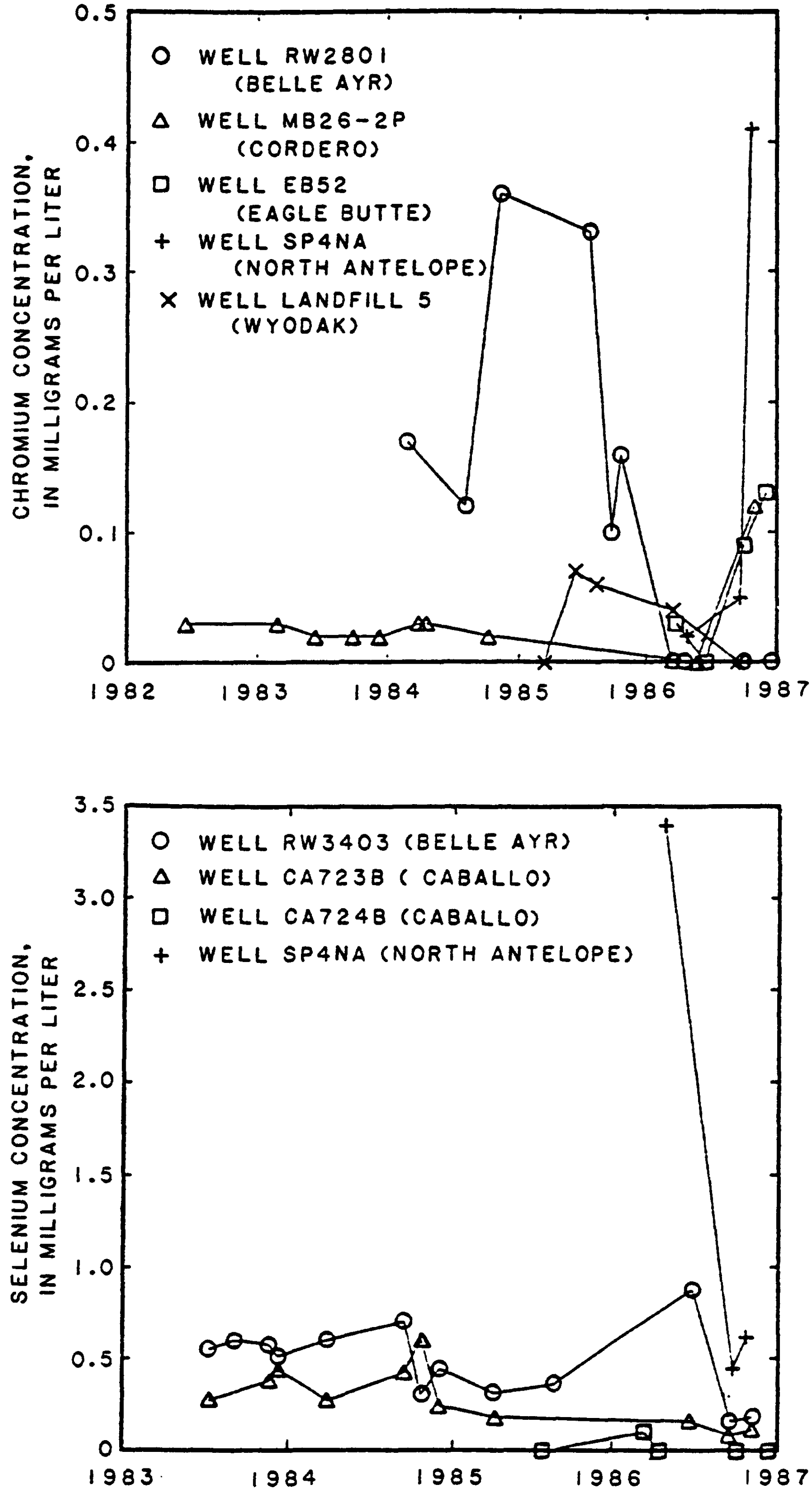


Figure 12.--Changes in the chromium and selenium concentrations, as a function of time, in water samples from wells completed in the spoil aquifers at selected mines.

On the basis of the comparison between the existing water-quality data compiled for the Wasatch aquifer and the data compiled for the Wyodak coal aquifer and the spoil aquifers, surface coal mining will initially degrade ground-water quality in the areas of mining. Because dissolved-solids and sulfate concentrations in water from the Wasatch aquifer and the Wyodak coal aquifer already exceed the State standard for domestic use (table 4), the primary concern is water-quality degradation that might make the water unsuitable for livestock. In general, the quality of current (1987) and future water from the majority of spoil aquifers will meet the State standard for livestock. Based on the existing water-quality data from the spoil aquifers, the primary chemical constituents in selected wells that exceed the State standard for livestock are dissolved solids, sulfate, nitrate, chromium, and selenium. Except for the consistently detected decrease in nitrate and selenium concentrations (figs. 11 and 12), data for the other constituents of concern (dissolved solids, sulfate, and chromium) do not indicate consistent decreases in concentration with time. Additional monitoring data is needed to determine if the concentrations of all constituents of concern (dissolved solids, sulfate, nitrate, chromium, and selenium) will decrease and become less than the State standard for livestock.

Additional surface coal mining in the study area probably will produce postmining ground water of similar quality as that previously identified in table 4. Because only 10 of the 16 coal mines in the study area currently (1987) have spoil aquifers, additional mining at these 16 active mines and the 6 proposed mines probably will increase the number of spoil aquifers. Assuming that the water quality in future spoil aquifers will be similar to the quality indicated by the water-quality data for the existing spoil aquifers, the increase in the number and extent of spoil aquifers resulting from future mining will expand the areal extent of the recent (through 1986) effects of surface coal mining on water quality.

Analysis of Variance

The number of samples needed to define representative concentrations of chemical constituents in ground water from a particular aquifer is directly related to the natural variation of concentrations in time and space. If the chemical composition of ground water from a particular aquifer does not change with time and is spatially homogenous, then one sample anywhere in the aquifer will describe the concentration of the chemical constituent of interest, assuming sampling and analytical errors do not exist. However, in a realistic situation, many different factors affect the concentration of a dissolved chemical constituent in an aquifer. For example, the concentration of a particular chemical constituent can be affected by different components of the total variance (geologic, geographic, temporal, analytical, and so forth). By assessing the individual variance components in the existing premining (Wyodak coal aquifer) and postmining (spoil aquifers) data, insights into required sampling density and frequency during current (1987) and future programs for ground-water quality monitoring can be gained. The insights gained from analyzing the variance components at existing mines will be useful in designing future monitoring programs at future mines planned in the study area. Assessing these components of variance can aid in the interpretation and application of present and future monitoring data.

In order to analyze the variance components described above, a hierarchial or nested analysis of variance (NANOVA) was applied to water-quality data sets for the Wyodak coal and spoil aquifers that were compiled from the existing water-quality information. A three-level, nested design is used (fig. 13) and is unbalanced after the first level. The first two levels are associated with geographic scales; the third level measures temporal variation within each well. The top-level of this design (among mines) consists of mines in the eastern Powder River basin (fig. 13). Data were available from 7 mines for the premining analysis and 10 mines for the postmining analysis. The second level (among wells) consists of numerous monitoring wells within each mine, and the third level (within a well) consists of different sampling times at each well. This type of sampling design and interpretation has been applied to premining ground-water-quality data in the eastern Powder River basin (U.S. Geological Survey, 1975, p. 58-61; 1977, p. 173-178). For a detailed description of the application of NANOVA calculations to sampling design, the reader is referred to Klusman and others (1980).

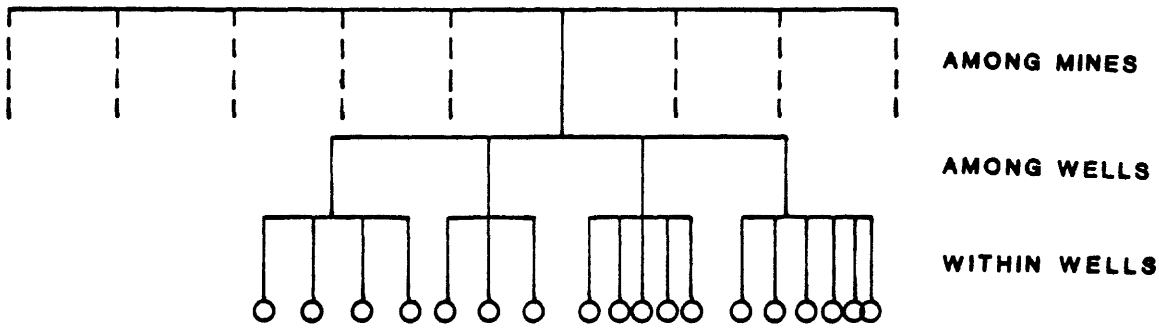


Figure 13.--Design of unbalanced analysis of variance used for water-quality data sets for the Wyodak coal aquifer and spoil aquifers.

Because the data bases consist of existing water-quality data, a completely randomized sample selection is not possible. By imposing the three-level, nested design on the existing water-quality data bases for the Wyodak coal and spoil aquifers, a qualitative indication of variance distributions is derived.

Only selected chemical constituents were chosen for analysis of variance. If more than 20 percent of the concentrations for a particular constituent were less than the detection limit, the constituent was not chosen for analysis of variance. For samples with fewer than 20 percent of the concentrations less than the detection limit, a concentration equal to 0.7 of the detection limit was substituted for the concentrations less than the detection limit (Miesch, 1976, p. A26).

The sample variance (s^2) for ground water from both the Wyodak coal (premining) aquifer and spoil (postmining) aquifers is partitioned into three components according to the following:

$$s^2_{total} = s^2_{among\ mines} + s^2_{among\ wells} + s^2_{within\ wells}. \tag{1}$$

Due to the lack of analytical and sampling duplicates in the existing data sets, the analytical and sampling variance components could not be evaluated for their contribution to the total variance.

In order to evaluate the importance of the among-mines variance component, the variance ratio (v_r) as referenced by Klusman and others (1980) is calculated. The variance ratio for the among-mines level is calculated by the following:

$$v_r = \frac{N_v}{D_v} = \frac{s^2_{among\ mines}}{s^2_{among\ wells} + s^2_{within\ wells}} \tag{2}$$

where N_v = the estimated variance among mines, and

D_v = the estimated variance within mines.

The larger the variance ratio, the more likely the among-mines variance is significant. For example, a chemical constituent with a large variance ratio has a large degree of variance in concentration at the among-mines level, which indicates that a minewide average of this constituent can be estimated using a small number of samples and still be distinguishable among mines. In contrast, a chemical constituent with a small variance ratio indicates a large part of the total variance is associated with small scale, or within-mine variance. A large proportion of small-scale variance for a particular constituent indicates that a large number of water-quality samples collected from the Wyodak coal aquifer or spoil aquifers need to be analyzed.

Calculation of the variance ratios for selected chemical constituents can provide important information on the sampling adequacy in monitoring programs of the Wyodak coal (premining) aquifer and spoil (postmining) aquifers. Klusman and others (1980) have used the variance ratio to quantify the number of random samples that are required within a unit cell so the averages of the two unit cells can be distinguished. This same technique can be used to quantify the number of samples needed within a mine area so that the chemical quality of water at two mines can be distinguished. The variance ratio (v_r) can be used to determine the number of random samples needed per unit cell (mine, for example) at both the 80- and 95-percent confidence limits (fig. 14). For example, according to figure 14, a variance ratio of 0.9 would require five water samples per mine to differentiate average concentrations of chemical constituents among mines at the 95-percent confidence limit.

Estimates of the logarithmic variance components $s^2_{(among\ mines)}$, $s^2_{(among\ wells)}$, and $s^2_{(within\ wells)}$, and their corresponding percentage of the total variance $s^2_{(total)}$ for selected dissolved chemical constituents are given in table 6. Variance estimates for selected chemical constituents from the Wyodak coal aquifer and spoil aquifers were derived using the UANOVA (unvariate analysis of variance) computer code (Garrett and Goss, 1980) for nested analysis of variance with unequal subclasses.

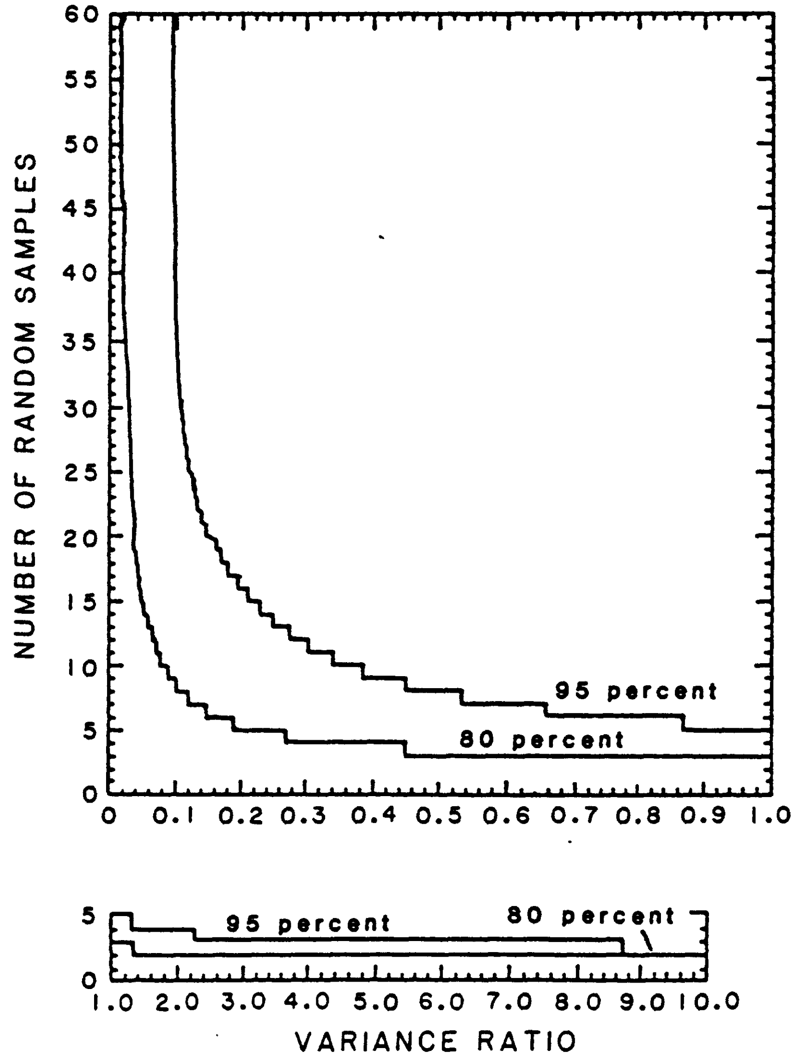


Figure 14.--The variance ratio that can be used to approximate the number of random water samples needed from each unit area in order to describe the gross differences among a number of units (from Dean and others, 1979).

Table 6.--Comparison of estimated logarithmic variance components for selected chemical properties and constituents in samples of water from the Wyodak coal aquifer and spoil aquifers

[Concentrations in milligrams per liter unless noted otherwise; variance components are expressed as percentages of the total logarithmic variance for each chemical constituent. Symbols: v_r, variance ratio for mines; n_r, minimum number of random samples per mine needed to estimate the average concentration of the selected chemical constituent at the 95-percent confidence level; n.d., not determined because n_r is infinitely large]

Chemical property or constituent and aquifer	Total $\log_{10}$ variance	Percentage of total variance: Among mines	Among wells	Within wells	v_r	n_r
pH (units)[1]						
Wyodak coal aquifer	0.143	26.33	16.89	56.78	0.357	10
Spoil aquifer	.331	45.48	26.09	28.43	.834	5
Alkalinity (as HCO_3^-)						
Wyodak coal aquifer	.043	.79	76.11	23.10	.008	n.d.
Spoil aquifer	.057	.00	82.20	17.80	.059	n.d.
Dissolved solids						
Wyodak coal aquifer	.059	23.97	64.81	11.21	.315	11
Spoil aquifer	.080	20.22	71.74	8.04	.253	13
Calcium						
Wyodak coal aquifer	.170	22.37	65.09	12.54	.288	12
Spoil aquifer	.258	39.81	46.78	13.40	.662	6
Magnesium						
Wyodak coal aquifer	.206	24.75	56.85	18.40	.329	11
Spoil aquifer	.178	24.21	61.45	14.34	.319	11
Sodium						
Wyodak coal aquifer	.052	.00	82.42	17.58	.003	n.d.
Spoil aquifer	.060	7.69	82.60	9.71	.083	n.d.
Potassium						
Wyodak coal aquifer	.053	31.60	43.44	24.96	.462	8
Spoil aquifer	.050	40.32	31.99	27.69	.676	6

Table 6.--Comparison of estimated logarithmic variance components for selected chemical properties and constituents in samples of water from the Wyodak coal aquifer and spoil aquifers--Continued

Chemical property or constituent and aquifer	Total $\log_{10}$ variance	Percentage of total variance: Among mines	Among wells	Within wells	v_r	n_r
Sulfate						
Wyodak coal aquifer	1.01	18.94	70.81	10.25	0.234	14
Spoil aquifer	.500	16.99	69.77	13.24	.205	15
Chloride						
Wyodak coal aquifer	.121	6.93	73.40	19.68	.074	n.d.
Spoil aquifer	.237	48.69	40.78	10.54	.949	5
Fluoride						
Wyodak coal aquifer	.097	5.91	20.68	73.41	.063	n.d.
Spoil aquifer	.104	19.30	37.82	42.87	.104	29
Boron						
Wyodak coal aquifer	.068	.69	39.29	60.01	.007	n.d.
Spoil aquifer	.218	25.29	42.75	31.96	.338	11

[1] pH, by definition, is a logarithmic value and was not transformed for this analysis.

The results of the analysis of variance calculations indicate a large component of the total variance at the within-mines level ($s^2_{among\ wells}$ plus $s^2_{within\ wells}$). In general, most of the within-mines ($s^2_{among\text{-}wells}$ plus $s^2_{within\ wells}$) variance is associated with the among-wells component rather than the within-wells component (table 6). This variance analysis indicates that temporal variation of concentration within a well was relatively small compared to the among-wells variation. Therefore, a large number of water samples are needed to characterize the chemistry of the ground water from the Wyodak coal aquifer and spoil aquifers within a mine site. Because most of the water-quality monitoring data for the Wyodak coal aquifer and spoil aquifers generally were from periods of less than 5 years, the relative proportion of temporal variance could change as more data become available in the future.

The calculated variance ratios (v_r) are presented in table 6 for selected chemical properties and constituents in samples of water from the Wyodak coal aquifer and spoil aquifers. Based on analysis-of-variance results and calculated variance ratios for the selected chemical properties and constituents, considerations for current (1987) and future ground-water-quality monitoring of the Wyodak coal aquifer and spoil aquifers include the following:

1. Sampling efforts need to focus on completing numerous wells in spoil aquifers rather than collecting a large number of water samples, numerous times, from a only a few wells. The current (1986) number of monitoring wells completed in spoil aquifers at each mine in the study area ranges from 1 well at the Rawhide Mine to 11 wells at the Caballo Mine.

2. For maximum sampling effectiveness with the minimum possible cost and the maximum usefulness of present and future monitoring data, different sampling densities need to be investigated for different chemical properties and constituents. The exact number of sampled wells or number of times to collect samples cannot be determined with the information in this report; however, some generalized conclusions can be made. Chemical properties and constituents with large proportions (greater than 40 percent) of the total variance at the among-mines level (pH, potassium, and chloride) only need a small number of samples at each mine site to calculate a representative minewide average; whereas, chemical constituents with small proportions (less than 40 percent) of the total variance at the among-mines level (alkalinity, dissolved solids, calcium, magnesium, sodium, sulfate, fluoride and boron) need a larger number of samples at each mine site to calculate a representative average for the mine.

Laboratory Simulations

Batch-mixing and column-leaching tests are common laboratory procedures used to simulate the postmining water quality that might occur in the spoil aquifer at the mine. Results from batch-mixing and column-leaching tests were compiled to evaluate the predictive capabilities of these procedures by comparing the laboratory results to the actual postmining water quality in the spoil aquifers in the study area.

Batch-mixing experiments can be conducted by mixing water from the Wyodak coal aquifer and spoil material in a specified ratio of water to spoil material, then allowing the water and spoil material to react for a specified time. During the interaction of the water and spoil material, the batch-mixing vessel is usually shaken or rotated. Davis (1984, p. 9) describes the procedure used in this study, which is one of the many batch-mixing procedures.

Naftz (in press) compared the major-ion chemistry of water derived from batch-mixing experiments (batch-extract water) with the actual postmining quality of water samples collected during July 1984 from a well completed in the spoil aquifer at the Cordero Mine; selected results are presented in figure 15. In the batch-mixing experiments, using a ratio of water to spoil material of 2:1 (by weight), the batch-extract water had smaller concentrations of major ions, except for alkalinity, than did water samples representing the water quality of the spoil aquifer in July 1984. If a smaller ratio of water to spoil material had been used in this particular set of batch-mixing experiments, then the quality of the batch-extract water would have more closely simulated the postmining water quality of the spoil aquifer at the Cordero Mine (Naftz, in press).

Column-leaching tests are done by packing a cylindrical column with spoil material and then injecting water into the column. Effluent water from the column is then analyzed at different time intervals to obtain an indication of how the postmining water quality will change with time. Column-leaching tests vary in the flow rate, degree of saturation, column length, type and packing of spoil material, and source of water.

Data from column-leaching tests were compiled from mining permits obtained from the Wyoming Department of Environmental Quality in an attempt to evaluate whether the tests could simulate postmining water quality. Data from column-leaching tests at Caballo, Keeline, and Rawhide Mines were used in this compilation. The general procedure used for all three of the column-leaching tests is described by McWhorter and Landers (1985). Deionized water was used in the column-leaching tests at the Caballo and Rawhide Mines to simulate recharge; whereas, water from the Wyodak coal aquifer was used in the tests at the Keeline Mine to simulate recharge.

Changes in the concentrations of dissolved solids and dissolved nitrate (as nitrogen) during the three sets of column-leaching tests were compared with median concentrations of dissolved solids and nitrate in existing spoil aquifers at 10 surface coal mines in the eastern Powder River basin (figs. 16 and 17). In general, median concentrations of dissolved solids and nitrate in the spoil aquifers are exceeded until at least 1 pore volume of water has passed through the columns (figs. 16 and 17). A distinct flattening of the slope of the line for dissolved-solids and nitrate concentrations occurs after about 1 pore volume of water has passed through the columns (figs. 16 and 17). The flattening of slope after 1 pore volume possibly is indicative of future improvements in postmining water quality after the initial dissolution and desorption reactions have occurred in the newly created spoil aquifer.

The column-leaching tests using water from the Wyodak coal aquifer at the Keeline Mine indicate larger concentrations of dissolved solids after 1 pore volume has passed through the column compared to the column-leaching tests using deionized water (fig. 16). This was due to the larger initial concentration of dissolved solids in water from the Wyodak coal aquifer (2,200 mg/L) compared to the deionized water. If the major source of recharge to a spoil aquifer is water from the coal aquifer, the use of water from a coal aquifer in column-leaching tests possibly represents the long-term postmining water quality more accurately than does the use of deionized water.

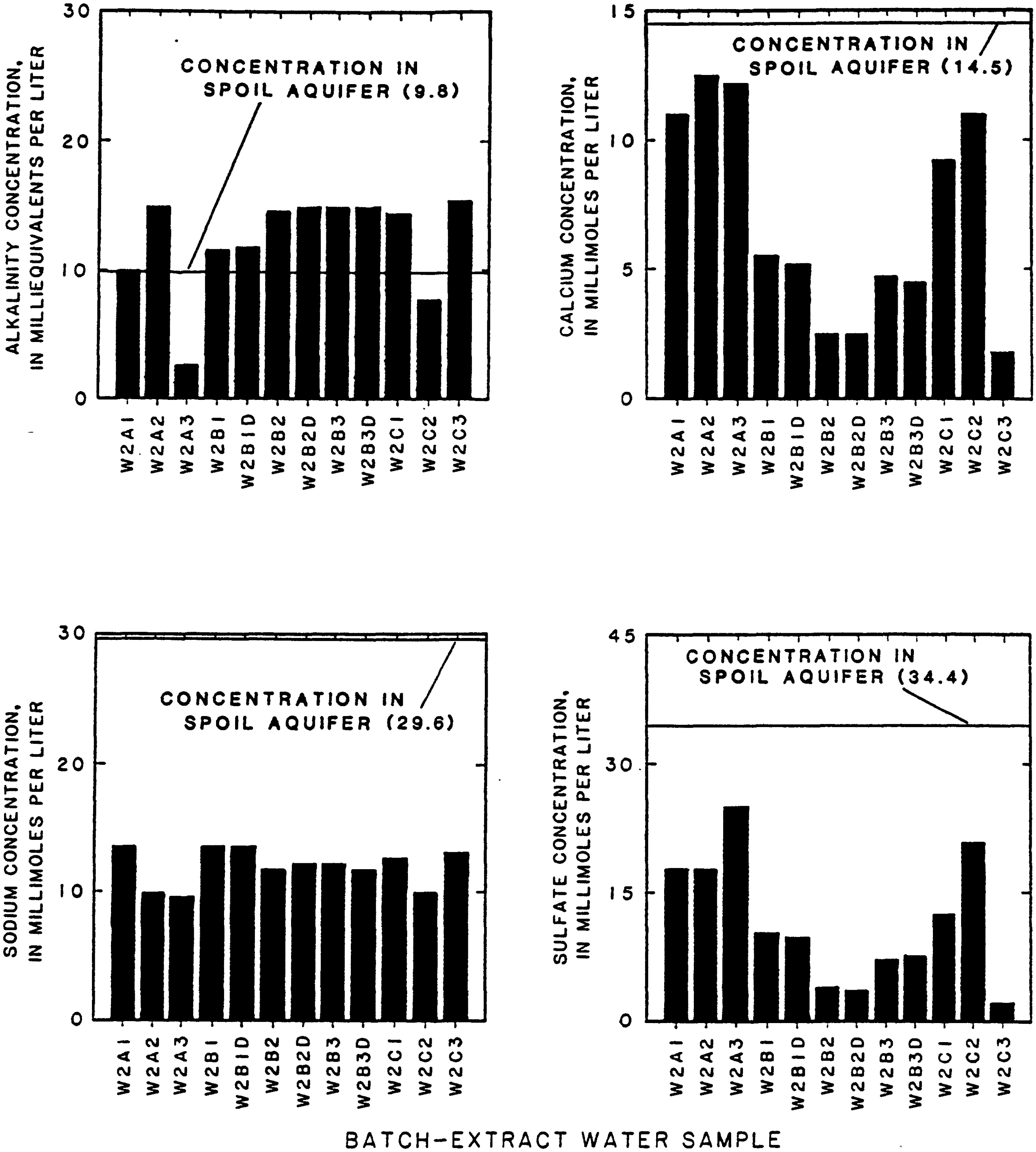


Figure 15.--Comparison of concentrations in batch-extract water to actual concentrations of alkalinity, calcium, sodium, and sulfate in water from the spoil aquifer sampled during July 1984 at the Cordero Mine (from Naftz, in press).

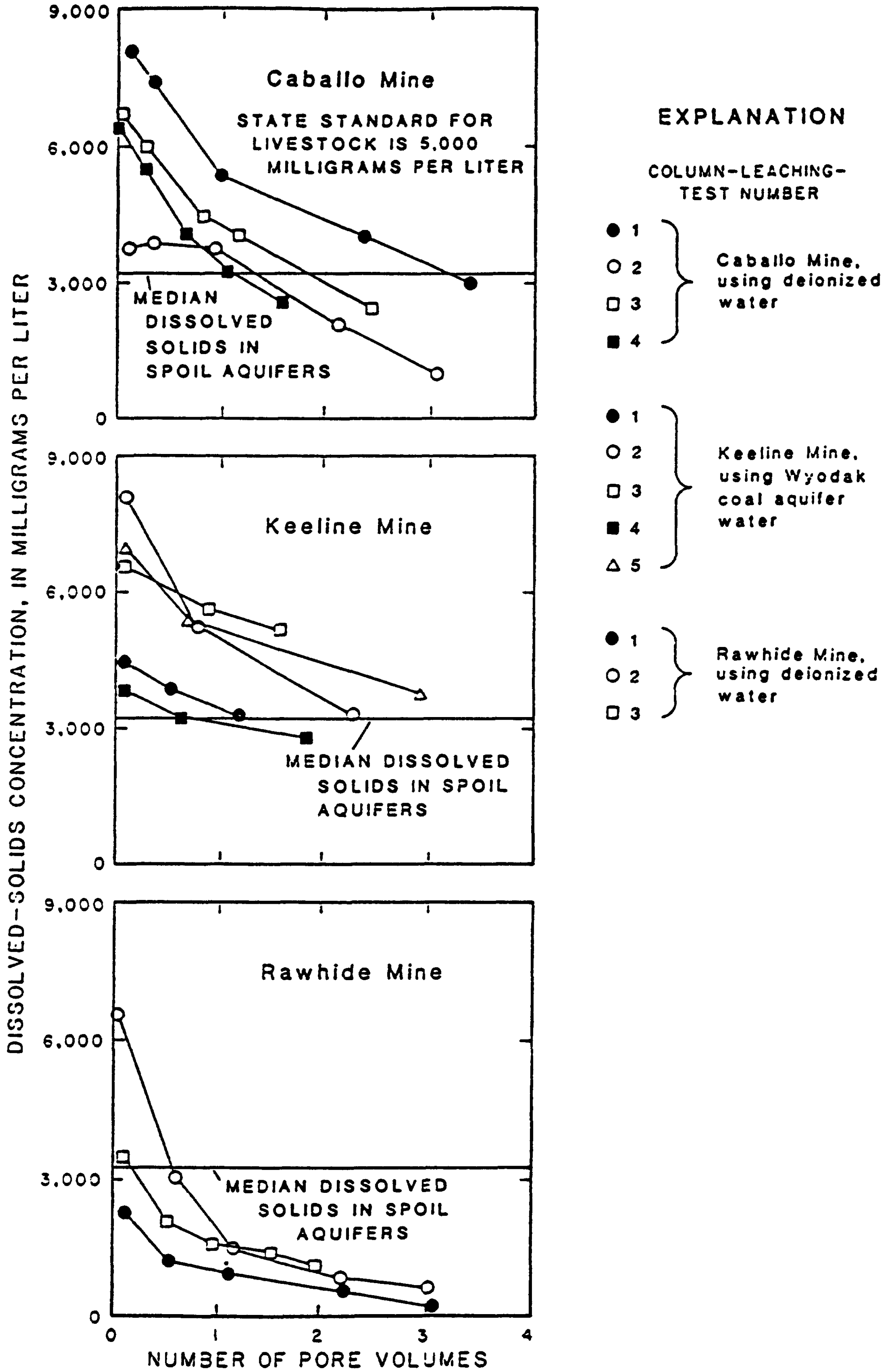


Figure 16.--Comparison of dissolved-solids concentration in water derived from selected column-leaching tests to the number of pore volumes of water leached through the overburden.

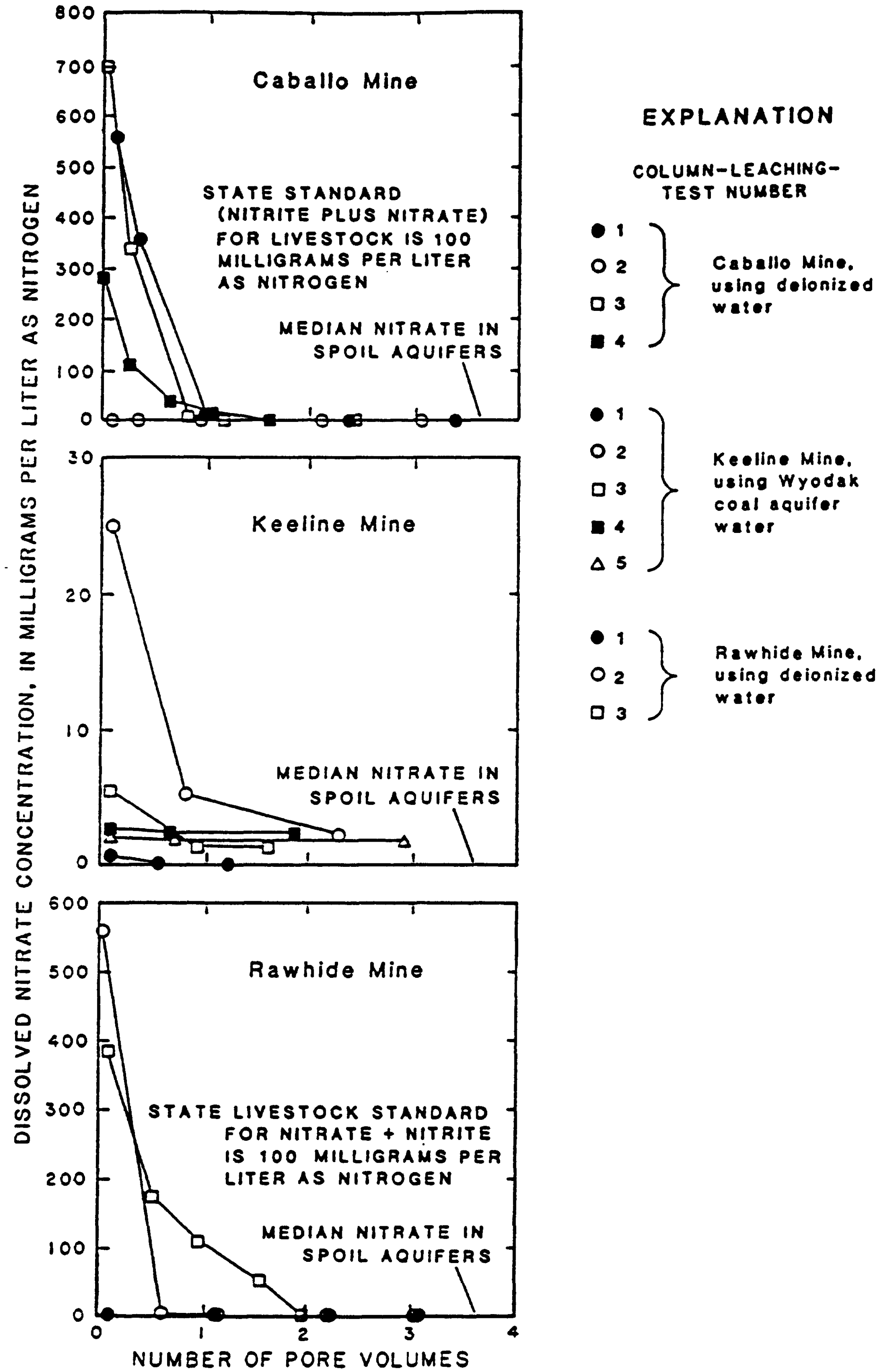


Figure 17.--Comparison of dissolved-nitrate concentration in water derived from selected column-leaching tests to the number of pore volumes of water leached through the overburden.

The dissolved-selenium concentrations in water derived from column-leaching tests at the three mines became smaller as the number of pore volumes leaching through the columns increased (fig. 18). The largest concentration of dissolved selenium measured in the initial column effluent exceeded 1.5 mg/L using spoil material from Rawhide Mine (fig. 18). Ground water with selenium concentrations larger than 0.05 mg/L is considered unsuitable for consumption by livestock (Wyoming Department of Environmental Quality, 1980a, p. 9). Dissolved-selenium concentrations in the spoil aquifer at the Caballo Mine initially exceeded 0.5 mg/L. Similar to the dissolved-solids and nitrate concentrations in the effluent waters, the graphs for dissolved selenium concentrations show a distinct flattening of the slope that occurred after about 1 pore volume of water was leached through the columns (fig. 18). Effluent waters derived after about 1 pore volume had passed through the columns generally had selenium concentrations exceeding the State standard for livestock of 0.05 mg/L (fig. 18).

Determination of overburden suitability for aquifer restoration may be another important use of column-leaching tests. The specific conductance of overburden and the content of nitrate in overburden in relation to concentrations of dissolved solids and dissolved nitrate (as nitrogen) in the first effluent water (less than 0.11 pore volume) in the three sets of column-leaching tests are shown in figure 19. When the specific conductance of the overburden material was greater than 2,900 μS/cm (microsiemens per centimeter at 25 °C), it produced an initial effluent water with a dissolved-solids concentration greater than the State standard for livestock (fig. 19). No standard for specific conductance of the overburden material is recommended for aquifer restoration (Wyoming Department of Environmental Quality, 1984).

Contents of extractable nitrate greater than 30 μg/g (micrograms per gram) as nitrogen in the overburden material produced an initial effluent water with a dissolved-nitrate concentration exceeding the State standard for livestock (fig. 19). Overburden material with contents of extractable nitrate less than 50 μg/g as nitrogen are considered suitable for aquifer restoration after mining (Wyoming Department of Environmental Quality, 1984).

In general, water-soluble selenium contents of overburden material do not indicate the total quantity of selenium that could be released to ground water after mining. Although selenium concentrations in water derived from column-leaching tests were usually much larger than 0.005 mg/L, the water-soluble selenium contents in the overburden material used in the column-leaching tests were generally less than the detection limit of 20 μg/kg (micrograms per kilogram). Total-selenium contents in overburden samples from the Keeline and Caballo Mines (not the same overburden material used in the column-leaching tests) were determined (fig. 20), and ranged from less than 100 to 3,800 μg/kg. In general, the sandstone samples from these mines had total-selenium contents less than 500 μg/kg; whereas, the shale samples had total-selenium contents ranging from 800 μg/kg to 3,800 μg/kg (fig. 20). Ebens and Shacklette (1982, p. 121) reported the average selenium content as 190 μg/kg in sandstone from the Fort Union Formation. Spoil-material samples from the Dave Johnston Mine had an average selenium content of 280 μg/kg (Ebens and Shacklette, 1982, p. 120).

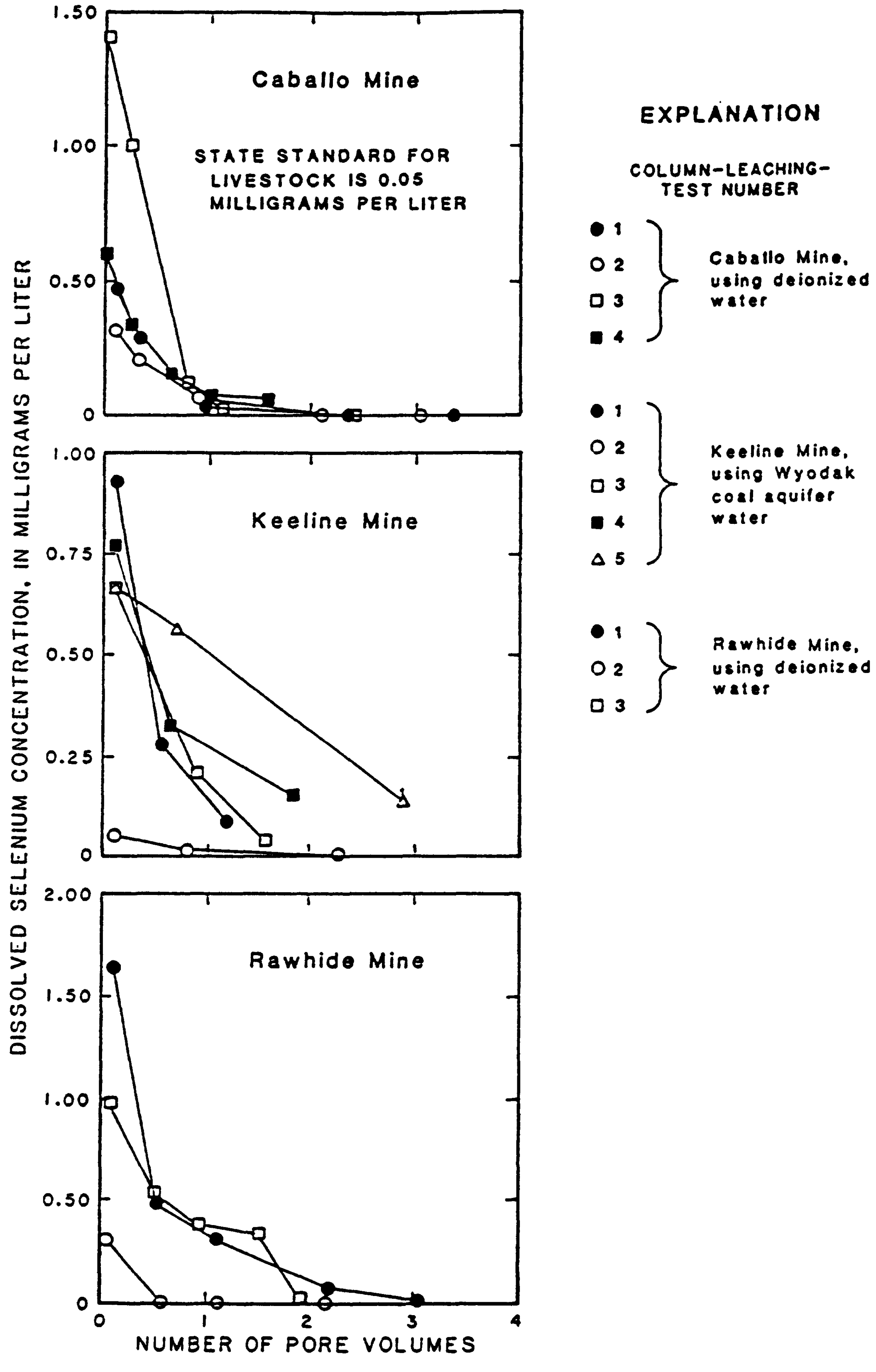


Figure 18.--Comparison of dissolved-selenium concentration in water derived from selected column-leaching tests to the number of pore volumes of water leached through the overburden.

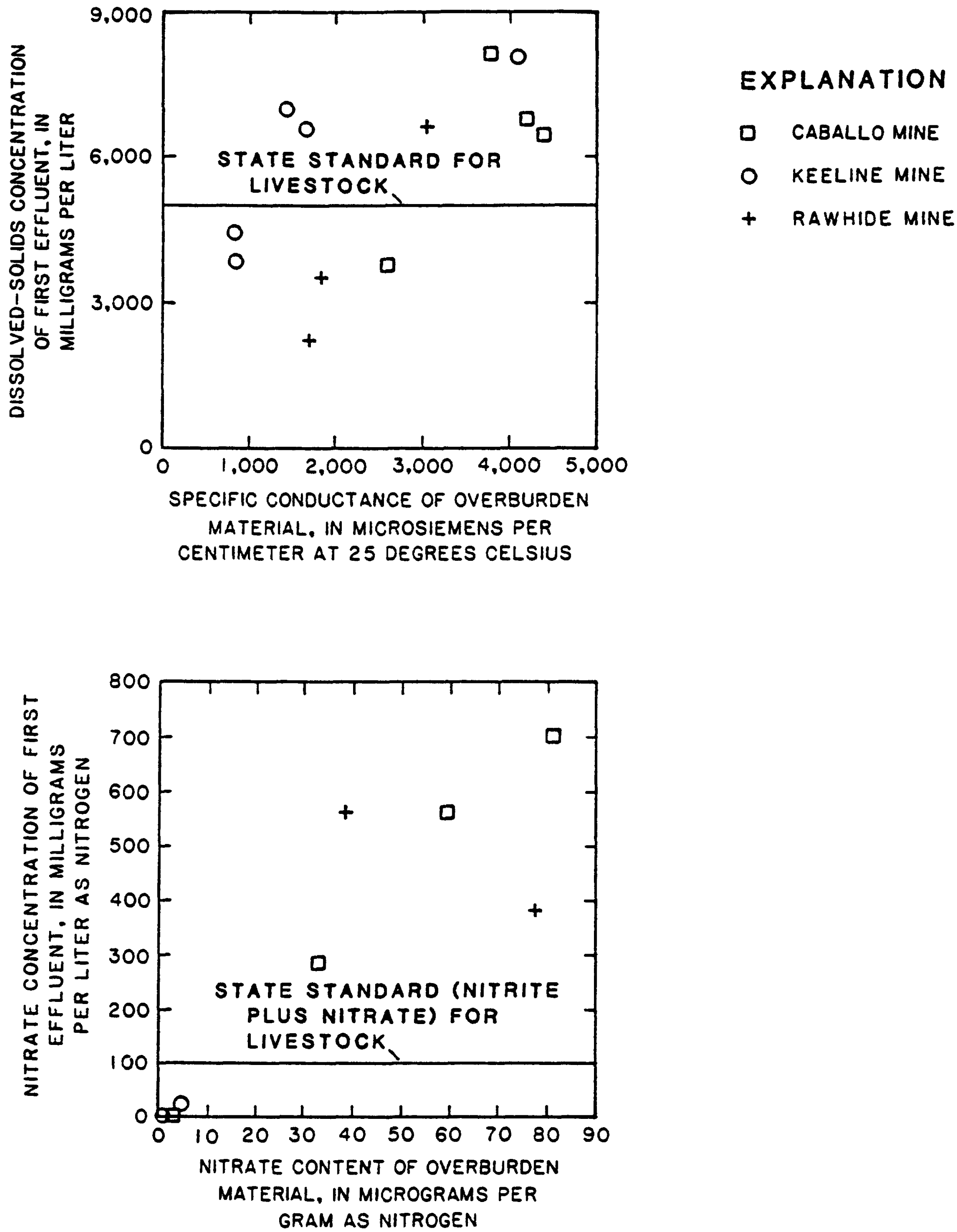


Figure 19.--Dissolved-solids and nitrate concentrations in the first effluent from selected column-leaching tests in relation to the specific conductance and extractable-nitrate content in the overburden material used in the tests.

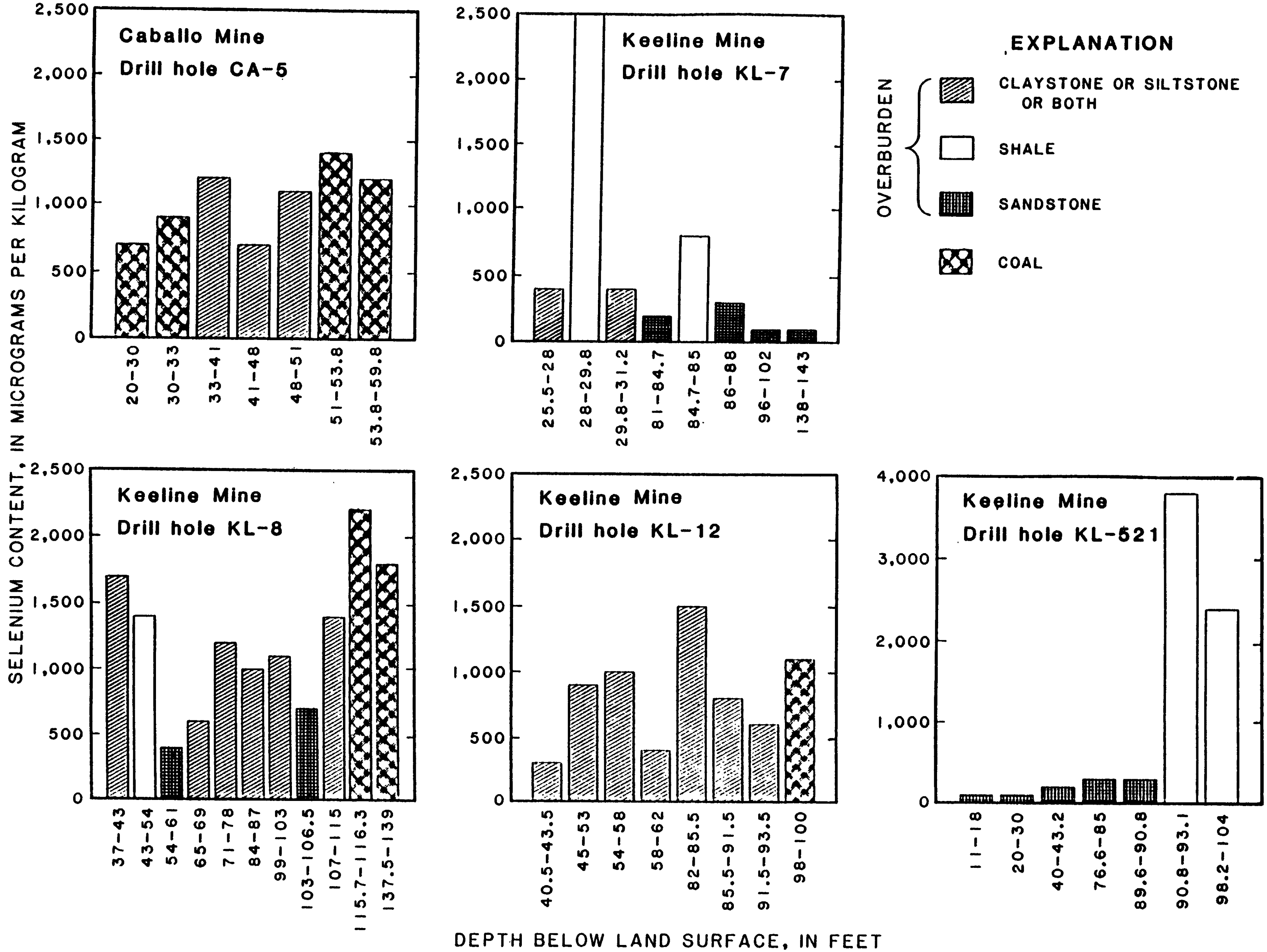


Figure 20.--Total-selenium content in overburden and coal samples from the Caballo and Keeline Mines.

In summary, batch-mixing experiments using a water-to-spoil material ratio of 2:1 (by weight), had smaller major-ion concentrations compared to a July 1984 sample of the water quality in the spoil aquifer at the Cordero Mine. Column-leaching test results were highly variable depending on the type of water used in the columns (deionized or water from a coal aquifer) and the chemical composition of the overburden. The median dissolved-solids and nitrate concentrations using all postmining water analyses in the study area were generally exceeded until at least one pore volume had passed through the columns. Smaller concentrations of dissolved solids, nitrate, and selenium in future postmining water were predicted by the column-leaching test results. Actual postmining nitrate and selenium concentrations are currently (1986) indicating decreases with time at selected wells in the study area (figs. 11 and 12).

Site-Specific Geochemical Studies

The Cordero and Dave Johnston Mines (fig. 10) were selected for detailed study. Detailed geochemical data were collected from these mines and used to interpret the hydrogeology of the spoil-aquifer systems and the possible geochemical reactions controlling the evolution of postmining ground-water quality. Conclusions drawn from the following site-specific studies may not apply to all mine sites in the study area because of differences in overburden quality, hydrologic conditions, methods of mining, and so forth.

Cordero Mine

Hydrogeology

Ground water at the Cordero Mine is present in the Wasatch aquifer, Wyodak coal aquifer, and spoil aquifers. Except for a few isolated areas, yields from wells completed in the Wasatch aquifer are small (Cordero Mine personnel, written commun., 1983). Clinker along the eastern edge of the Cordero Mine (fig. 21) is partially saturated except where mine dewatering operations have taken place. The spoil aquifer studied at the Cordero Mine (fig. 22), which was created during pit backfilling, currently (1987) is partially saturated.

The potentiometric surface of the Wyodak coal aquifer is based on ground-water levels measured during December 1981 (fig. 21). Discharge to the spoil aquifer from the Wyodak coal aquifer is indicated by the configuration of the potentiometric surface (fig. 21). The proximity of clinker along the eastern extent of the mine (fig. 21) creates a potential source of recharge to the spoil aquifer. One additional source of recharge to the spoil aquifer is water from a pond created to store water for dust suppression (site CSW-1). One possible source of recharge to the Wyodak coal aquifer was from the clinker-coal outcrop. Recharge to the Wyodak coal aquifer from the clinker has been estimated to be about 4.5 (gal/d)/ft^2 of clinker-coal contact (Cordero Mine personnel, written commun., 1983).

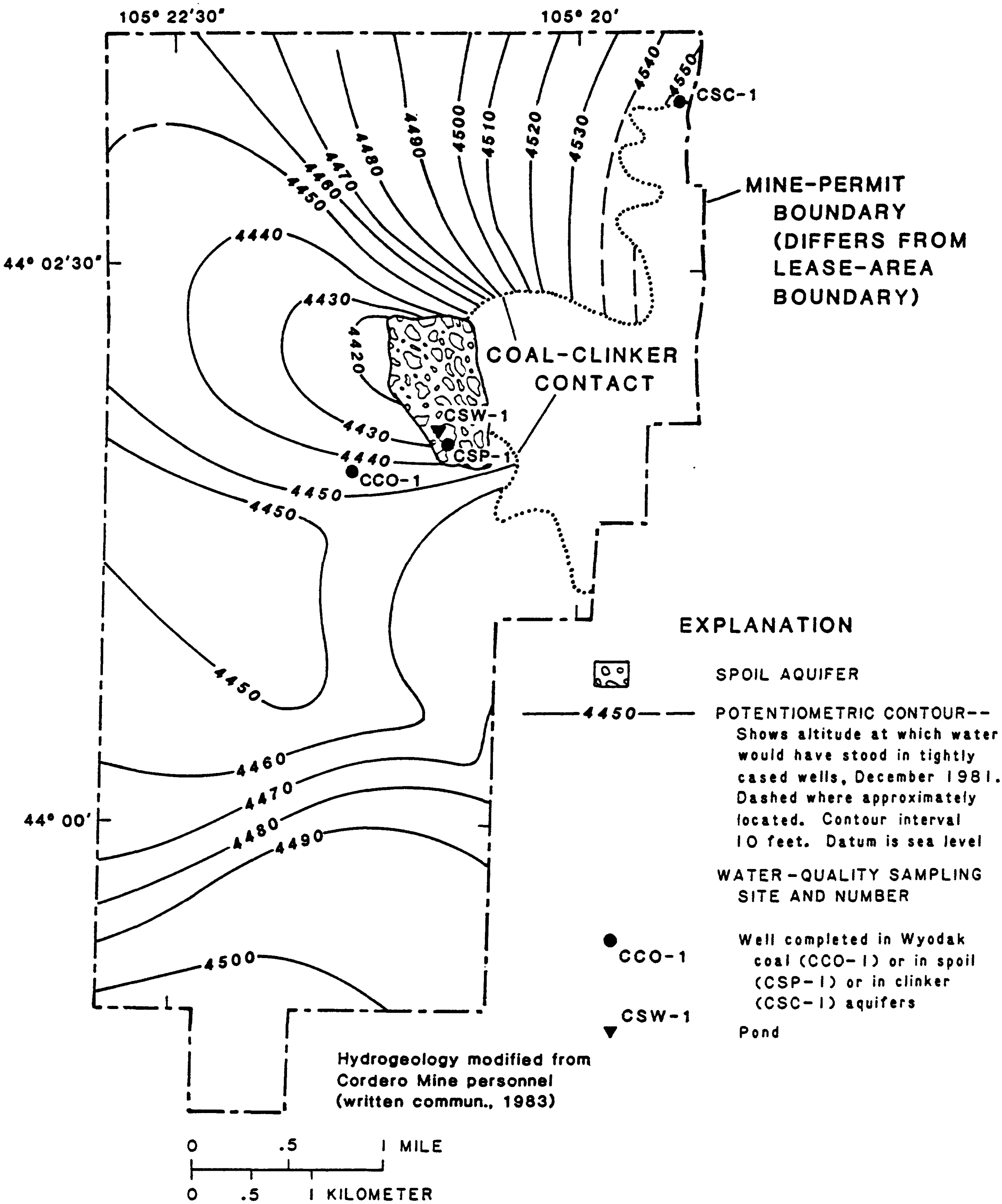


Figure 21.--Potentiometric surface of the Wyodak coal aquifer during December 1981 and location of water-quality sampling sites, Cordero Mine.

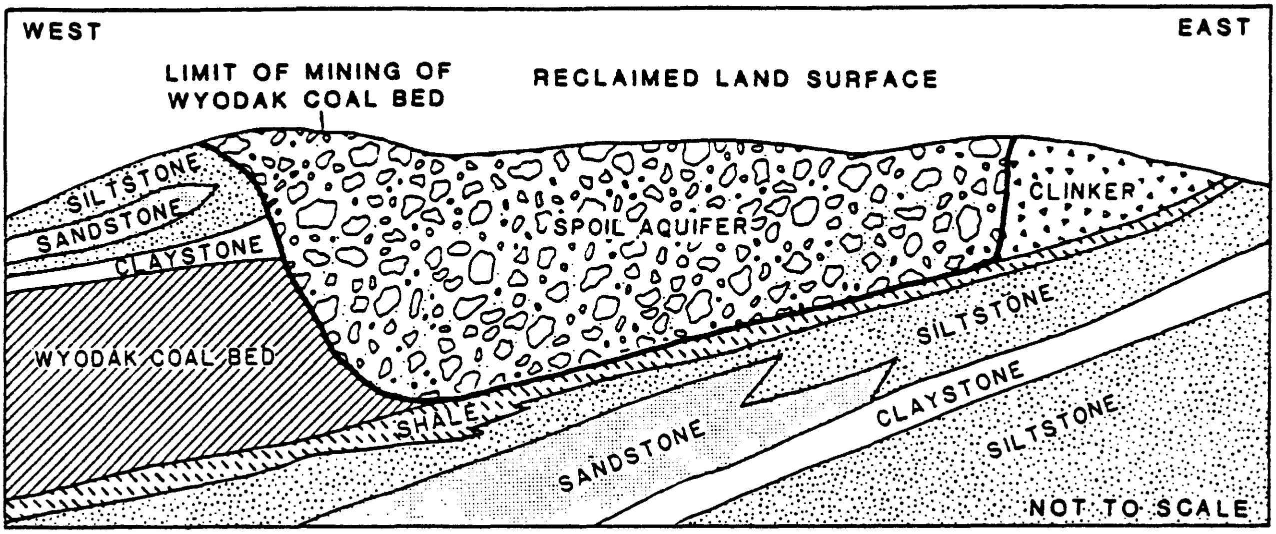


Figure 22.--Diagrammatic geologic section of the Wyodak coal bed of the Tongue River Member of the Fort Union Formation and associated strata, and the spoil aquifer after mining, Cordero Mine.

The concentrations of stable and radioactive isotopes in ground and surface water from the Cordero Mine were used to confirm previously identified recharge sources to the spoil aquifer. Water samples were collected from wells completed in the Wyodak coal aquifer (well CCO-1), the spoil aquifer (well CSP-1), and the clinker aquifer (well CSC-1), and from a pond overlying the spoil aquifer (site CSW-1) (fig. 21). The isotopic compositions of ground and surface water from the Cordero Mine are shown in table 7.

The $\delta^{18}O$ (oxygen-18/oxygen-16 isotopic ratio) and δD (deuterium/hydrogen isotopic ratio) values for ground- and surface-water samples collected from the Cordero Mine were compared to the composition of the North American continental precipitation as reported by Gat (1980) ($\delta D = (7.95\delta^{18}O) + 6.03$). The $\delta^{18}O$ and δD values from all four samples represented in figure 23 approximately correspond to the composition of North American continental precipitation, indicating the presence of present-day meteoric water in the aquifers. The $\delta^{18}O$ and δD composition of the water samples from wells CSP-1 (spoil aquifer) and CCO-1 (Wyodak coal aquifer) were similar (fig. 23), which indicates water from the coal aquifer may be a principal source of recharge to the spoil aquifer. However, significant quantities of water from the Wyodak coal aquifer recharging the spoil aquifer is not supported by the tritium content of water from the spoil aquifer.

Table 7.--Isotopic ratios or activities of isotopes in ground- and surface-water samples collected at Cordero Mine

[SO_4^{-2}, sulfate; $\delta^{18}O$, oxygen-18/oxygen-16 isotopic ratio; δD, deuterium/hydrogen isotopic ratio; $\delta^{13}C$, carbon-13/carbon-12 isotopic ratio; $\delta^{34}S$, sulfur-34/sulfur-32 isotopic ratio; pCi/L, picocuries per liter]

Well or site	Source	Per mil				Tritium (pCi/L)
		Oxygen ($\delta^{18}O$)	Hydrogen (δD)	Carbon ($\delta^{13}C$)	Sulfur, SO_4^{-2} ($\delta^{34}S$)	
CCO-1	Wyodak coal aquifer	-16.5	-127	-8.2	-9.8	4
CSP-1	Spoil aquifer	-16.1	-127	-12.3	-8.1	130
CSC-1	Clinker aquifer	-18.9	-146	-15.2	-7.8	180
CSW-1	Pond	-16.6	-113	-7.5	-7.8	71

Tritium concentrations in water samples from the Cordero Mine ranged from 71 to 180 pCi/L (picocuries per liter) except for water from well CCO-1 (completed in Wyodak coal aquifer), which had a concentration of 4 pCi/L (table 7). The small tritium concentration in the water sample from the Wyodak coal aquifer indicates the lack of substantial quantities of recent (post-1952) recharge. The large tritium concentration in water from the spoil aquifer indicates a substantial proportion of the total recharge is recent recharge. Because water from well CCO-1 (completed in Wyodak coal aquifer) had a small tritium concentration, water from the Wyodak coal aquifer was not considered to be a principal source of recharge to the spoil aquifer. The large tritium concentrations in water from well CSC-1 (completed in clinker aquifer) and CSW-1 (pond) indicates these are the possible major recharge sources to the spoil aquifer. Direct infiltration of precipitation also could be a recharge source to the spoil aquifer. Although the tritium concentration in precipitation was not measured, recent precipitation probably has a tritium concentration similar to that in water from site CSW-1 (pond).

The approximate temperature of recharge water was derived from $\delta^{18}O$ values for samples of ground water collected at the Cordero Mine. The $\delta^{18}O$ values for continental precipitation have been correlated with average surface temperatures by Yurtsever (1975), allowing a determination of recharge-water temperature to be made. The $\delta^{18}O$ values from ground-water samples collected at the Cordero Mine ranged from -18.9 to -16.1 per mil, indicating a recharge-water temperature of about 0 °C (fig. 24). An average recharge-water temperature of about 0 °C indicates that most recharge to ground water at the mine is derived from spring snowmelt rather than late spring and early summer rainfall.

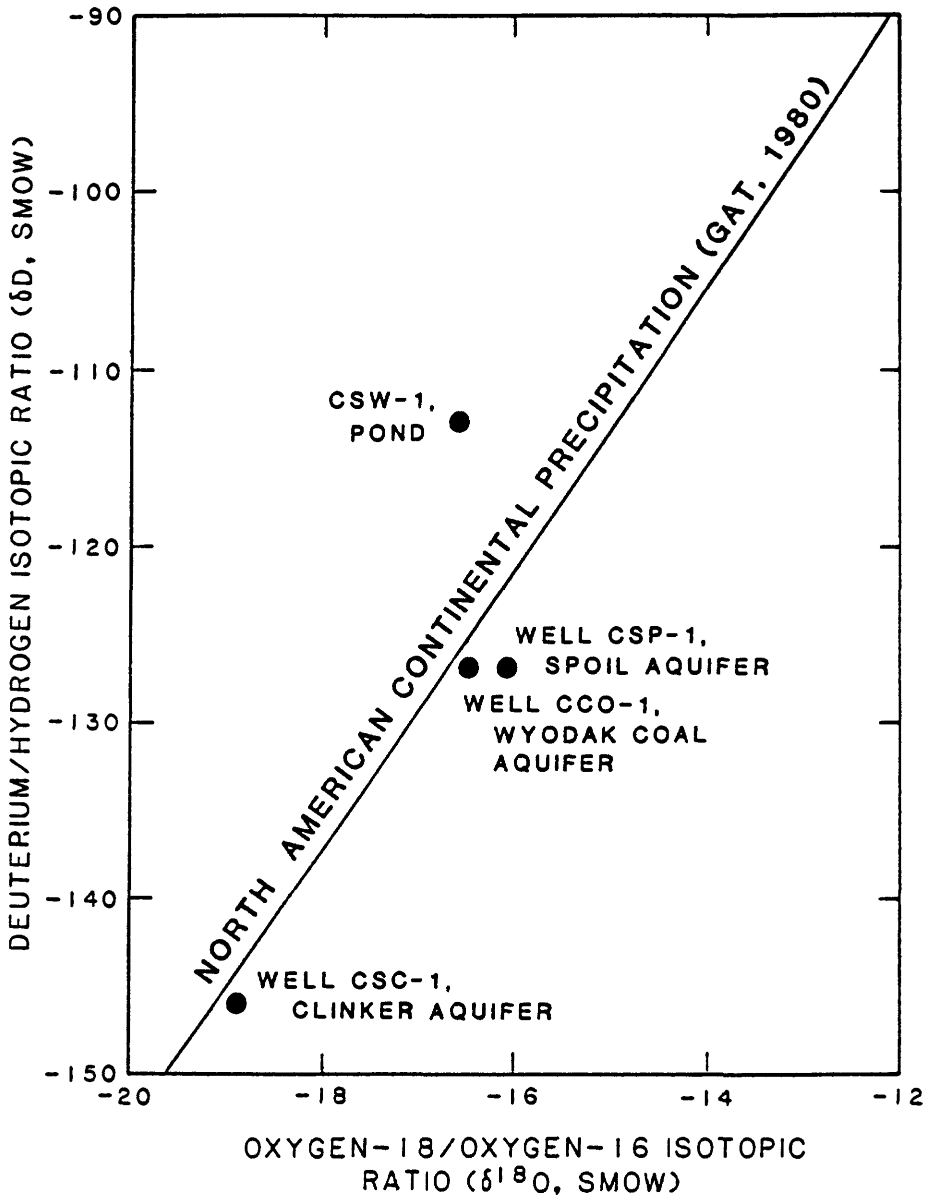


Figure 23.--Comparison of the isotopic composition of ground-water samples from the Cordero Mine to the isotopic composition of North American continental precipitation. SMOW, standard mean ocean water.

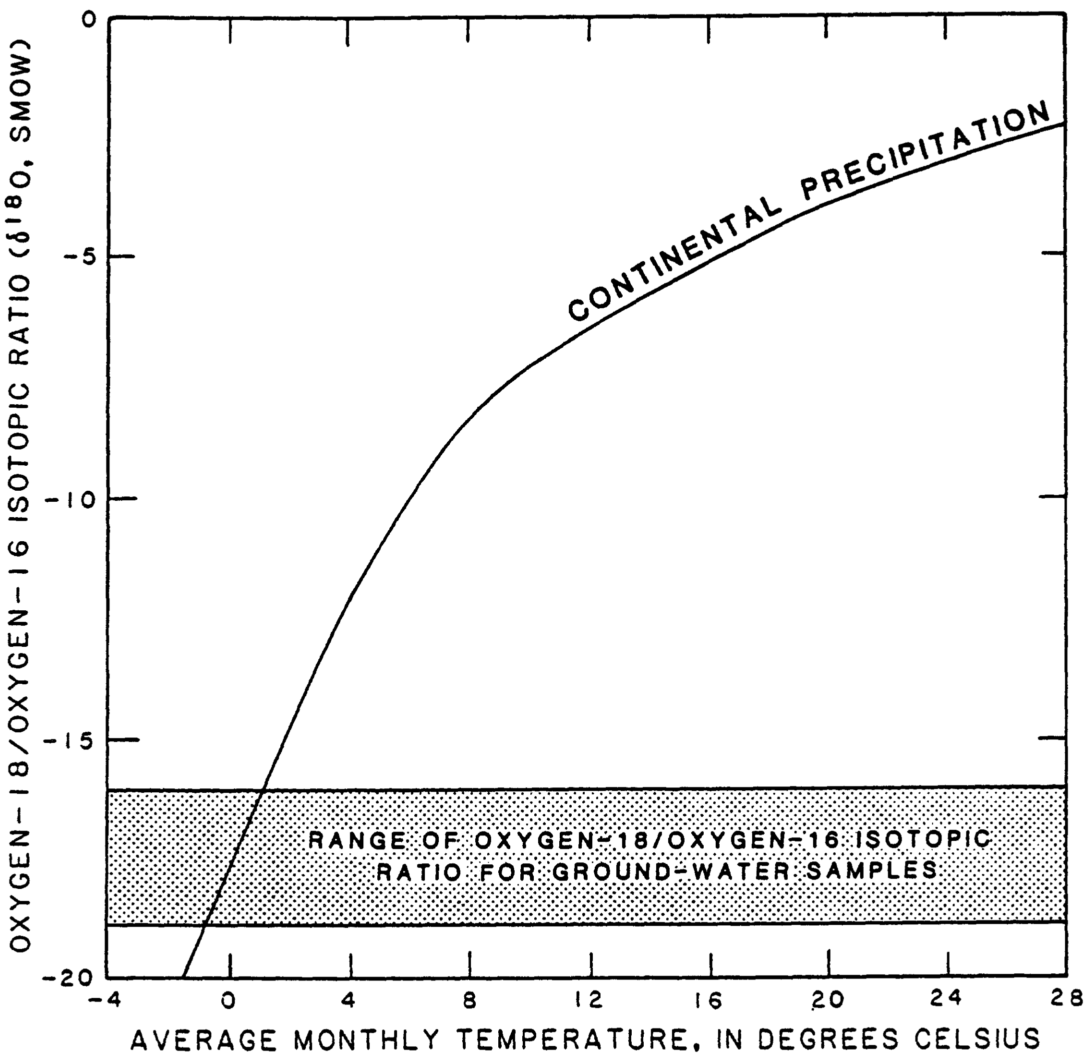


Figure 24.--Correlation of $\delta^{18}O$ composition of continental precipitation compared to the average monthly temperature from continental stations (Yurtsever, 1975) superposed with the $\delta^{18}O$ composition of ground-water samples from the Cordero Mine. SMOW, standard mean ocean water.

Mineral-water relations

Mass-balance and thermodynamic calculations, in combination with the mineralogy of the spoil material, were used to establish a plausible set of chemical reactions that would simulate the actual changes in water quality during recharge of the spoil aquifer. By identifying the possible chemical reactions controlling the actual changes in water quality during recharge of the spoil aquifer, probable solid-phase sources of the solutes may be determined. In addition, further changes in postmining water quality can be evaluated.

The computer program WATEQF (Plummer and others, 1978) was used to calculate the activities of the aqueous species in the water samples that were collected. Based on the activities calculated by WATEQF for the various species of interest, the degree of saturation with respect to a particular mineral phase was determined for each water analysis. The degree of saturation with respect to a particular mineral phase is defined as the ion-activity product divided by the equilibrium constant for the mineral of interest. Log transformation of this ratio is referred to as a saturation index (SI). In general, a positive SI for a particular mineral phase denotes that the mineral, if present, will tend to precipitate from solution; whereas, a negative SI denotes that the mineral will tend to dissolve. An SI of about zero signifies that the solution is in equilibrium with respect to the mineral of interest. The results of the speciation calculations for calcite and gypsum are given in table 8.

Mass-balance calculations, using the computer program BALANCE (Parkhurst and others, 1982a), were performed to determine the proportions of plausible phases that could enter or leave the water to result in the actual changes in water quality. The general chemical reaction is in the form of the following:

$$\text{initial solution composition} + \text{reactant phases} \longrightarrow \text{final solution composition} + \text{product phases},$$

where the terms "reactant phases" and "product phases" refer to constituents that enter or leave the aqueous phase during a reaction. The possible reactant and product phases were determined by the mineralogical analyses of the spoil material as well as from speciation calculations and geological inferences derived from the spoil material.

On the basis of the stable isotope data, possible sources of recharge to the spoil aquifer include water from the clinker aquifer and the pond. Mass-balance calculations were made for both possible sources. For the first calculation, the chemical composition of water from well CSC-1 (table 8, completed in clinker aquifer) was considered to be the chemical composition of all recharge water. For the second calculation, the chemical composition of water from site CSW-1 (table 8, pond) was considered to be the chemical composition of all recharge water. The chemical composition of water from well CSP-1, (table 8, completed in spoil aquifer) was considered to be the chemical composition of the final water in both mass-balance calculations.

Table 8.--Water-quality data used in the geochemical-reaction models, Cordero Mine

[Concentration, in millimoles per liter, except as indicated]

Chemical property or constituent	Well completed in clinker aquifer (well CSC-1)	Well completed in spoil aquifer (well CSP-1)	Pond (site CSW-1)
pH (units)	6.9	6.8	7.2
Dissolved oxygen	[1].156	.025	[1].156
Redox state	109.747	258.584	13.892
Calcium	10.728	14.471	.649
Magnesium	3.414	12.751	.346
Sodium	1.479	29.578	1.479
Potassium	.639	.844	.079
Sulfur	12.492	34.354	1.562
Chloride	.178	3.667	.118
Fluoride	.032	.016	.010
Silica	.632	.216	.020
Aluminum	[1].000	[1].000	[1].000
Iron	.005	.004	.000
Carbon, total	8.389	13.087	.974
Saturation index:			
Calcite	.143	.099	-1.462
Gypsum	-.170	.117	-1.719

[1] Estimated concentration; analytical datum was either less than detection limit or was not available.

Plausible phases considered in the following geochemical-reaction models are based on the mineralogical and sulfur-form analyses of the spoil material at the Cordero Mine (L.R. Larson, U.S. Geological Survey, written commun., 1986). The following minerals were identified by X-ray diffraction: smectite, chlorite, illite, kaolinite, gypsum, quartz, potassium feldspar, plagioclase feldspar, dolomite, and calcite. Pyrite was inferred by the sulfur-form analyses. Seven reaction sets of plausible phases are considered for both sources of recharge to the spoil aquifer (table 9). In each of the seven sets of phases considered, magnesium is derived from chlorite or epsomite or both; sodium from cation exchange and halite dissolution; potassium from the dissolution of potassium feldspar; chloride from halite dissolution; and silica from potassium feldspar and chlorite. Precipitation of chalcedony and kaolinite was the sink for silica, and precipitation of kaolinite is the sink for aluminum.

Table 9.--Selected reaction sets of plausible phases for mass-balance calculations, Cordero Mine

Reaction set	Plausible phases
1	Calcite, carbon dioxide, cation exchange, chlorite, goethite, halite, kaolinite, oxygen, potassium feldspar, pyrite, silica
2	Carbon dioxide, cation exchange, chlorite, goethite, gypsum, halite, kaolinite, oxygen, potassium feldspar, pyrite, silica
3	Calcite, cation exchange, chlorite, goethite, gypsum, halite, kaolinite, oxygen, potassium feldspar, pyrite, silica
4	Calcite, cation exchange, chlorite, goethite, gypsum, halite, kaolinite, organic carbon, oxygen, potassium feldspar, silica
5	Calcite, carbon dioxide, cation exchange, chlorite, goethite, gypsum, halite, kaolinite, oxygen, potassium feldspar, silica
6	Calcite, carbon dioxide, cation exchange, chlorite, gypsum, halite, kaolinite, potassium feldspar, silica
7	Calcite, cation exchange, chlorite, epsomite, gypsum, halite, kaolinite, potassium feldspar, silica

Possible sources considered for the actual sulfate increases include pyrite, gypsum, and epsomite. In reaction set 1, pyrite oxidation is the only source of sulfate considered; whereas reaction sets 2 and 3 also considered gypsum. Gypsum dissolution is considered as the only source of sulfate in reaction sets 4, 5, and 6; whereas reaction set 7 also considered epsomite in combination with gypsum as sulfate sources.

Pyrite and chlorite are considered as possible sources of iron with goethite as the only iron sink considered. In reaction sets 1, 2, and 3, pyrite is the primary iron source. Chlorite weathering is the source of iron in reaction sets 4 and 5. As noted by Powell and Larson (1985, p. 7), ferrous iron can substitute for magnesium in the chlorite structure. Reaction sets 6 and 7 do not include iron sources or sinks because iron is not assumed to be in the chlorite mineral structure for these reaction sets.

Carbon sources and sinks considered in the reaction sets include calcite, carbon dioxide, and organic matter (for example, carbon with a valence of 0). Reaction sets 1, 2, 5, and 6 are open to exchange with carbon dioxide; reaction sets 3, 4, and 7 are not.

Oxidation-reduction reactions are considered as possible geochemical reactions in reaction sets 1, 2, 3, 4, and 5; whereas they are not considered in reaction sets 6 and 7. Oxidation-reduction reactions considered include pyrite oxidation (table 10, reaction 1), oxidation of ferrous iron (table 10, reaction 3), and oxidation of organic matter (table 10, reaction 4).

Table 10.--Pertinent chemical reactions

[Subscript (g) denotes gaseous phase]

Reaction number	Reaction
	Oxidation-reduction
1	$FeS_2 + 3.5_{2(g)} + H_2O = Fe^{+2} + 2SO_4^{-2} + 2H^+$ (pyrite)
2	$Fe_2O_3 + 2SO_4^{-2} + 4.5CH_2O + 1.5H_2O = 2FeS + 4.5HCO_3^- + 0.5H^+$ (iron oxide) (organic matter) (ferrous sulfide)
3	$Fe^{+2} + 0.25O_2 + H^+ = Fe^{+3} + 0.5H_2O$
4	$CH_2O + O_2 = CO_{2(g)} + H_2O$ (organic matter)
	Mineral precipitation
5	$Ca^{+2} + 2HCO_3^- = CaCO_3 + CO_2 + H_2O$ (calcite)

The redox state (RS) shown in table 8 is a means of keeping track of electron transfer in the redox reactions considered. Redox state is defined as follows:

$$RS = \sum_{i=1}^{I} m_i v_i \qquad (3)$$

where I = the number of species in solution,

m_i = the molality of the i'th species in solution, and

v_i = the operational valance of the species.

Plummer and others (1983, p. 4-6) address the definition of operational valance.

Mass-balance calculation results for the seven reaction sets of combined plausible phases (table 11) identify reaction models that can be used to explain water-quality changes that occurred during recharge of the spoil aquifer from both possible recharge sources. Each reaction set in table 11 represents the results of a particular combination of the plausible phases considered. The values in the columns indicate the concentration of each phase (in millimoles per kilogram of water) either entering or leaving the water. A positive value (+) indicates dissolution of the phase; a negative value (-) indicates formation of the phase.

The feasibility of reaction model 1 may be tested by comparing the measured $\delta^{34}S$ in water from well CSP-1 (completed in spoil aquifer) with the calculated isotopic composition of dissolved sulfate in the sample indicated by the mass transfer of pyrite in reaction model 1 (table 11). This calculation can be done with both sources of recharge water. Because no sulfur minerals are forming in reaction model 1, the calculated $\delta^{34}S$ of dissolved sulfate in water from well CSP-1 can be approximated according to the linear isotope-balance equation (Plummer and others, 1983, p. 675):

$$\delta^{34}S_{(\text{spoil aquifer})} = \frac{[2a_{\text{pyrite}}(\text{PYIC}) + a_{\text{gypsum}}(\text{GYIC}) + SO_4^{-2}{}_{(\text{recharge})}(\text{RWIC})]}{SO_4^{-2}{}_{(\text{spoil aquifer})}} \qquad (4)$$

where

a_{pyrite} = the stoichiometric coefficient of pyrite from the reaction model (table 11),

PYIC = the $\delta^{34}S$ composition of pyrite,

a_{gypsum} = the stoichiometric coefficient of gypsum from the reaction model,

GYIC = the $\delta^{34}S$ composition of gypsum,

RWIC = the $\delta^{34}S$ composition of the recharge water, and

SO_4^{-2}(recharge) and SO_4^{-2}(spoil water) = the total concentration of SO_4^{-2} in the recharge water and spoil water, respectively.

The value of -4.7 per mil, used for the $\delta^{34}S$ composition of pyrite is derived from the average $\delta^{34}S$ composition of 10 samples containing disseminated pyrite collected from the Wyodak coal bed in the Powder River structural basin by Hackley and Anderson (1986, p. 1706).

Using equation 4 and the calculated mass transfer of pyrite from reaction model 1 (table 11), the values of $\delta^{34}S$ in water from well CSP-1 (completed in spoil aquifer) are calculated for both possible recharge sources. The calculated values of $\delta^{34}S$ for water from well CSP-1 are -5.8 per mil using the clinker-aquifer recharge source and -4.8 per mil using the surface-pond recharge source. The actual $\delta^{34}S$ of water from well CSP-1 is -8.1 per mil (table 7). Lack of agreement between the calculated and actual $\delta^{34}S$ values indicates that reaction model 1 may not be representative of actual conditions. However, the site specific $\delta^{34}S$ composition of disseminated pyrite at the Cordero Mine needs to be determined for more precise isotope-balance calculations.

The water-quality changes occurring at the Cordero Mine probably are not represented by reaction models 1, 2, and 3. Reaction models 1, 2, and 3 all derive at least part of the actual increase in dissolved sulfate from pyrite dissolution (table 11). Because the pH of water from well CSP-1 (completed in spoil aquifer) is 6.8 (table 8), any pyrite dissolution that occurs must be buffered by calcite dissolution. Reaction model 2 does not consider calcite dissolution as a plausible phase to buffer the acidity produced by the pyrite oxidation and, therefore, is eliminated from further consideration.

Although reaction models 1 and 3 have substantial calcite dissolution and pyrite oxidation (table 11), the dissolution is not sufficient to buffer all of the acidity. For every 1 mmol (millimole) of pyrite oxidized, at least 4 mmol of acidity are produced (Drever, 1982, p. 62). The concentration of alkalinity available for the buffering of pyrite oxidation is a function of the partial pressure of carbon dioxide and the solubility of the calcite. The calcite-pyrite equilibrium line shown in figure 25 is derived from the addition of oxygen to each of the initial recharge waters, while maintaining equilibrium with calcite, pyrite, and goethite. The quantity of calcite and pyrite dissolution predicted by reaction models 1 and 3 also is plotted in figure 25. As shown in figure 25, the quantity of calcite dissolution accompanying the pyrite oxidation in reaction models 1 and 3 is insufficient for complete acid buffering. Because the pH measured in water from well CSP-1 (completed in spoil aquifer) is not acidic enough to indicate unbuffered pyrite dissolution, reaction models 1 and 3 are eliminated as representative models.

Table 11.--Results of mass-balance calculations for water from the well

[Data for phases shown in millimoles per of the phase; -, indicates formation

Plausible phases	Reaction model 1: Well completed in clinker aquifer	Reaction model 1: Pond	Reaction model 2: Well completed in clinker aquifer	Reaction model 2: Pond	Reaction model 3: Well completed in clinker aquifer	Reaction model 3: Pond
Calcite	+16.0480	+26.0970	--	--	+4.6980	+12.1130
Carbon dioxide	-11.3500	-13.9840	+4.6980	+12.1130	--	--
Cation exchange	+12.3050	+12.2750	+12.3050	+12.2750	+12.3050	+12.2750
Chlorite	+3.1123	+4.1350	+3.1123	+4.1350	+3.1123	+4.1350
Epsomite	--	--	--	--	--	--
Goethite	-17.1567	-24.6620	-9.1327	-11.6135	-11.4817	-17.6700
Gypsum	--	--	+16.0480	+26.0970	+11.3500	+13.9840
Halite	+3.4890	+3.5490	+3.4890	+3.5490	+3.4890	+3.5490
Kaolinite	-3.2148	-4.5175	-3.2148	-4.5175	-3.2148	-4.5175
Organic carbon	--	--	--	--	--	--
Oxygen	+42.2664	+63.4215	+12.1764	+14.4896	+20.9852	+37.2015
Potassium feldspar	+.2050	+.7650	+.2050	+.7650	+.2050	+.7650
Pyrite	+10.9310	+16.3960	+2.9070	+3.3475	+5.2560	+9.4040
Silica	-3.9383	-5.4690	-3.9383	-5.4690	-3.9383	-5.4690

completed in the clinker aquifer and from the pond at Cordero Mine

kilogram of water. +, indicates dissolution of the phase; --, indicates no data]

Reaction model							
4		5		6		7	
Well completed in clinker aquifer	Pond	Well completed in clinker aquifer	Pond	Well completed in clinker aquifer	Pond	Well completed in clinker aquifer	Pond
+5.8140	-6.6950	-5.8140	-6.6950	-5.8140	-6.6950	+4.6980	+12.1130
--	--	+10.5120	+18.8080	+10.5120	+18.8080	--	--
+12.3050	+12.2750	+12.3050	+12.2750	+12.3050	+12.2750	+12.3050	+12.2750
+3.1123	+4.1350	+3.1123	+4.1350	+1.8674	+2.4810	+2.4810	-1.2806
--	--	--	--	--	--	+10.5120	+18.8080
-6.2257	-8.2660	-6.2257	-8.2660	--	--	--	--
+21.8620	+32.7920	+21.8620	+32.7920	+21.8620	+32.7920	+11.3500	+13.9840
+3.4890	+3.5490	+3.4890	+3.5490	+3.4890	+3.5490	+3.4890	+3.5490
-3.2148	-4.5175	-3.2148	-4.5175	-1.9699	-2.8635	-.1325	+.8981
+10.5120	+18.8080	--	--	--	--	--	--
+11.7872	+20.7445	+1.2752	+1.9365	--	--	--	--
+.2050	+.7650	+.2050	+.7650	+.2050	+.7650	+.2050	+.7650
--	--	--	--	--	--	--	--
-3.9383	-5.4690	-3.9383	-5.4690	-2.6934	-3.8150	-0.5910	-0.0534

Both recharge sources in reaction model 4 derive the increase in carbon from oxidation of organic carbon (table 11). Organic matter in sedimentary rocks is generally refractory (Drever, 1982, p. 292) and probably is not easily oxidized by percolating waters. Therefore, reaction model 4 probably is not representative of actual conditions.

Reaction model 7 is inconsistent with the saturation indexes for calcite in table 8 for the clinker-aquifer recharge source. Reaction model 7 also indicates dissolution of large quantities of calcite (table 11), which is not possible because the clinker-aquifer recharge is initially oversaturated with respect to calcite; therefore, this model is not representative of actual conditions.

Reaction models 5 and 6 are the only models remaining that are consistent with the available data. Although the $\delta^{34}S$ of sulfate minerals was not determined for overburden samples from within the eastern Powder River basin, equation 4 was used to calculate the $\delta^{34}S$ of gypsum (relative to the Canyon Diablo meteorite) for each source of recharge water used in reaction models 5 and 6. The calculated $\delta^{34}S$ for gypsum required for models 5 and 6, with a recharge source from the clinker, is -8.3 per mil. The calculated

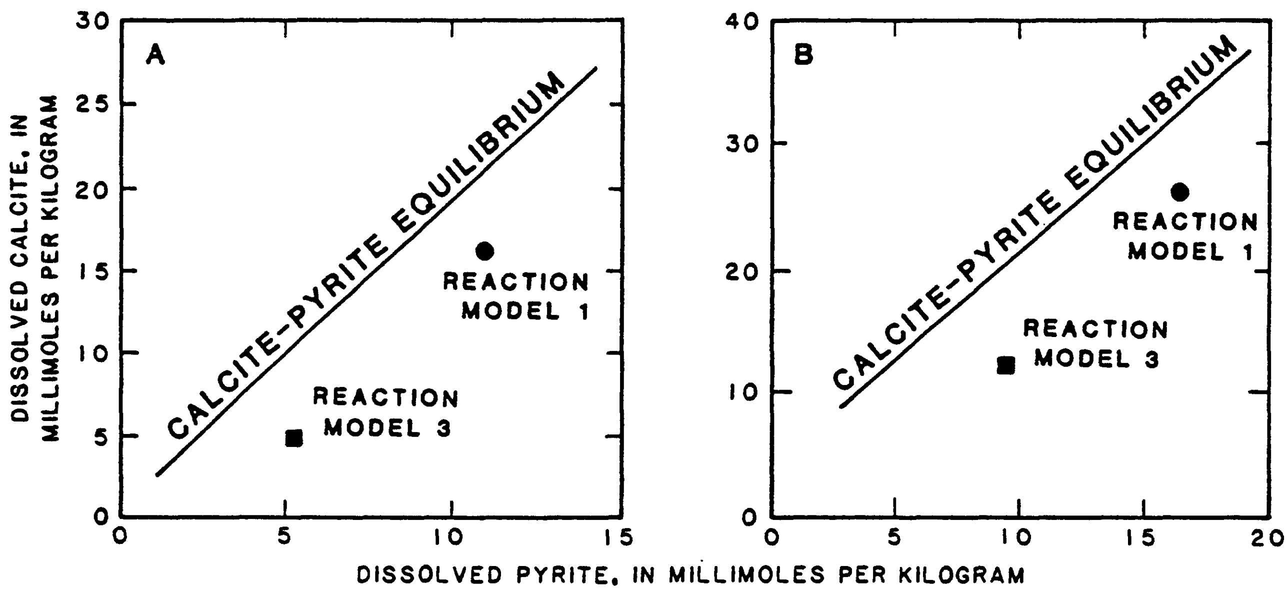


Figure 25.--Quantity of dissolved calcite in relation to quantity of dissolved pyrite predicted to dissolve in water under equilibrium conditions superposed with the quantities of dissolved calcite and pyrite predicted by reaction models 1 and 3, Cordero Mine: A, recharge from clinker aquifer, B, recharge from pond.

$\delta^{34}S$ for gypsum required for reaction models 5 and 6 using a recharge source from the pond is -8.1 per mil. These calculated values do not agree with the $\delta^{34}S$ of 14 oxidized-sulfur samples collected in North Dakota by Houghton and others (1985, p. 26). The $\delta^{34}S$ values determined by Houghton and others (1985) were all positive, ranging from 5.4 to 26.2 per mil (relative to the Canyon Diablo meteorite). Site-specific $\delta^{34}S$ data are needed for sulfate containing minerals within the study area to further confirm reaction models 5 and 6.

Based on the isotope data and mass-balance modeling results at the Cordero Mine, predictions concerning future ground-water quality changes and methods to minimize future postmining water-quality degradation are noted and summarized. Because the postmining water is in equilibrium with respect to gypsum, it is unlikely that the dissolved-solids concentrations will increase further. Naftz (in press) has determined that contact of postmining ground water from the Cordero Mine with recently backfilled spoil material resulted in minimal increases in dissolved constituents. Dissolved-solids concentrations have not decreased substantially during the almost 4 years of record (fig. 11); however, Houghton and others (1987, p. 62) estimate at least 1 pore volume of water must leach the spoil before the dissolved-solids concentration in the water would be similar to the premining dissolved-solids concentration in studies done in North Dakota.

The time required to pass 1 pore volume of water through the spoil aquifer is greater than the time required for the postmining ground-water system to re-establish equilibrium. Current estimates of the time required for the ground-water system to re-establish equilibrium varies from a few tens of years to hundreds of years.

During future reclamation at the Cordero Mine and other mines with similar hydrogeologic and geochemical conditions, steps could be taken to minimize increases of dissolved-solids concentrations in postmining ground water. According to reaction models 5 and 6, gypsum dissolution coupled with cation exchange is a major contributor to the actual increase in dissolved-solids concentration (table 11). Isolation of overburden material with large soluble-salt contents to areas above the postmining ground-water table in conjunction with decreasing the rates of infiltration of precipitation and runoff in the spoil aquifer could minimize future increases in dissolved-solids concentrations. Finally, as noted by Houghton and others (1987, p. 65), isolation of spoil material with large soluble-salt contents from clay-rich and organic-rich strata during backfilling also will minimize increases in dissolved-solids concentrations in postmining ground water.

Dave Johnston Mine

The Dave Johnston Mine is located outside of the study area; it was chosen for additional study because data concerning postmining water-quality changes were available for the mine, and water-level data indicates movement of postmining ground water from the spoil aquifer into the adjacent coal aquifer. Understanding the processes affecting water-quality changes associated with movement of postmining water from the spoil aquifer into the adjacent coal aquifer is important for assessing the impacts of surface coal mining on offsite users of ground water.

Hydrogeology

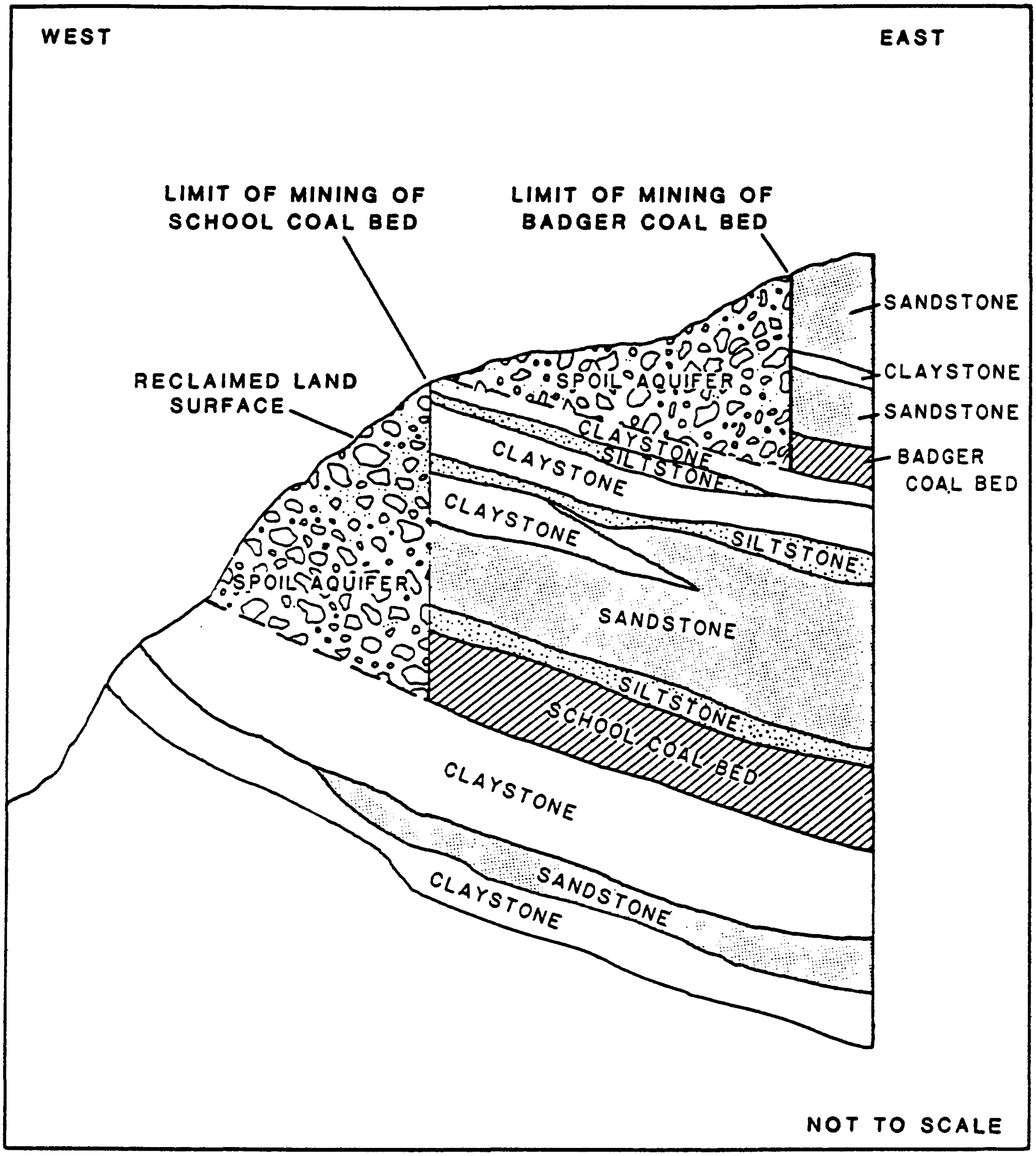
Ground water at the Dave Johnston Mine is present primarily in the Badger and School coal beds and adjacent strata (Dave Johnston Mine personnel, written commun., 1983). The Badger and School coal beds occur in the lower part of the Wasatch Formation. The Badger coal bed is stratigraphically above the School coal bed (fig. 26). The two coal beds are separated by a 110- to 180-ft zone consisting of claystone, siltstone, and fine-grained silty sandstone. Claystone layers associated with the two coal beds have hydraulically isolated the Badger and School coal beds from each other (fig. 26). Water also occurs locally in clinker along outcrops of the Badger and School coal beds. The clinker provides increased recharge to the adjacent coal beds. The School coal bed also is referred to as the School coal aquifer.

The potentiometric surface of the School coal aquifer, based on ground-water levels measured during April 1981, is shown in figure 27. The direction of flow within the School coal aquifer is generally to the east and northeast, in the direction of the dip of the coal bed. Before mining, recharge to the School coal aquifer was from infiltration of precipitation in the vicinity of the outcrop. After mining and replacement of the coal with rubblized spoil, precipitation must first percolate through the spoil aquifer before recharging the unmined parts of the School coal aquifer (fig. 26).

Mining and reclamation has been and is being accomplished at the Dave Johnston Mine using a dragline compared to shovels and trucks used at most mines within the study area. Use of a dragline during mine reclamation can result in greater permeability of the spoil material compared to the permeability of spoil material associated with shovel-and-truck mining and reclamation operations. The greater permeability of the spoil material associated with dragline reclamation at the Dave Johnston Mine has probably increased the rate of recharge to the spoil aquifer compared to similar recharge rates at mines using shovel-and-truck reclamation methods.

The concentrations of stable and radioactive isotopes in ground-water samples from the Dave Johnston Mine (table 12) were used to confirm sources of recharge to the spoil aquifer and movement of water from the spoil aquifer into the School coal aquifer. As shown in figure 28, the $\delta^{18}O$ and δD values of ground-water samples from the Dave Johnston Mine approximately correspond to the composition of the North American continental precipitation as reported by Gat (1980) ($\delta D = (7.95\delta^{18}O) + 6.03$), indicating the presence of mostly meteoric water in the aquifers.

The $\delta^{18}O$ and δD isotopic composition of a water formed by combining two or more components with different isotopic compositions is additive. Water from well DSP-1 (completed in spoil aquifer) is isotopically heavy relative to water from wells DCO-37 and DCO-12 (completed in School coal aquifer), which are located about 0.4 and 0.7 mi downgradient from the spoil aquifer (fig. 27). On the basis of the linear plot of δD versus $\delta^{18}O$ (fig. 28), water from well DCO-30 (completed in the School coal aquifer), 0.1 mi downgradient from the spoil aquifer (fig. 27), appears to be a mixture of 40 percent water from the spoil aquifer and 60 percent water from the School coal aquifer.



Modified from Dave Johnston Mine personnel (written commun., 1983)

Figure 26.--Diagrammatic geologic section showing the Badger and School coal beds of the Wasatch Formation, and associated strata after mining, Dave Johnston Mine.

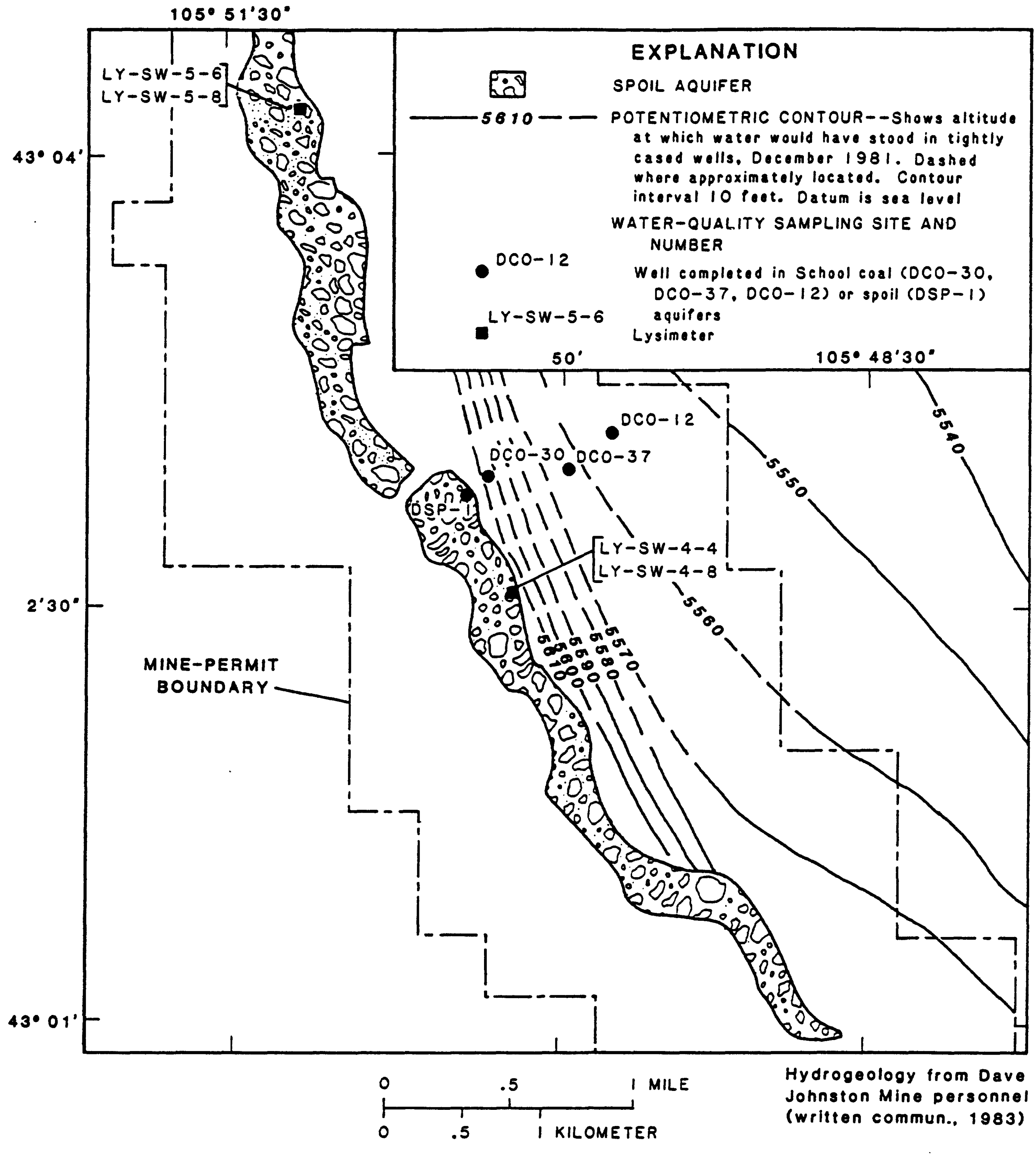


Figure 27.--Potentiometric surface of the School coal aquifer during December 1981 and location of water-quality sampling sites, Dave Johnston Mine.

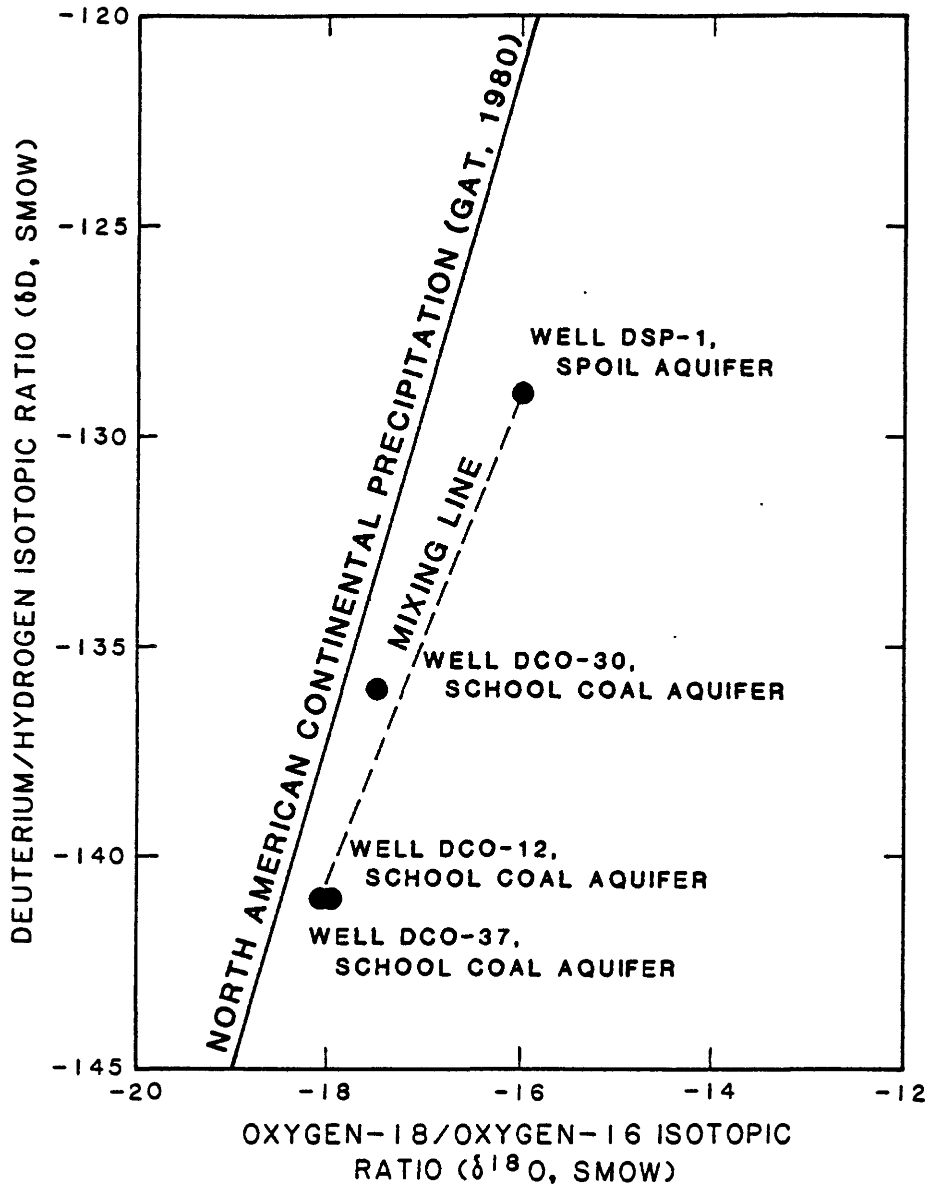


Figure 28.--Comparison of the isotopic composition of ground-water samples from the Dave Johnston Mine to the isotopic composition of North American continental precipitation. SMOW, standard mean ocean water.

The $\delta^{18}O$ values from ground-water samples collected at the Dave Johnston Mine ranged from -18.1 to -16.0 per mil. Comparison of the range of $\delta^{18}O$ values with the continental precipitation data of Yurtsever (1975) (fig. 29) indicates that recharge-water temperature was about 0 °C, such as for spring snowmelt.

The tritium concentrations in ground-water samples from the Dave Johnston Mine decrease in a downgradient direction from the spoil aquifer (fig. 30). The tritium concentration in water from wells DSP-1 and DCO-30 was 92 and 21 pCi/L, whereas the tritium concentration in water from wells DCO-37 and DCO-12 was less than 1 pCi/L (table 12). The tritium data coupled with the potentiometric surface of the School coal aquifer (fig. 27) indicate infiltration of recent precipitation as the dominant source of recharge to the spoil aquifer. Although the large tritium concentration in water from well DCO-30 indicates infiltration of recent recharge, the small tritium concentrations in water from wells DCO-37 and DCO-12, collected further downgradient in the School coal aquifer, indicate that substantial volumes of recent (post-1952) recharge water have not yet moved into this part of the coal aquifer.

Mineral-water relations

The water chemistry of the unsaturated zone was determined by personnel at the Dave Johnston Mine using pressure-vacuum lysimeters located in the unsaturated zone of the spoil aquifer at the mine (fig. 27). Specific conductance of the water collected from the lysimeters ranged from 3,400 to 3,900 µS/cm (table 13). The pH of water samples collected from lysimeter LY-SW-5-6 was 4.8 and that from lysimeter LY-SW-5-8 was 4.9 (fig. 27 and table 13). Lysimeter-water samples with small pH values (lysimeters LY-SW-5-6 and LY-SW-5-8) also had large concentrations of aluminum, cadmium, copper, iron, manganese, nickel, selenium, and zinc, compared to lysimeter-water samples with pH values of 8.1 and 7.7 (table 13). Water with small pH values and large concentrations of trace elements is characteristic of acid generation by pyrite oxidation (Drever, 1982, p. 62-63).

The quality of water from the saturated zone of the spoil aquifer effects (well DSP-1) also indicates the effects of pyrite oxidation in the unsaturated zone. The pH of water from well DSP-1 was 5.8; the concentration of dissolved iron was 2.0 mg/L and the concentration of dissolved manganese was 1.0 mg/L.

The negative $\delta^{34}S$ composition of water from well DSP-1 (-15.2 per mil) also indicates possible pyrite oxidation in the unsaturated zone. In general, the $\delta^{34}S$ of biogenic pyrite is depleted with respect to the standard and ranges from +4 to -35 per mil (Drever, 1982, p. 346); whereas the $\delta^{34}S$ of evaporite deposits (sulfate salts) is generally greater than 0 per mil. Therefore, if most of the sulfate contained in the water from well DSP-1 is derived from pyrite oxidation, a negative $\delta^{34}S$ value would be expected, assuming the effects of isotope fractionation by bacteria are negligible.

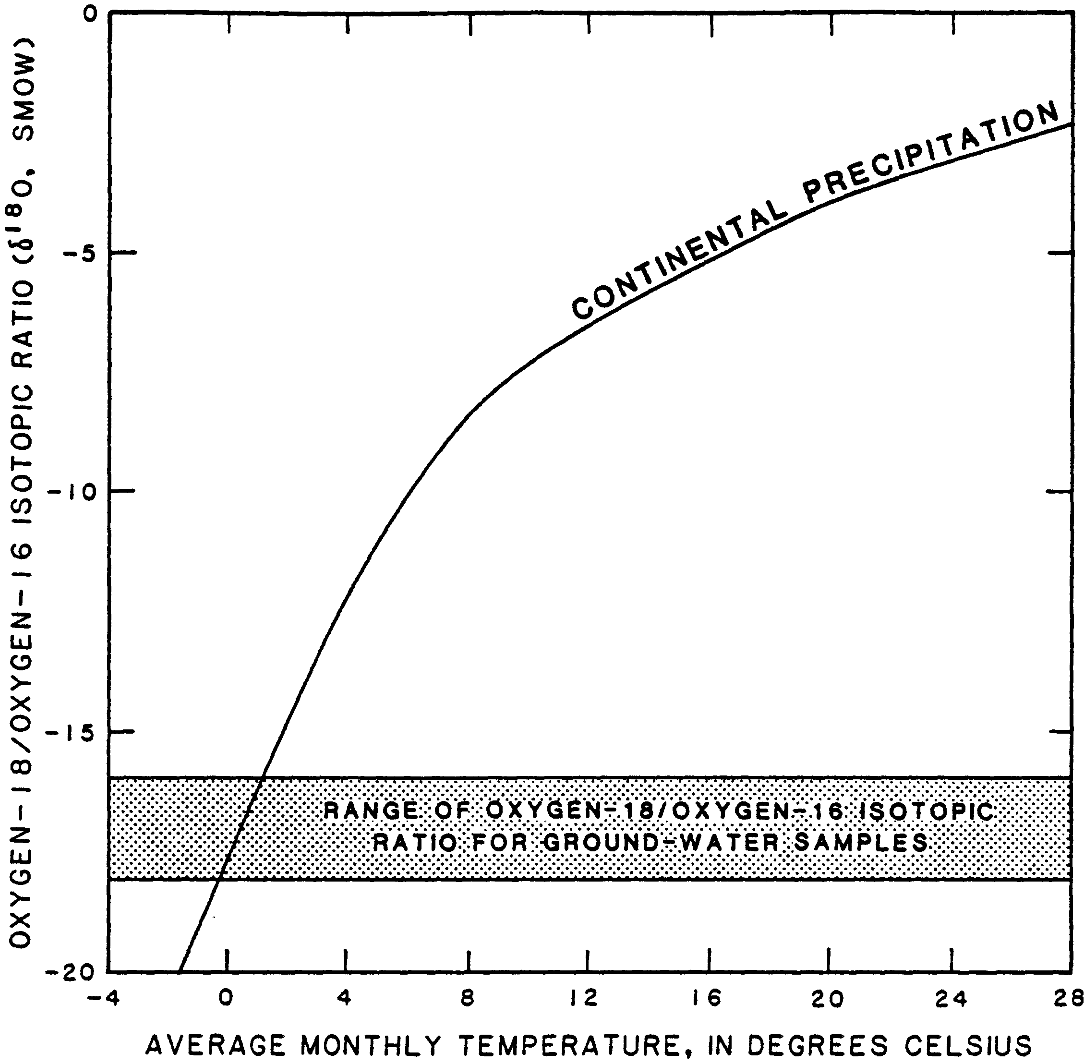


Figure 29.--Correlation of $\delta^{18}O$ composition of continental precipitation compared to the average monthly temperature from continental stations (Yurtsever, 1975) superposed with the $\delta^{18}O$ composition of ground-water samples from the Dave Johnston Mine. SMOW, standard mean ocean water.

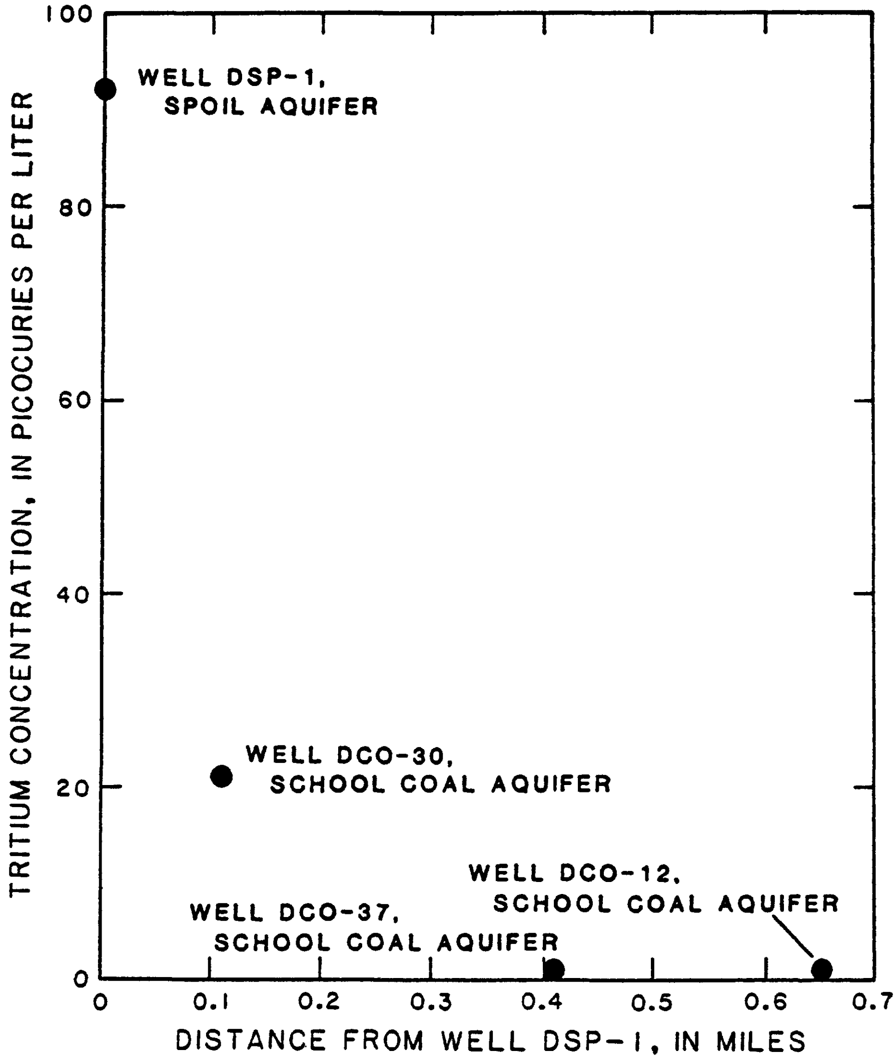


Figure 30.--Tritium concentration in ground-water samples in relation to the distance downgradient from well DSP-1 completed in the spoil aquifer, Dave Johnston Mine.

Table 12.--Isotopic ratios or activities of isotopes in ground-water samples collected at Dave Johnston Mine

[SO_4^{-2}, sulfate; $\delta^{18}O$, oxygen-18/oxygen-16 isotopic ratio; δD, deuterium/hydrogen isotopic ratio; $\delta^{13}C$, carbon-13/carbon-12 isotopic ratio; $\delta^{34}S$, sulfur-34/sulfur-32 isotopic ratio; pCi/L, picocuries per liter; <, indicates concentration less than detection limit for the analysis; --, data not available]

Well	Source	Per mil Oxygen ($\delta^{18}O$)	Per mil Hydrogen (δD)	Per mil Carbon ($\delta^{13}C$)	Per mil Sulfur, SO_4^{-2} ($\delta^{34}S$)	Tritium (pCi/L)
DSP-1	Spoil aquifer	-16.0	-129	-14.2	-15.2	92
DCO-30	School coal aquifer	-17.5	-136	-15.4	-2.8	21
DCO-37	School coal aquifer	-18.0	-141	6.7	12.5	<1
DCO-12	School coal aquifer	-18.1	-141	9.1	--	<1

Table 13.--Chemical analyses of water samples collected from pressure-vacuum lysimeters at Dave Johnston Mine

[Concentrations in milligrams per liter unless noted otherwise; µS/cm, microsiemens per centimeter at 25 degrees Celsius; <, less than detection limit. Data from Dave Johnston Mine personnel, written commun., 1986]

Chemical property or constituent	Lysimeter number			
	LY-SW-4-4	LY-SW-4-8	LY-SW-5-6	LY-SW-5-8
	Properties			
Specific conductance (µS/cm)	3,400	3,400	3,810	3,900
pH (units)	8.1	7.7	4.8	4.9
	Major constituents			
Calcium	627	671	575	565
Magnesium	203	204	276	296
Sodium	90	63	77	85
Potassium	12	7.4	44	41
Bicarbonate	261	569	61	4
Sulfate	2,230	2,040	2,170	2,230
Chloride	75	61	65	75
Nitrite plus nitrate (reported as nitrogen)	.36	3.59	142	124
	Trace constituents			
Aluminum	0.1	<0.1	6.0	2.9
Arsenic	<.005	.005	<.005	<.005
Barium	<.5	<.5	<.5	<.5
Cadmium	<.002	<.002	.005	.004
Chromium	.03	.02	<.02	<.02
Copper	.03	.02	.05	.04
Iron	<.05	<.05	.07	.06
Lead	<.02	<.02	<.02	<.02
Manganese	<.02	.16	2.59	2.66
Mercury	.001	<.001	<.001	<.001
Nickel	.07	.08	.52	.32
Selenium	.01	<.005	.525	.45
Zinc	.03	<.01	2.17	3.15

The dissolved-solids concentration in the spoil-aquifer water changes as it moves downgradient into the School coal aquifer (fig. 31). According to the $\delta^{18}O$ and δD isotope data for ground-water samples at the mine (fig. 28), the water from well DCO-30 is possibly a mixture of 40 percent water from the spoil aquifer (well DSP-1) and 60 percent water from the School coal aquifer (wells DCO-37 and DCO-12). Mixing of the dissolved-solids concentrations in water from the spoil aquifer (well DSP-1) and the School coal aquifer (well DCO-37) in the ratio of 40 to 60 approximates the dissolved-solids concentration in water from well DCO-30 (fig. 31).

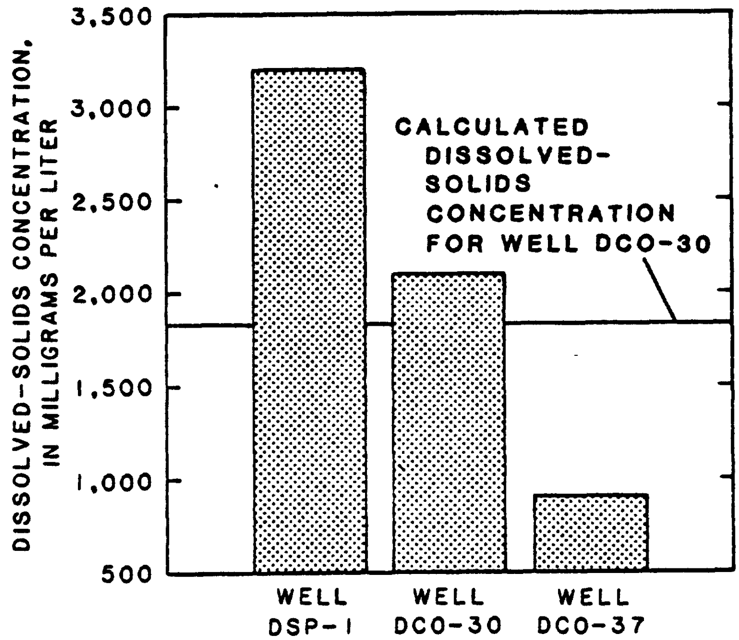


Figure 31.--Actual dissolved-solids concentrations in wells DSP-1, DCO-30, and DCO-37, and the calculated dissolved-solids concentration based on isotopic ratios for well DCO-30.

On the basis of the geochemical information collected at the Dave Johnston Mine, insights into possible changes in offsite water quality can be gained for mines within the study area. Because of the mining method and hydrogeologic and geochemical conditions present at the Dave Johnston Mine, these insights may not apply to all the mines within the study area. Isotopic analyses of the water indicates movement of postmining ground water from the spoil aquifer into the adjacent School coal aquifer and mixing with water from the School coal aquifer resulting in a net increase in the dissolved-solids concentration in water from the School coal aquifer. Because only a finite quantity of soluble salt is available for leaching in the spoil material, this increase in dissolved-solids concentration in water within the School coal aquifer will probably be temporary. As the soluble salts continue to leach from the spoil material, future postmining water entering the School coal aquifer will decrease in dissolved-solids concentration until a postmining equilibrium condition is attained. Based on the lack of recent (post-1952) recharge in water from wells DCO-37 and DCO-12 (about 0.4 and 0.7 mi downgradient from the spoil aquifer), movement of postmining water within the School coal aquifer will be slow, possibly minimizing the extent of water-quality degradation to offsite areas.

Possible Offsite Water-Quality Changes in the Wyodak Coal Aquifer

The larger concentrations of dissolved-solids in water from the spoil aquifers compared to concentrations in water from adjacent coal aquifers (table 4) indicates that deterioration of water quality may result from surface coal mining. A question that needs to be addressed is: "What are the possible water-quality changes that could occur as water from the spoil aquifer recharges a coal aquifer and begins to flow across the mine-permit boundary?" Davis and Dodge (1986) reported that water from a spoil aquifer that was mixed with coal during selected batch-mixing experiments had measurable decreases in dissolved-solids concentration.

The reaction-path geochemical model PHREEQE (Parkhurst and others, 1982b) was used to simulate possible water-quality changes that could occur under different sets of geochemical conditions as water with a large dissolved-solids concentration (spoil-aquifer water) recharges a coal aquifer with water having a chemical composition similar to water from well DCO-37 at the Dave Johnston Mine. Water from this well is a calcium bicarbonate type with a dissolved-solids concentration of 910 mg/L.

In the reaction-path simulations, the composition of the spoil-aquifer water was simulated by: (1) Beginning with chemically pure water, (2) allowing unlimited quantities of oxygen to enter the system, (3) allowing unlimited time for reaction, (4) using a temperature of 20 °C, and (5) allowing the weathering reactions to occur until the water was saturated with respect to gypsum, calcite, pyrite, goethite, and dolomite. The simulated spoil water had a dissolved-solids concentration of 3,540 mg/L and a dissolved-sulfate concentration of 2,160 mg/L (fig. 32). The median dissolved-solids concentration in water analyses from spoil aquifers in the eastern Powder River basin was 3,680 mg/L (table 4).

The reaction-path simulations did not include the effects of adsorption and cation exchange. Clay and organic matter within the spoil and coal aquifers could selectively remove specific chemical constituents. For example, if sodic clay is present within the spoil material, the calcium in the water derived from calcite dissolution will be partly removed from solution and exchanged for sodium on the clay. Removal of calcium from solution by ion exchange would increase the magnitude of calcite dissolution, which, in turn, would increase the sodium, bicarbonate, and dissolved-solids concentrations in the simulated spoil-aquifer water. This process can and does occur at coal mines within the study area.

The simulated chemical composition of the spoil-aquifer water was then subjected to four possible sets of chemical simulations that could occur during movement of spoil-aquifer water into a coal aquifer. Simulation 1 was based on the assumption that constant volume mixing of spoil-aquifer water with coal-aquifer water in a system where organic carbon within the coal aquifer is available for use by sulfate-reducing bacteria and that equilibrium is maintained between calcite, goethite, and amorphous ferrous sulfide. According to the stable-isotope data collected at the Dave Johnston Mine, water samples from the spoil and School coal aquifers indicate a large degree of mixing immediately downgradient from the interface between spoil and School coal aquifers (fig. 28). Simulation 1 also was based on the assumption that the simulated composition of the spoil-aquifer water is mixed with water having the composition of water from well DCO-37, completed in the School coal aquifer, in a purely hypothetical ratio of 0.15 to 0.85 by volume. Four millimoles per liter of carbon with a valance of zero was added to the hypothetically mixed solution, while maintaining equilibrium with calcite, goethite, and amorphous ferrous sulfide. The composition of this ground water was saved and subjected to the same set of chemical reactions described previously. These reaction sets were repeated five times and are operationally defined as reaction increments.

The reaction constraints imposed on simulations 2, 3, and 4 were similar to those imposed on simulation 1. Simulation 2 had the same reaction constraints as simulation 1 except that dolomite equilibrium also was maintained. Simulation 3 had the same reaction constraints as simulation 1 except that goethite was not present for dissolution within the coal aquifer. Simulation 4 had the same reaction constraints as simulation 1 except the organic carbon within the coal aquifer was not available to sulfate-reducing bacteria and goethite was not available for dissolution. Drever (1982, p. 292) has noted that sulfate reduction in some coal aquifers is a slow process because the sulfate-reducing bacteria are incapable of utilizing the carbon compounds in the coal.

The simulated changes in water quality for the four different reaction simulations described previously are shown in figure 32. The decrease in calcium, sulfate, and dissolved-solids concentrations are largest for simulations 1 and 2. Simulations 1 and 2 had a carbon source that could be utilized by bacteria to reduce the sulfate to sulfide (table 10, reaction 2) and an iron source to provide iron for the formation of amorphous ferrous sulfide.

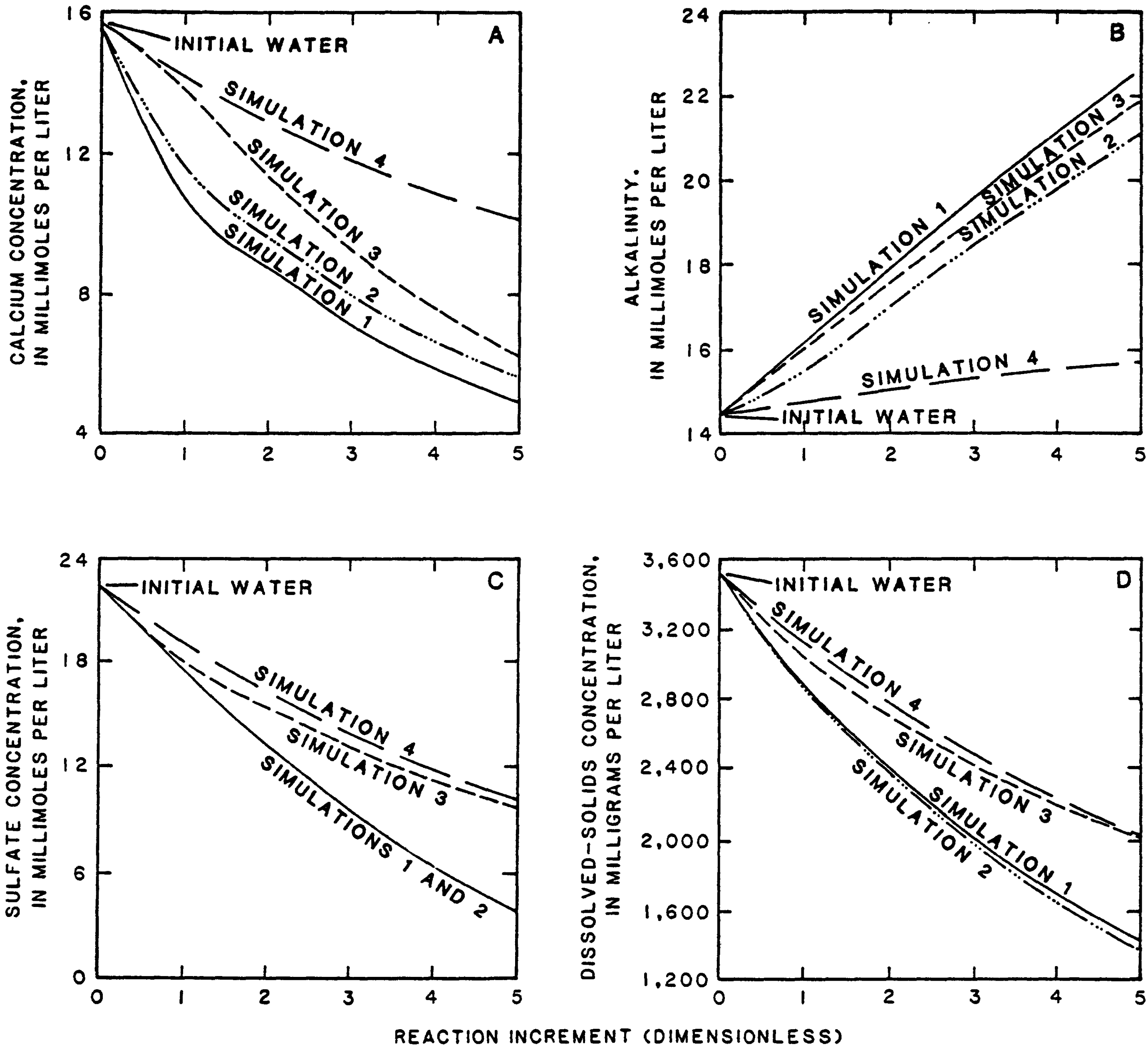


Figure 32.--Changes in concentrations of calcium, alkalinity, sulfate, and dissolved-solids in relation to the reaction increments using the reaction-path geochemical model PHREEQE.

Reaction simulations 3 and 4 do not indicate as large a decrease in calcium, sulfate, and dissolved-solids concentrations as reaction simulations 1 and 2 (fig. 32). Although a carbon source was provided in simulation 3, an iron source was not provided. The lack of an iron source for simulation 3 prevents the reduced sulfur generated from reaction 2 (table 10) to form as much amorphous ferrous sulfide as is formed in reaction simulations 1 and 2, thereby preventing as much sulfate reduction as occurred in reaction simulations 1 and 2. Less sulfate reduction in reaction simulation 3 results in a larger calcium concentration relative to reaction simulations 1 and 2 (fig. 32) because smaller quantities of reduced carbon are being oxidized (table 10, reaction 2). Less carbon oxidation results in less carbonate precipitation (table 10, reaction 5). Because a reduced carbon source was not available in reaction simulation 4, sulfate reduction could not occur, resulting in only moderate decreases in dissolved-solids concentration as a function of reaction increment (fig. 32).

The results of the modeling exercise indicate the potential for improvements in postmining water quality as a postmining ground water with a large dissolved-solids concentration (3,540 mg/L) moves into a coal aquifer with relatively small dissolved-solids concentrations (910 mg/L). The modeling results are purely hypothetical; however, the results do indicate geochemical conditions that are most ideal for large decreases in dissolved-solids concentrations in coal aquifers receiving recharge from a spoil aquifer. According to the modeling results, a coal aquifer with the following geochemical conditions would be most ideal for large decreases in dissolved-solids concentrations:

1. Bacteria populations capable of reducing sulfate.

2. Organic-carbon sources that can be utilized by bacteria to facilitate sulfate reduction.

3. A source of iron that will facilitate the removal, by mineral precipitation, of the sulfide produced by sulfate reduction.

Geochemical condition 1, previously described, probably is operating within the study area. Based on indirect geochemical evidence, sulfate-reducing bacteria probably are present in at least a few aquifers within the study area. Work done by Houghton and others (1985, p. 38) reported sulfate-reducing bacteria in lignite, sandstone, and spoil aquifers located in North Dakota. In the study by Houghton and others (1985), ground-water samples with detectable concentrations of sulfide and large concentrations of dissolved organic carbon (DOC) had the largest bacterial populations. Water samples from the coal aquifers at the Dave Johnston and Cordero Mines had detectable sulfide concentrations, and samples from the spoil aquifer at the Caballo Mine had DOC concentrations exceeding 250 mg/L. As noted previously, the presence of these bacteria could decrease the dissolved-solids concentrations in postmining ground water as it moves offsite. Additional study is needed to identify if geochemical conditions 2 and 3 are operating within the coal aquifers.

Impacts of Surface Coal Mining on Ground-Water Quality

Surface coal mining will initially degrade ground-water quality in the areas of mining. In general, the chemical quality of current (1986) and future water from the spoil aquifers will meet the State standard for livestock. The primary chemical constituents that exceeded and might exceed the State standard for livestock in selected samples are dissolved solids, sulfate, nitrate, chromium, and selenium. Additional monitoring data are needed to determine if the concentrations of all constituents of concern (dissolved solids, sulfate, nitrate, chromium, and selenium) will decrease to and stabilize at concentrations less than the State standard for livestock. Assuming that the water quality in future spoil aquifers will be similar to the quality indicated by the water-quality data for the existing spoil aquifers, the increase in the number and extent of spoil aquifers resulting from future mining will expand the extent of the area where water quality currently (1986) is affected by surface coal mining. Smaller concentrations of dissolved solids, nitrate, and selenium in future postmining water were predicted by column-leaching-test results.

Dissolved-solids concentrations have not decreased substantially during the almost 4 years of record at the Cordero Mine (fig. 11); however, Houghton and others (1987, p. 62), on the basis of studies done in North Dakota, estimate that at least 1 pore volume of water needs to leach the spoil material before the water would contain a dissolved-solids concentration similar to the premining dissolved-solids concentration. The time required to pass 1 pore volume of water through the spoil aquifer is greater than the time required for the postmining ground-water system to re-establish equilibrium. Current (1987) estimates of the time required for the postmining ground-water system to re-establish equilibrium varies from a few tens of years to hundreds of years.

During future reclamation at the Cordero Mine and at other mines with similar hydrogeologic and geochemical conditions, steps could be taken to minimize increases of dissolved-solids concentrations in postmining ground water. Isolation of overburden material with large soluble-salt contents to areas above the postmining ground-water table in conjunction with decreasing the rates of surface-water infiltration in the spoil aquifer could minimize future increases in dissolved-solids concentrations. In addition, isolation of spoil material with large soluble-salt contents from clay-rich and organic-rich strata during backfilling also could minimize increases in dissolved-solids concentrations in postmining ground water.

On the basis of the geochemical information collected at the Dave Johnston Mine, movement of postmining ground water from the spoil aquifer into the adjacent School coal aquifer initially resulted in a net increase in the dissolved-solids concentration in water from the School coal aquifer. Because only a finite quantity of soluble salt is available for leaching in the spoil material, this increase in dissolved-solids concentration in water within the School coal aquifer will probably be temporary. As the soluble salts continue to leach from the spoil material, future postmining water entering the School coal aquifer will decrease in dissolved-solids concentration until a postmining equilibrium condition is attained.

According to geochemical modeling results, a coal aquifer with the following geochemical conditions would be most ideal for large decreases in dissolved-solids concentrations:

1. Bacteria populations capable of reducing sulfate.

2. Organic-carbon sources that can be utilized by bacteria to facilitate sulfate reduction.

3. A source of iron that will facilitate the removal, by mineral precipitation, of the sulfide produced by sulfate reduction.

Based on indirect geochemical evidence, sulfate-reducing bacteria probably are present in at least a few aquifers within the study area.

SURFACE-WATER HYDROLOGY

The purpose of the surface-water analysis is to determine the premining hydrologic characteristics and the cumulative impacts that surface coal mining will have on surface-water flow, quality, and sediment yield. Major streams draining the study area are described in the topography and drainage section of this report.

The location of streamflow-gaging stations operated by the U.S. Geological Survey and the coal-mining companies is shown on plate 4. Information, such as location and period of record, for stations operated by the Survey is listed in table 14; similar information for stations operated by the coal-mining companies is listed in table 33 in the Supplemental Data section. Records of streamflow and water quality collected in the study area by the Survey are published in a series of annual reports. They also may be retrieved through computerized data systems, WATSTORE, of the Survey. A summary of statistical analyses of streamflow data for Survey-operated stations has recently been prepared by Peterson (in press).

The streamflow and water-quality data collected by the coal-mining companies are submitted annually to the Wyoming Department of Environmental Quality, Land Quality Division. Several of the coal-mining companies have their own computerized file systems for storage and retrieval of their individual data; however, a centralized data system currently (1987) does not exist for compiling and analyzing the company data.

The list of company-operated stations in table 33 was compiled from mine-permit applications and annual reports on file with the Wyoming Department of Environmental Quality. In addition, each company was asked to provide a refined list of their surface-water data stations having high-quality records. The intent of the compilation and refinement was to obtain an index of surface-water data stations operated by the coal-mining companies. Not all companies responded to the request; therefore, table 33 likely still contains some stations for which the records are of marginal value for assessing streamflow and water quality.

Table 14.--Streamflow-gaging stations operated by the U.S. Geological Survey

[*, number is equivalent to latitude and longitude designations; latitude and longitude in degrees, minutes, and seconds; ND, not determined; --, no data collected]

Site number (fig. 14)	Station number	Station name	Latitude	Longitude	Drainage area (square miles)	Period during which the types of data indicated below were collected (water years): Discharge	Quality	Sediment	Biological
1	*	Donkey Creek below Wyodak Mine, near Gillette	44 17 13	105 22 30	ND	--	1975	--	1978
2	*	Donkey Creek above Lee Draw, near Gillette	44 16 23	105 24 08	ND	--	--	--	1978
3	06324790	Little Powder River at State Highway 59	44 26 08	105 27 19	ND	--	1980	--	1980-81
4	06324800	Little Powder River tributary near Gillette	44 26 50	105 27 40	.81	1960-81	--	--	--
5	06324810	Box Draw tributary near Gillette	44 26 00	105 37 00	.50	1965-72	--	--	--
6	06324820	Rawhide Creek tributary near Gillette	44 25 00	105 34 00	2.60	1965-72	--	--	--
7	06324830	Rawhide Creek at U.S. Highways 14 and 16 near Gillette	44 25 30	105 33 50	ND	--	1975-78	1978	1975-76, 1978
8	06324890	Little Powder River below Corral Creek near Weston	44 29 40	105 28 00	204	1977-83	1975-83	1977-83	1975-81
9	06324900	Cedar Draw near Gillette	44 31 00	105 26 40	3.45	1959-81	--	--	--
10	06324910	Cow Creek tributary near Weston	44 32 35	105 21 40	.72	1971-82	--	--	--
11	06324912	Little Powder River above Cottonwood Creek near Weston	44 35 35	105 18 50	ND	1975-76	1975-76	1976	1975-76
12	06324918	Cottonwood Creek at mouth, near Weston	44 36 30	105 17 40	ND	--	1975-77	1976	1975-76
13	06324925	Little Powder River near Weston	44 39 00	105 18 50	540	1969, 1977-81	1969, 1975-81	1976-81	1975-81
14	06324970	Little Powder River above Dry Creek, near Weston	44 55 45	105 21 06	1,235	1972-85	1975-82	1975-82	1975-81
15	06324985	Little Powder River near Wyoming-Montana State line	44 59 00	105 20 40	ND	1968	1969-70	--	--
16	06363700	Porcupine Creek near Turnercrest	43 37 40	105 28 00	31.5	1959-76	--	--	--
17	06364700	Antelope Creek near Teckla	43 29 07	105 13 29	959	1977-81	1977-81	1977-81	1977-81
18	06765300	Dry Fork Cheyenne River near Bill	43 13 21	105 40 00	128	1976-81	1977-81	1977-81	1977-81
19	06365900	Cheyenne River near Dull Center	43 25 45	105 02 43	1,527	1976-81	1975-81	1975-81	1975-81
20	06375600	Little Thunder Creek near Hampshire	43 39 20	104 54 20	234	1977-81	1977-81	1977-81	1977-81
21	06376300	Black Thunder Creek near Hampshire	43 34 51	104 43 04	535	1972-85	1979-81	1979-81	1979-81
22	06378300	Lodgepole Creek near Hampshire	43 33 40	104 33 40	354	1977-81	1977-81	1977-81	1977-81
23	06386500	Cheyenne River near Riverview	43 25 00	104 08 00	5,270	1948-74	1969-70, 1975	1951-54, 1971-74	1975-80
24	06425720	Belle Fourche River below Rattlesnake Creek, near Piney	43 59 04	105 23 16	495	1975-83	1975-83	1975-83	1975-82
25	06425750	Coal Creek near Piney	43 58 22	105 19 53	71.6	1980-83	1980-83	1980-83	1981
26	06425780	Belle Fourche River above Dry Creek, near Piney	44 01 30	105 19 35	594	1975-83	1975-83	1975-83	1975-82
27	06425900	Caballo Creek at mouth near Piney	44 04 48	105 15 59	260	1977-83	1977-83	1977-83	1978-80
28	06425950	Raven Creek near Moorcroft	44 10 04	105 05 11	76	1977-83	1977-83	1977-82	1978-80
29	06426000	Belle Fourche River near Moorcroft	44 16 30	104 58 35	1,380	1923-33	--	--	--
30	06426195	Donkey Creek tributary above reservoir, near Gillette	44 16 57	105 25 38	.20	1970-82	--	--	--
31	06426200	Donkey Creek tributary near Gillette	44 17 00	105 25 40	.28	1960-76	--	--	--
32	06426400	Donkey Creek near Moorcroft	44 16 58	105 03 48	246	1977-81	1977-85	1977-81	1977-81
33	06426500	Belle Fourche River below Moorcroft	44 17 44	104 58 35	1,670	1943-70, 1975-83	1946-47, 1949-57, 1975-85	1947-52, 1976-82	1975-81

A large sample of the streamflow records for company-operated stations was reviewed for adequacy of data for hydrologic analysis. The streamflow records were both short and incomplete. Some streamflow-gaging stations were moved as mining and reclamation progressed. Periods of record during recorder malfunction were not estimated; therefore, an annual average-flow value could not be estimated and large discharges may not have been recorded. At most stations, streamflow measurements were not used to verify the stage-discharge ratings.

Streamflow

Three primary streamflow characteristics are considered in the analysis of cumulative hydrologic impacts: average runoff, peak flow, and low flow. These characteristics are a function of precipitation and infiltration of precipitation into the soil column. A change in infiltration will result in a direct or indirect change in all three streamflow characteristics.

Average runoff is the sum of annual average discharges for the period of the record divided by the number of years. At least 5 water years of record are preferred to estimate the average runoff. Seven streamflow-gaging stations in the study area have sufficient length of record to compute average annual runoff. Streamflow-gaging stations, drainage area, period of record, average annual runoff in units of acre-feet and inches are listed in table 15. The location of these streamflow-gaging stations is shown in figure 33. Average annual precipitation for the study area is about 14 in. The weighted mean annual runoff computed from the data in table 15 is 0.185 in.; 1.3 percent of the annual precipitation becomes runoff.

Floodflow of an undisturbed natural stream is a function of drainage area, basin slope, channel slope, maximum relief, infiltration, and precipitation. Relations for estimating peak flows for small natural streams in the study area were developed by Craig and Rankl (1978) as part of a report describing runoff from ephemeral streams. The relations are applicable for streams with drainage areas between 0.69 and 10.8 mi^2, basin slopes between 240 and 929 ft/mi, channel slopes between 59 and 204 ft/mi, and maximum basin relief between 173 and 752 ft. The following equations from Craig and Rankl (1978, p. 27) are used to estimate peak flow for selected recurrence intervals:

$$Q_2 = 34.06\ A^{1.134} S_B^{1.216} R_M^{-1.609} S_{10/85}^{0.539} \qquad (5)$$

$$Q_5 = 30.77\ A^{1.105} S_B^{1.135} R_M^{-1.412} S_{10/85}^{0.588} \qquad (6)$$

$$Q_{10} = 32.99\ A^{1.094} S_B^{1.000} R_M^{-1.308} S_{10/85}^{0.603} \qquad (7)$$

$$Q_{25} = 37.73\ A^{1.086} S_B^{1.012} R_M^{-1.192} S_{10/85}^{0.613} \quad (8)$$

$$Q_{50} = 43.88\ A^{1.084} S_B^{0.962} R_M^{-1.118} S_{10/85}^{0.616} \quad (9)$$

$$Q_{100} = 50.25\ A^{1.082} S_B^{0.914} R_M^{-1.047} S_{10/85}^{0.615} \quad (10)$$

where Q_t = annual peak flow, in cubic feet per second, with subscript t designating the average recurrence interval, in years;

A = contributing drainage area, in square miles;

S_B = average basin slope, in feet per mile, obtained by measuring the lengths (in miles) of all contour lines within the drainage basin boundary, multiplying by the contour interval in feet, and dividing by the drainage area in square miles;

R_M = maximum relief in the drainage basin, in feet, determined by taking the difference in elevation between the channel at the streamflow-gaging station and the highest point in the drainage basin; and

$S_{10/85}$ = main-channel slope in feet per mile, determined from the elevations at points 10 and 85 percent of the distance along the channel from the streamflow-gaging station to drainage-basin divide.

A typical basin and computations of basin characteristics and the 100-year peak flow are shown in figure 34.

The estimating equations 5-10 were developed through an analysis of data collected for 8 years at 22 streamflow-gaging stations. The annual peak flow data were extended in time (73 years) using rainfall and runoff modeling techniques.

In addition to the magnitude and frequency of floodflows, Craig and Rankl (1978) defined the magnitude and frequency of flood volumes in the plains and intermontane valleys of Wyoming. Flood volumes were related to drainage area, maximum relief, and basin slope. A dimensionless hydrograph was developed to provide a synthetic, single-peak hydrograph using peak and volume estimated from basin characteristics. Procedures for estimating the peak discharge and the associated runoff volume to compute the synthetic, single-peak hydrograph are described by Craig and Rankl (1978).

Table 15.--Average annual runoff from drainage basins upstream from streamflow-gaging stations with more than 5 water years of record

[Site No., site number for streamflow-gaging station listed in table 14 and located on plate 4 and in figure 33]

Site No.	Station name	Drainage area upstream from gaging station (square miles)	Period of record (water years)	Annual runoff (acre-feet)	Annual runoff (inches)
8	Little Powder River below Corral Creek, near Weston	204	1977-83	4,270	0.392
14	Little Powder River above Dry Creek, near Weston	1,235	1972-85	16,520	.251
21	Black Thunder Creek near Hampshire	535	1972-85	5,110	.179
24	Belle Fourche River below Rattlesnake Creek, near Piney	495	1975-83	1,820	.069
26	Belle Fourche River above Dry Creek, near Piney	594	1975-83	3,170	.100
27	Caballo Creek at mouth, near Piney	260	1977-83	1,890	.136
33	Belle Fourche River below Moorcroft	1,670	1943-70, 1975-83	16,590	.186

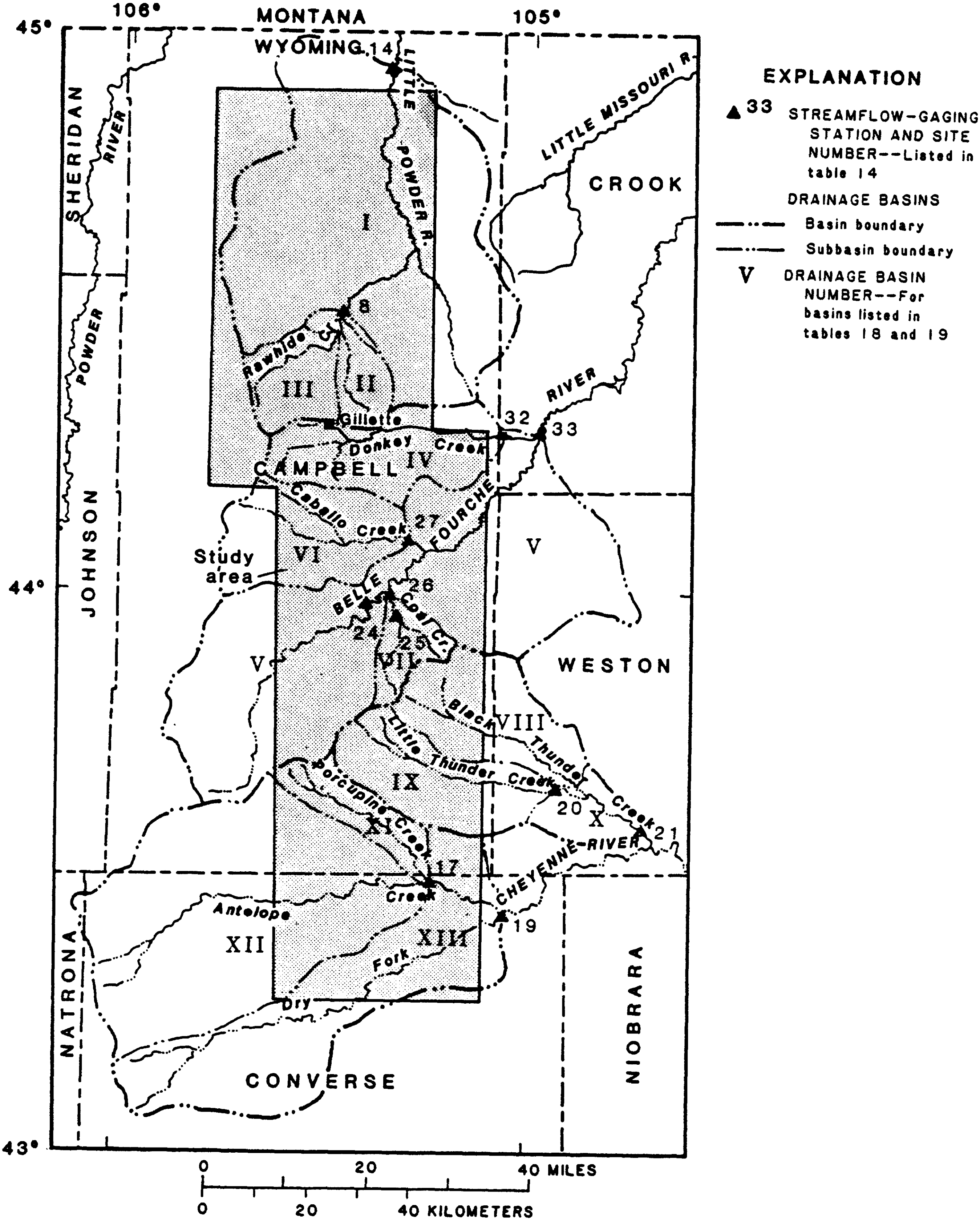
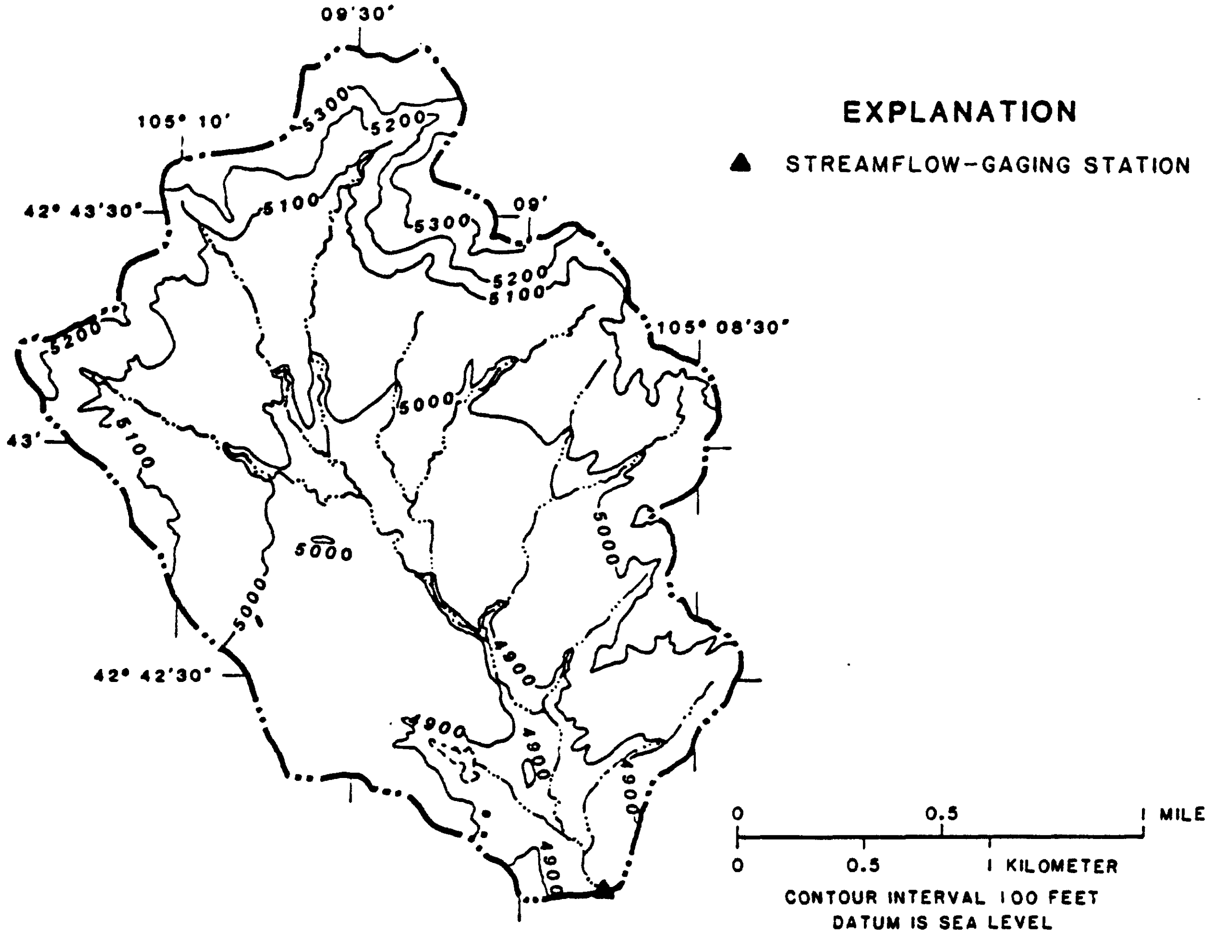


Figure 33.--Location of streamflow-gaging stations and drainage basins used in surface-water analyses.



Area of drainage basin (A) = 2.12 square miles

Total length of 100-foot contour lines (L) = 14.9 miles

$$\text{Basin slope } (S_B) = \frac{L \times \text{Contour interval}}{A} = \frac{14.9 \times 100}{2.12} = 703 \text{ feet per mile}$$

Maximum relief (R_M) = Highest elevation in drainage basin - stream channel elevation at gage = 5,370 - 4,822 = 548 feet

$$\text{Stream channel slope } (S_{10/85}) = \frac{\text{Elevation}_{85} - \text{Elevation}_{10}}{\text{Distance}_{85} - \text{Distance}_{10}}$$

$$(S_{10/85}) = \frac{221}{2.05} = 108 \text{ feet per mile}$$

Where the elevations are determined at points 10 and 85 percent of the distance along the stream channel from the streamflow-gaging station to the drainage-basin divide.

$$\text{100-year peak flow} = Q_{100} = 50.25A^{1.082} S_B^{0.914} R_M^{-1.047} S_{10/85}^{0.615}$$

$$Q_{100} = 1{,}093 \text{ cubic feet per second}$$

Figure 34.--Typical drainage basin used for analysis of runoff and an example of runoff computation.

Equations for estimating floodflows for basins between 10.8 and 5,270 mi^2 were developed by Lowham (1976). H.W. Lowham (U.S. Geological Survey, oral commun., 1987) currently (1987) is developing an updated set of equations using all peak flow data used in the earlier reports plus the data collected since 1976. Both the report by Craig and Rankl (1978) and the updated equations being developed by H.W. Lowham (oral commun., 1987) show drainage area and basin slope as the two most significant basin features affecting peak flows. Thus, the magnitude of peak flows in reclaimed basins will be affected to some extent by re-construction of these features.

Sustained low flows commonly are the result of discharge to stream channels from water stored in aquifers and natural surface reservoirs. Low flow of streams in the study area is the result of discharge from the alluvial and bedrock aquifers. Armentrout and Wilson (1987) analyzed streamflow-gaging-station records for streams in northeastern Wyoming, which includes the study area, and reported that the streams cease to flow for many days each year. Druse and others (1981), as part of a study of low flow and chemical quality of streams in the northern Great Plains area, measured low flows in 1978 to determine gain or loss in reaches of streams in this study area.

Only one station, Belle Fourche River below Moorcroft, had a record of sufficient length to compute probabilities of no flow (Armentrout and Wilson, 1987). During any 1 year, the probability of having 1 to 3 days of no flow is 90 percent. The probability of no flow is 87 percent for 7 days and 14 days. Flow in the Belle Fourche River is typical of the streams in the southern part of the study area. The Little Powder River, which has extensive alluvial deposits, has a small low flow of about 1 ft^3/s (cubic foot per second) and is dry only a few days each year (Rankl and Lowry, in press).

Streamflow Quality

Premining surface-water quality within and adjacent to the study area is described in detail by Lowry, Wilson, and others (1986, p. 56-87). Average dissolved-solids concentrations in most streams in the area exceed the national secondary standard for public water supplies of 500 mg/L established by the U.S. Environmental Protection Agency (1986b). Average alkalinity concentrations in streams at stations within the study area exceed 200 mg/L. Based on data compiled by Larson (1986a, p. 62), all surface water in the study area had a pH greater than 6.0.

Although selenium concentrations in excess of the national primary standard for public water supplies of 0.01 mg/L (U.S. Environmental Protection Agency, 1986a) have been reported in surface waters to the west of the study area (Larson, 1986c, p. 68), selenium and other trace-element concentrations in streams within the study area generally do not exceed national water-quality standards. Exceptions include selected surface-water samples within the study area that had iron and manganese concentrations exceeding the secondary standard for public water supplies (U.S. Environmental Protection Agency, 1986b).

Sediment Yield

Daily records of sediment concentration and discharge have been collected by the U.S. Geological Survey at three streamflow-gaging stations in the study area; all are in the Belle Fourche River basin. Two of the stations are located about 7 river mi apart on the Belle Fourche River. These stations are located upstream and downstream from active mining, but the disturbed areas were small at the time data were collected. The third station is located on Coal Creek, a tributary flowing into the Belle Fourche River between the the two mainstem stations. Coal Creek accounts for almost three-fourths of the intervening drainage area between the two mainstem stations. The drainage area of the Belle Fourche River basin contributing to the flow at the upstream station is 495 mi^2 and at the downstream station it is 594 mi^2; the drainage area upstream from the station on Coal Creek is 71.8 mi^2. Data for the total sediment discharge (suspended and bedload) collected at the three streamflow-gaging stations are presented in table 16. The sediment samples were collected from the turbulent section of a weir by an automatic sampler. All sediment sampled was in suspension. Particle-size analyses of samples from all three stations indicate that all sediment is sand-size or smaller (less than 0.062 millimeter in diameter).

In 2 years, sufficient sediment samples were collected at Coal Creek near Piney to define the total sediment load for 12 peak flows. A relation between peak discharge and total sediment load (Rankl, 1987) is being developed through a cooperative program between the Wyoming State Engineer and the U.S. Geological Survey. This relation is useful for estimating sediment loads for ephemeral streams where peak-flow-frequency data or methods of estimating peak-flow frequency are available. The peak-discharge/sediment-load relation for Coal Creek is applicable only for Coal Creek (fig. 35). Both peak discharge and sediment data are being collected at streamflow-gaging stations in and near the study area in order to define a regional relation.

Sediment data also have been collected by several of the coal-mining companies; for example, Antelope Coal Company has operated automatic sediment samplers at five sites. However, the records, especially for ephemeral streams, are limited to three or four peak flows, which provides insufficient data to determine the annual sediment yield or differences in sediment yield between natural and reclaimed drainages.

The sediment records collected for the Belle Fourche River basin are not of sufficient length for a statistical analysis, but general characteristics can be described. The median annual sediment discharge and sediment yield for the downstream streamflow-gaging station on the Belle Fourche River (site 26) is about eight times the sediment discharge and sediment yield at the upstream station (site 24), but the drainage area is only 20 percent larger. The increase in sediment yield appears to be attributable to Coal Creek (site 25), which flows into the Belle Fourche River about 1 river mi upstream from the downstream station (site 26).

Table 16.--Sediment data for three sediment-sampling stations in the Belle Fourche River basin

[--, data not available]

Water year	Total sediment discharge (tons per year): Belle Fourche River below Rattlesnake Creek, near Piney (site 24)	Coal Creek near Piney (site 25)	Belle Fourche River above Dry Creek, near Piney (site 26)
1977	80.4	--	1,260
1978	5,740	--	58,500
1979	522	--	2,440
1980	9.31	--	36.6
1981	49.4	5,030	3,850
1982	409	1,820	3,460
1983	--	--	228
Median sediment discharge (tons per year)	245	[1]	2,440
Drainage area (square miles)	495	71.8	594
Suspended sediment yield (tons per square mile per year)	.5	[1]	4.1

[1] Insufficient record to calculate median sediment discharge and sediment yield.

A landsat image of the Belle Fourche River basin drainage shows that the Coal Creek drainage basin is dissected, steep-sloped, and subject to erosion. Large areas of Renohill clay loam and Renohill loam developed on land with slopes between 15 and 20 percent are present along the channels of East Fork Coal Creek and Middle Fork Coal Creek (Glassey and others, 1955, p. 40-41). Natural erosion of these soils provides a source for large sediment yields from the basin. The soils in the upstream part of the Belle Fourche River basin are primarily Ulm loam, which has developed on flatter terrain and contains a moderate quantity of well-decomposed humus (Glassey and others, 1955, p. 47). Soil erodibility and steep slopes in the Coal Creek drainage basin account for the large sediment yield from the basin.

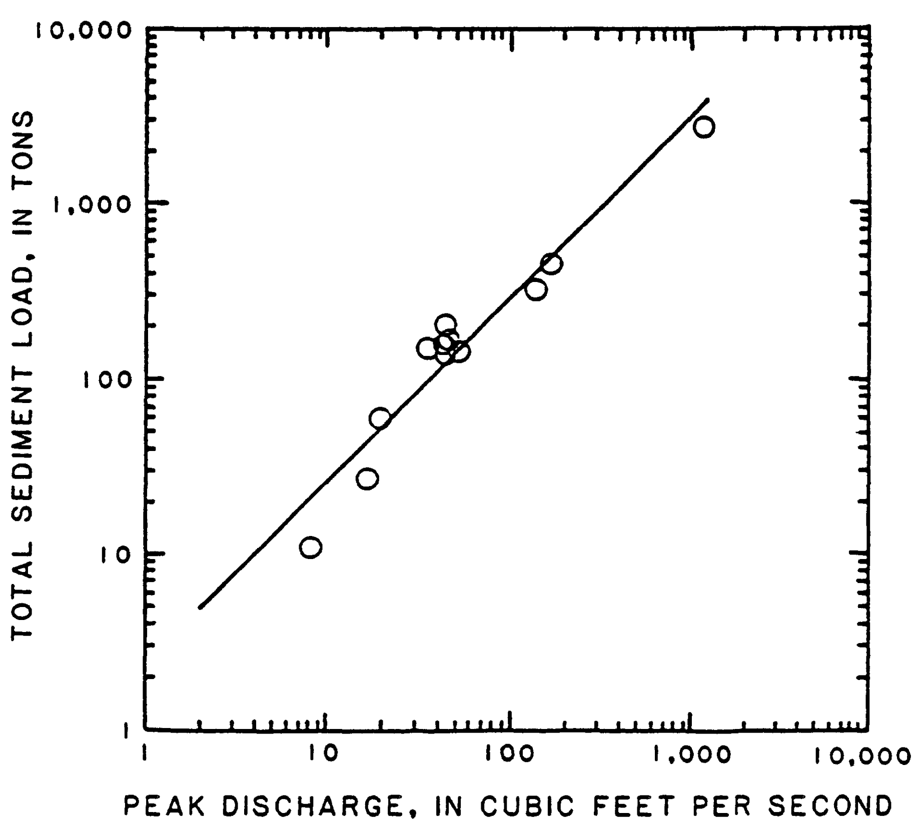


Figure 35.--Relation of total sediment load to peak discharge for storm runoff, Coal Creek near Piney.

Water Rights

The Wyoming Constitution declares that surface water within Wyoming is the property of the State (Wyoming Water Planning Program, 1972, p. 46). The Wyoming State Engineer's Office and the Wyoming Board of Control supervise the appropriation and distribution of surface water. Wyoming water laws establish the priority of adjudicated water rights on the basis of "first in time is first in right."

A listing of surface-water permits for an area including the lease areas and a 1-mi buffer from the lease boundaries was compiled in conjunction with the Wyoming State Engineer's Office. In 1987, there were permit records for 46 ditches, 2 enlargements, 292 reservoirs, and 158 stock reservoirs on file for the study area. Some unpermitted reservoirs may exist in the study area; these may decrease surface-water runoff. The location and identification of the permits are shown on plate 5. A complete listing of the permit information is on file in the office of the U.S. Geological Survey in Cheyenne; this listing also may be obtained from the Wyoming State Engineer. A review of the permits indicates that many of the permits on the lease areas are for sediment-retention ponds constructed by the coal-mining companies.

Impacts of Surface Coal Mining on Surface-Water Hydrology

Evaluation of impacts of surface coal mining on streamflow and streamflow quality requires special sample collection and measurement techniques that can be used to detect or measure changes in quantity and quality of surface water. An evaluation can be made provided a change can be detected in the flow system. Using present (1987) technology, four general approaches are available: (1) Collection of streamflow quantity and quality data before, during, and after mining has been completed, (2) analysis of rainfall and runoff data, (3) analysis of rainfall-simulator tests, and, (4) analysis of the sensitivity of the flow system to changes in the system. Each approach has advantages and disadvantages.

Concurrent with the expansion of energy development, particularly surface coal mining during mid-1970's, a network of streamflow-gaging stations was established in the eastern Powder River basin by the U.S. Geological Survey to collect surface-water quantity and quality data. The stations were selected to collect data from natural streams with little or no impacts from surface coal mining, streams draining the coal mining and proposed mining areas, and streams draining the areas of oil-field development. Because of funding limitations, data collection at most of the stations ceased before a record of sufficient length for statistical analysis could be collected. However, several local changes of short duration, such as increased streamflow resulting from mine dewatering and increased nitrate concentrations, were noted (U.S. Geological Survey, 1980, p. 359-361). But the records were too short to establish cumulative, long-term trends.

Three streamflow-gaging stations, Little Powder River above Dry Creek, near Weston (site 14), Black Thunder Creek near Hampshire (site 21), and Belle Fourche River below Moorcroft (site 33) have records before mining began until the present (1987). Although these stations are downstream from mines and should be useful for determining cumulative impacts, they were not established for that purpose and are too far downstream to detect even major changes in streamflow or streamflow quality.

Calibration of numerical models using rainfall and runoff data can be accomplished for small basins containing ephemeral streams (Craig and Rankl, 1978; Lowry and Rankl, 1987). Results from small-basin model studies provide information to evaluate site-specific hydrologic impacts, but cannot be used for cumulative impacts. Runoff in small ephemeral streams is periodic and cannot be summed to determine cumulative runoff; therefore, cumulative hydrologic impacts cannot be evaluated by numerical models using rainfall and runoff data from small basins. Large basins, the size required to evaluate cumulative hydrologic impacts by numerical models, seldom have a storm with precipitation that is widespread and areally uniform. The limited storm and runoff data do not provide the necessary information to accurately calibrate parameters used in a numerical model. The calibration of model parameters needs to be based on at least 3 years of record (Bloyd and others, 1986, p. 24).

Infiltration rates can be determined by two methods. First, infiltration rates can be computed from rainfall and runoff data; second, infiltration rates can be determined from the results of rainfall-simulator tests. However, the infiltration rates that are computed using these two methods do not provide comparable results.

Infiltration rates computed using rainfall and runoff data usually are slower than those computed using rainfall-simulator tests. The saturated hydraulic conductivity or the saturated infiltration rate determined from rainfall-runoff studies ranged from 0.02 in./h for clay soils to about 0.2 in./h for sandy soils (Rankl, 1982). Saturated infiltration rates computed from rainfall and runoff model calibrations (Craig and Rankl, 1978, p. 15), ranged from 0.017 to 0.105 in./h. Equations used to compute infiltration for the rainfall and runoff studies account for the antecedant moisture conditions, in this case initially dry soil.

Rainfall-simulator tests performed on soils developed from the Cody Shale of Cretaceous age resulted in a computed infiltration rate of 0.61 in./h, which is about three times greater than that computed using rainfall and runoff data (J.G. Rankl, U.S. Geological Survey, oral commun., 1987). The tests were performed on dry soils in order to simulate soil-moisture conditions common in a semiarid climate.

Rainfall-simulator tests were performed on reclaimed mine soil at three mines in the eastern Powder River basin. The majority of the tests were performed in 1979, 1981, 1983, and 1984 at the Belle Ayr Mine, which is in the study area (Gifford, 1983; Hutten and Gifford, 1984). The soils were classified into three categories--heavy, medium, and light--except for the test in 1984. In order to determine that the results of infiltration studies at the Belle Ayr Mine were not totally due to the reclamation process used at that mine, infiltration studies conducted by Lusby and Toy

(1976) at the Dave Johnston Mine in Converse County and at the Big Horn Mine near Sheridan in 1976 were included in this study. The rainfall-simulator tests were performed in pairs: natural soils and reclaimed soils. For all tests, the soil was prewetted in order to simulate a saturated soil-moisture content common to all tests. Information on the elapsed time between reclamation and the rainfall-simulator tests was not available. The tests for infiltration rates on reclaimed soils in 1979, 1981, and 1983 were conducted at the same 30 plots; therefore, the 1983 test was performed on reclaimed soils at least 4 years after reclamation. The elapsed time between reclamation and the 1984 rainfall-simulator tests was variable (Hutten and Gifford, 1984). A summary of the results is listed in table 17.

Differences between infiltration rates for natural soils and reclaimed soils may be masked by the variability of infiltration rates of soils and the variability of measuring infiltration rates. Statistical analysis of infiltration rates measured in 1984 at the Belle Ayr Mine indicates no significant differences between infiltration rates of natural and reclaimed soils (Hutten and Gifford, 1984). Although a significant difference in infiltration rates between natural and reclaimed soils cannot be established from the individual studies, a tendency of reclaimed soils to have infiltration rates that are slightly less than those for natural soils is indicated by the data in table 17. The weighted mean difference for all samples indicates that reclaimed soils have an infiltration rate of about 29 percent less than that for natural soils.

Infiltration rates for reclaimed soils probably will increase to or nearly to rates of infiltration for undisturbed soils. Little information is available on the time before infiltration rates increase to premining rates for soils in a semiarid climate, but some data are available for a study of grazing lands in Idaho (Gifford, 1982). That study, conducted during a 12-year period, indicated that a complete recovery of infiltration rates due to plowing would require at least 6 years. Grazing of the plowed lands would increase the time for recovery. Regardless that the infiltration rates increased on both the natural and reclaimed soils, the average percentage difference between infiltration rates for natural and reclaimed soils at the Belle Ayr Mine for 1979, 1981, and 1983 indicates a similar trend (fig. 36).

Streamflow

For this study, the measured change in infiltration rates is the best measure of a change in average runoff. A change in infiltration rates does not have an inverse corresponding change in runoff, but on the average, the change in infiltration rates is a good index of the change in runoff. Runoff is a function of total storm precipitation, storm intensity, natural storage, land slope, evaporation, and infiltration. Runoff will be least changed by changes in infiltration for short-duration storms with intense precipitation and most changed by changes in infiltration for long-duration storms with less intense precipitation. For this study, the runoff from reclaimed mine areas was assumed to be 29 percent greater than that from unmined areas, due to the average 29-percent decrease in infiltration rate for reclaimed soils.

Table 17.--Summary of rainfall-simulator tests comparing infiltration rates for natural and reclaimed soils

[DJ, Dave Johnson Mine; BH, Big Horn Mine; BA, Belle Ayr Mine]

Year and location of test	Soil category	Natural soil: Infiltration rate (inches per hour)	Natural soil: Number of plots	Reclaimed soil: Infiltration rate (inches per hour)	Reclaimed soil: Number of plots	Difference in infiltration rate (percent)
1976-DJ[1]	Undefined	1.44	1	0.60	1	-58
1976-BH[1]	Undefined	3.04	1	1.51	1	-50
1979-BA[2]	Heavy	.6	10	.7	10	+17
1979-BA[2]	Medium	1.9	10	.6	10	-68
1979-BA[2]	Light	2.1	10	.3	10	-86
1981-BA[2]	Heavy	1.8	10	1.4	10	-22
1981-BA[2]	Medium	2.7	10	1.5	10	-44
1981-BA[2]	Light	2.3	10	1.8	10	-22
1983-BA[2]	Heavy	2.6	10	2.8	10	+8
1983-BA[2]	Medium	3.5	10	2.4	10	-31
1983-BA[2]	Light	3.8	10	2.8	10	-26
1984-BA[3]	Undifferentiated	1.66	30	1.52	30	-8
Average (weighted)		2.19		1.56		-29

[1] From Lusby and Toy (1976, p. 381)
[2] From Gifford (1983)
[3] From Hutten and Gifford (1984, p. 24-25)

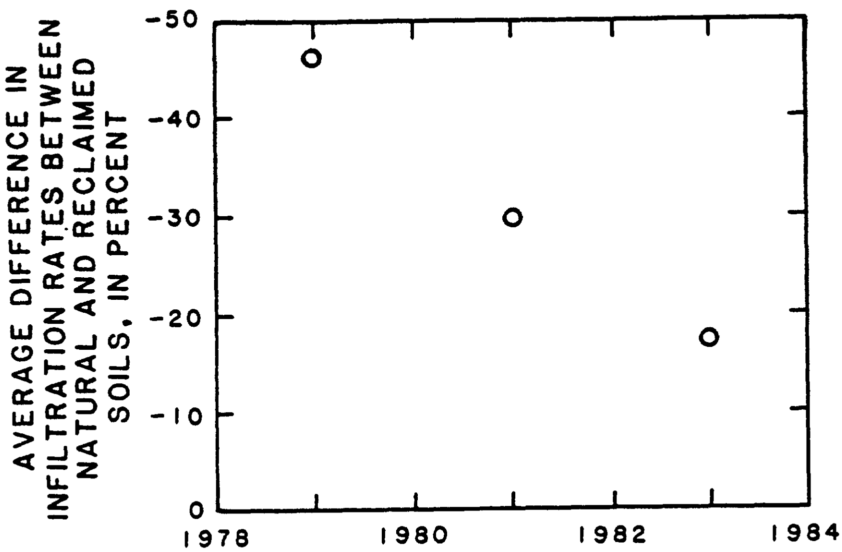


Figure 36.--Average percentage difference between infiltration rates for natural and reclaimed soils at the Belle Ayr Mine.

Projected maximum areas to be disturbed during mining, which were obtained from the Wyoming Department of Environmental Quality, were digitized; disturbed areas (mine pits and reclaimed areas) were computed for each major drainage basin. Drainage basins used in this study were jointly selected by hydrologists from the Wyoming Department of Environmental Quality and the U.S. Geological Survey. The criteria used for the selection of the basins was the proximity of mining and the availability of streamflow data. If the location of a streamflow-gaging station is near the mouth of the basin, the station is used for the point of reference; otherwise the point of reference is the mouth of the basin. The projected maximum disturbed areas are shown on plate 4. A summary of projected maximum disturbed areas in the major drainage basins (fig. 33) in the study area is listed in table 18.

A sensitivity analysis was made for theoretical changes in flow for Black Thunder Creek near Hampshire. An assumption was made that flow from the disturbed area of the basin (32.2 mi^2) both increased and decreased by 10, 30, and 50 percent. The cumulative change was computed in a downstream direction with an increasing drainage area to determine the effective change in flow in relation to the natural flow. If a statistical analysis were performed on the flow data before and after mining for a drainage area of 300 mi^2 with a 50-percent change in runoff from the mined areas, a significant difference could not be determined because the change in flow would be less than the measurement accuracy and the annual variability of flow. The sensitivity analysis is presented in graphical form in figure 37.

Table 18.--Projected maximum areas of drainage basins to be disturbed during mining of selected existing and proposed mines, and increases in runoff in major drainage basins

Drainage basin number (fig. 33)	Drainage basin	Drainage area (square miles)	Projected maximum area of drainage basin to be disturbed by mining (square miles)	Percentage of drainage area to be disturbed by mining	Increase in runoff resulting from areas disturbed by mining	
					Inches	Percent
I	Little Powder River above Dry Creek, near Weston[1] [2]	1,235	25.1	2.0	0.0011	0.6
II	Little Powder River below Corral Creek, near Weston[1] [2]	204	25.1	12.3	.0066	3.6
III	Rawhide Creek at confluence with Little Powder River	120	13.6	11.3	.0061	3.3
IV	Donkey Creek near Moorcroft[1]	246	6.02	2.4	.0013	.7
V	Belle Fourche River below Moorcroft[1] [3]	1,670	57.7	3.5	.0018	1.0
VI	Caballo Creek at mouth, near Piney[1]	260	29.3	11.3	.0061	3.3
VII	Coal Creek at confluence with Belle Fourche River	74.7	11.1	14.9	.0080	4.3
VIII	Black Thunder Creek at confluence with Little Thunder Creek	217	9.19	4.2	.0023	1.2
IX	Little Thunder Creek near Hampshire[1]	234	23.0	9.8	.0053	2.9
X	Black Thunder Creek near Hampshire[1] [4]	535	32.2	6.0	.0032	1.7
XI	Porcupine Creek at confluence with Antelope Creek	139	9.75	7.0	.0038	2.0
XII	Antelope Creek near Teckla[1] [5]	959	18.2	1.9	.0010	.6
XIII	Cheyenne River near Dull Center[1] [6]	1,527	20.0	1.3	.001	.4

[1] Drainage area upstream from streamflow-gaging station
[2] Includes the drainage and disturbed areas of Rawhide Creek
[3] Includes the drainage and disturbed areas of Donkey Creek, Coal Creek and Caballo Creek
[4] Includes the drainage and disturbed areas of Little Thunder Creek
[5] Includes the drainage and disturbed areas of Porcupine Creek
[6] Includes the drainage and disturbed areas of Porcupine and Antelope Creek

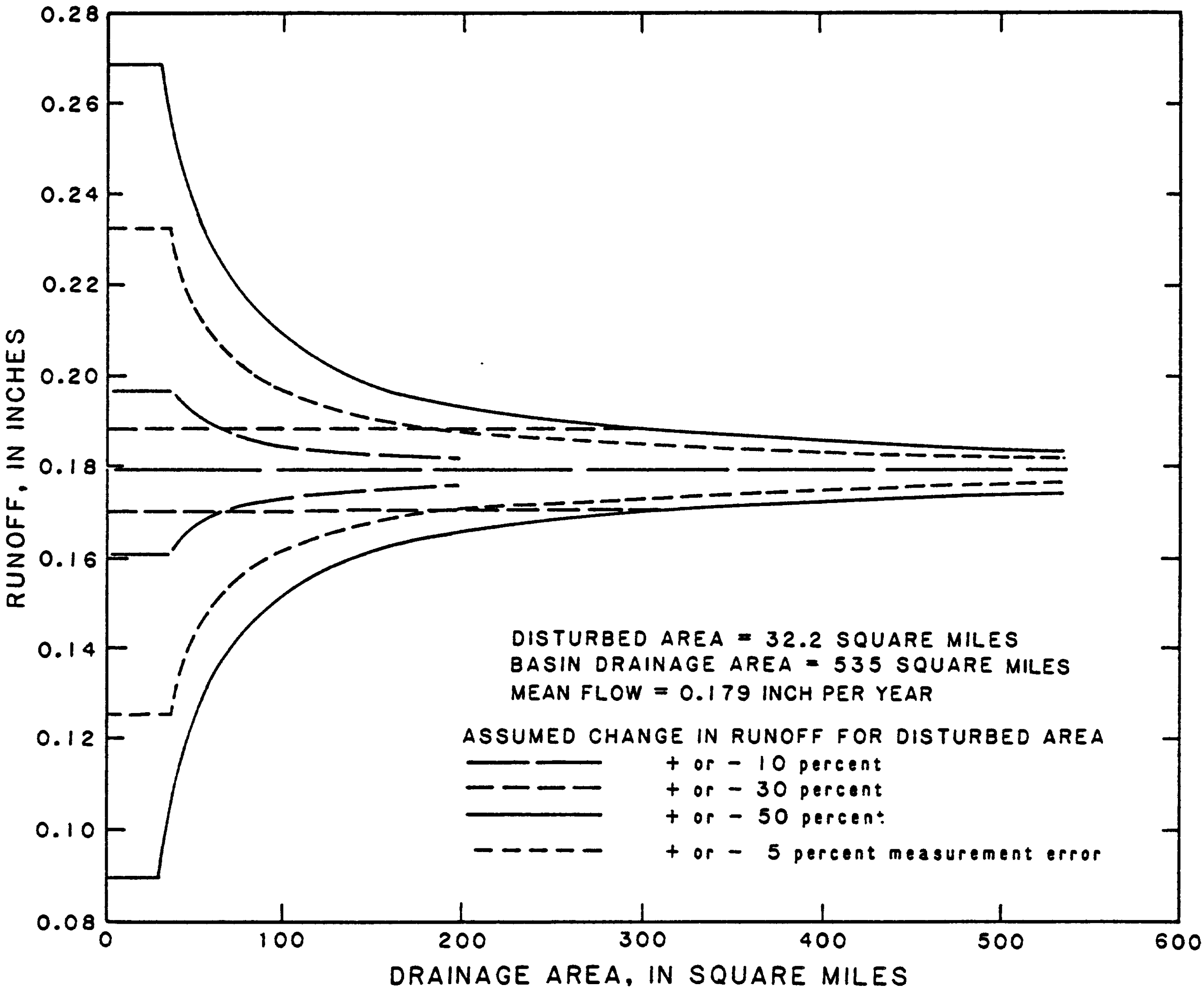


Figure 37.--Sensitivity analysis for hypothetical changes in runoff in Black Thunder Creek.

Black Thunder Creek (site 21) was used in the analysis because the streamflow-gaging station (site 21) on Black Thunder Creek has 13 years of streamflow record, the basin has a large projected maximum disturbed area, and the disturbed areas are located at the headwaters of the drainage basin. From the analysis, changes in quantity and quality could not be detected at the streamflow-gaging station located at the mouth of the basin (site 21).

An analysis of increase in runoff was made for each drainage basin listed in table 18. A 29-percent increase in runoff was assumed for all projected maximum disturbed areas. A weighted mean runoff value of 0.185 in. was computed using the runoff data listed in table 15. The runoff data were weighted using drainage area. The mean runoff value was used to compute increases in runoff and percentage changes in runoff for each of the drainage basins. The following equations were used to compute the increase in runoff:

$$IR = \left| \frac{(DISA * 0.185 * 1.29) + ((DA-DISA) * 0.185)}{DA} \right| -0.185 \qquad (11)$$

and

$$PCR = (CIR/0.185) * 100 \qquad (12)$$

where IR = increase in runoff, in inches;

DISA = disturbed area, in square miles;

DA = drainage area, in square miles; and

PCR = change in runoff, in percent.

For each drainage basin, the computed increase in runoff and the percentage change in runoff is listed in table 18. The percentage change in runoff for all of the basins would be less than 5 percent, which is less than the accuracy of most streamflow records (Druse and others, 1987, p. 15).

Runoff from Coal Creek, which occurred on May 27 and 28, 1981, was used to demonstrate the effect that the projected maximum disturbed area in the Coal Creek basin would have on runoff from an individual storm. The data used in the analysis were collected at the streamflow-gaging station, Coal Creek near Piney (site 25), which has a drainage area of 71.6 mi^2. The peak discharge was 1,170 ft^3/s, and the volume was 512 acre-ft. The increase in flow due to the disturbed area was computed as 4.5 percent. Because flow data are not available at the mouth of Coal Creek, the analysis was done on data collected at the streamflow-gaging station.

The analysis was accomplished in two steps. First, a mean dimensionless hydrograph (Craig and Rankl, 1978, p. 44-55) was used to produce a synthetic hydrograph. The synthetic hydrograph was nearly identical to the hydrograph of flow in Coal Creek except that the synthetic hydrograph was offset by 1 hour (fig. 38-A). Second, the volume of runoff was increased by 4.5 percent, from 512 acre-ft to 535 acre-ft. The increased value of runoff was used to compute a new synthetic hydrograph. The two synthetic hydrographs are compared in figure 38-B. The peak discharge of 1,170 ft^3/s was used to compute both synthetic hydrographs.

The Coal Creek drainage basin has the largest percentage of projected maximum areas to be disturbed by existing and proposed mining in the study area; therefore, changes in flow for individual storms for other basins in the study area would not be discernable.

Selected Coal Tracts and areas with Preference Right Lease Applications (pl. 1) were digitized and added to the projected maximum disturbed areas (pl. 4) for each of the drainage basins listed in table 18. Because mine plans were not available for the Selected Coal Tracts and the Preference Right Lease Applications areas shown on plate 1, the areas were considered disturbed. All of the disturbed areas were summed to determine a worst-case condition for the computation of runoff. A 29-percent increase in runoff was assumed for disturbed areas for all anticipated mining without the increased runoff decreasing to premining rates. The equations used to compute increases in runoff for the projected maximum areas disturbed by existing and proposed mines were used for the worst-case study. The results of the worst-case surface-water analyses for disturbed areas for all anticipated mining are presented in table 19.

Runoff in two drainage basins, Coal Creek and Little Thunder Creek, would increase by more than 5 percent for the worst-case analysis. If data were available to compute a 6-year recovery of infiltration rates for the entire disturbed area, all increases in runoff would be less than 5 percent.

Streamflow Quality

The possible impacts of mining on the streamflow quality in the eastern Powder River basin was assessed by Bloyd and others (1986, p. 33-41) using a computer model of the Belle Fourche River basin. Impacts of surface mining on streamflow quality in other basins will depend on climate, geologic and soil characteristics, vegetation, and streamflow, and those impacts may, therefore, be different in other basins than in Belle Fourche. After calibration and verification, the model was used to calculate the changes in dissolved-solids and sulfate concentrations that might result from mining. Two sets of measured and estimated rainfall and evaporation data were used for the modeling. The first set of data was for May and June 1980, a period of slightly less than average rainfall (rainfall A), and second set of data was for May and June 1982, a period of greater than average rainfall (rainfall B). Increases in average dissolved-solids and sulfate concentrations using rainfall A ranged from 1 to 7 percent from premining to postmining conditions. The simulated dissolved-solids and sulfate concentrations for flows exceeding 1.0 ft^3/s decreased by as much as 49 percent from premining to postmining conditions using rainfall B.

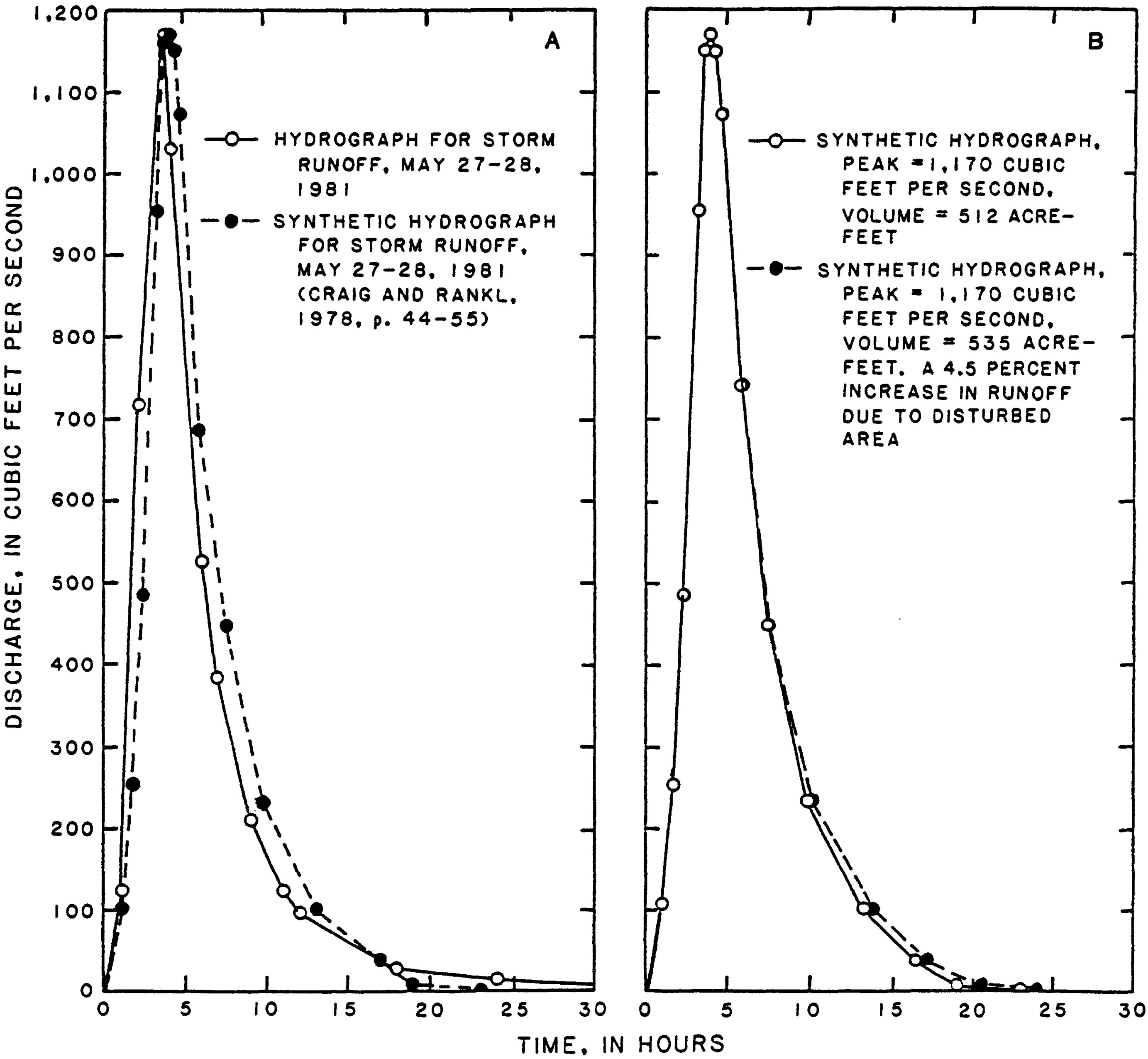


Figure 38.--Analysis of runoff and change in runoff for storm of May 27-28, 1981, Coal Creek near Piney.

Table 19.--Projected maximum areas of drainage basins to be disturbed during all anticipated mining and increases in runoff in major drainage basins

Drainage basin number (fig. 33)	Drainage basin	Drainage area (square miles)	Projected maximum area of drainage basin to be disturbed by mining (square miles)	Percentage of drainage area to be disturbed by mining	Increase in runoff resulting from areas disturbed by mining	
					Inches	Percent
I	Little Powder River above Dry Creek, near Weston[1] [2]	1,235	72.4	6.3	0.0032	1.8
III	Rawhide Creek at confluence with Little Powder River	120	14.3	11.9	.0064	3.5
IV	Donkey Creek near Moorcroft[1]	246	12.4	5.0	.0027	1.5
V	Belle Fourche River below Moorcroft[1] [3]	1,670	82.9	5.0	.0027	1.4
VI	Caballo Creek at Mouth, near Piney[1]	260	31.9	12.3	.0066	3.6
VII	Coal Creek at confluence with Belle Fourche River	74.7	19.6	26.2	.0141	7.6
VIII	Black Thunder Creek at confluence with Little Thunder Creek	217	13.1	6.0	.0032	1.8
IX	Little Thunder Creek near Hampshire[1]	234	42.6	18.2	.0098	5.3
X	Black Thunder Creek near Hampshire[1] [4]	535	55.7	10.4	.0056	3.0
XI	Porcupine Creek at confluence with Antelope Creek	139	15.9	11.4	.0061	3.3
XII	Antelope Creek near Teckla[1] [5]	959	39.4	4.1	.0022	1.2
XIII	Cheyenne River near Dull Center[1] [6]	1,527	41.7	2.7	.0015	.8

[1] Drainage area upstream from streamflow-gaging station
[2] Includes the drainage and disturbed areas of Rawhide Creek
[3] Includes the drainage and disturbed areas of Donkey Creek, Coal Creek and Caballo Creek
[4] Includes the drainage and disturbed areas of Little Thunder Creek
[5] Includes the drainage and disturbed areas of Porcupine Creek
[6] Includes the drainage and disturbed areas of Porcupine and Antelope Creek

Sediment Yield

Erosion studies at small soil plots were conducted in conjunction with the rainfall-simulator tests. Sediment detached by raindrop impact and washed from soil surfaces was collected at the downstream end of each soil plot. The sediment was dried and weighed to determine the yield from each plot. The data were converted to standard units, tons per square mile, in order to compare the results with different studies. The sediment-yield data are listed in table 20. A trend in the percentage difference in sediment yield for natural soil plots and reclaimed soil plots was not identified. The data indicate a six-fold decrease in sediment yield for reclaimed-soil plots between 1979 and 1983, but the natural-soil plots also had a five-fold decrease during the same period. Because of the variability of the data, a conclusion on the decrease in sediment yield for reclaimed-soil plots cannot be made.

Sediment yield from plots located on reclaimed soil was, on the average, 436 percent larger than sediment yield from plots on comparative natural soil. The sediment yields from the plots located on reclaimed soil were greater because of: (1) Steeper land slopes at the plots with reclaimed soil than at the plots with natural soil, (2) increased runoff from the reclaimed-soil plots due to slower infiltration rates, (3) lesser density of root development in the reclaimed-soil plots, and (4) lack of a well-developed soil profile in the reclaimed-soil plots, resulting in a loss of soil cohesiveness. Detailed data on slopes and vegetation cover of the soil plots were not available for the 1979, 1981, 1983 studies, but information was available for the studies conducted in 1984. The slope and vegetation data for 1984 was considered a representative sample for the studies at the Belle Ayr Mine. The average slope for the reclaimed-soil plots was 12.9 percent and for the natural-soil plots it was 9.4 percent. The reclaimed-soil plots had a 68-percent cover of litter, grass, forbs, and shrubs, and the natural-soil plots had a 95-percent cover. Particle-size analyses were not made for samples collected from the soil plots; therefore, the information needed to determine the type and source of sediment is not available.

Larger sediment yields probably will not be conveyed to the mouth of drainage basins listed in table 18 because of: (1) Sediment deposition occurring before runoff reaches the stream channel in areas where land-surface slopes decrease from hillside to stream channel, and (2) sediment deposition in settling ponds. A study of sediment sources and drainage-basin characteristics in eastern Wyoming determined that "Upland sediment yields cannot be used directly to determine sediment yield of larger basins, because with increased size of drainage basins, runoff and sediment rates decrease" (Hadley and Schumm, 1961, p. 137). They used 99 measurements to develop a relation between sediment accumulation in reservoirs and drainage area (fig. 39). The sediment yield for a 0.034-mi^2 drainage area was 10 times greater than the sediment yield for a 1.6-mi^2 drainage area; therefore, very little of the sediment measured at the soil plots will be conveyed to the major drainages. The small percentage of disturbed area in relation to undisturbed area in the drainage basins and the decrease in sediment conveyed to the main stream channels will result in a minor impact by sediment on the major drainage basins in the study area.

Table 20.--Erosion rates for natural and reclaimed soils

[DJ, Dave Johnson Mine; BH, Big Horn Mine; BA, Belle Ayr Mine]

Year and location of test	Soil category	Natural soil: Sediment yield (tons per square mile)	Natural soil: Number of plots	Reclaimed soil: Sediment yield (tons per square mile)	Reclaimed soil: Number of plots	Increase in sediment yield (percent)
1976-DJ[1]	Undefined	283	1	1,200	1	324
1976-BH[1]	Undefined	39.7	1	2,437	1	6,039
1979-BA[2]	Heavy	133	10	497	10	274
1979-BA[2]	Medium	20.9	10	400	10	1,814
1979-BA[2]	Light	31.3	10	359	10	1,047
1981-BA[2]	Heavy	61.5	10	132	10	115
1981-BA[2]	Medium	16.6	10	98.4	10	493
1981-BA[2]	Light	24.6	10	84.8	10	245
1983-BA[2]	Heavy	30.1	10	100	10	232
1983-BA[2]	Medium	6.1	10	77.5	10	1,170
1983-BA[2]	Light	3.7	10	21.5	10	481
1984-BA[3]	Undifferentiated	76.8	30	344	30	348
Average (weighted)		48.4		260		436

[1] From Lusby and Toy (1976, p. 381)
[2] From Gifford (1983)
[3] From Hutten and Gifford (1984, p. 26-27)

Water Rights

At the root of Wyoming water law is the protection of prior appropriators. Applications for stream-related developments such as sedimentation reservoirs or diversions are required by law to be filed with the Wyoming State Engineer, who reviews how such developments may affect downstream water users (Frank Trelease, III, Assistant Wyoming State Engineer, written commun., 1987). As shown on plate 5, most water rights in the lease areas have been permitted for coal-mining companies to construct sediment ponds. Several stock reservoirs and ditches are permitted on the lease areas; however, if they are physically destroyed, the appropriators are protected by law and proper restitution or compensation must be made, within legal constraints, to the owner's satisfaction. Likewise, water rights downstream from the mined areas are protected from a decrease in runoff due to mining activities.

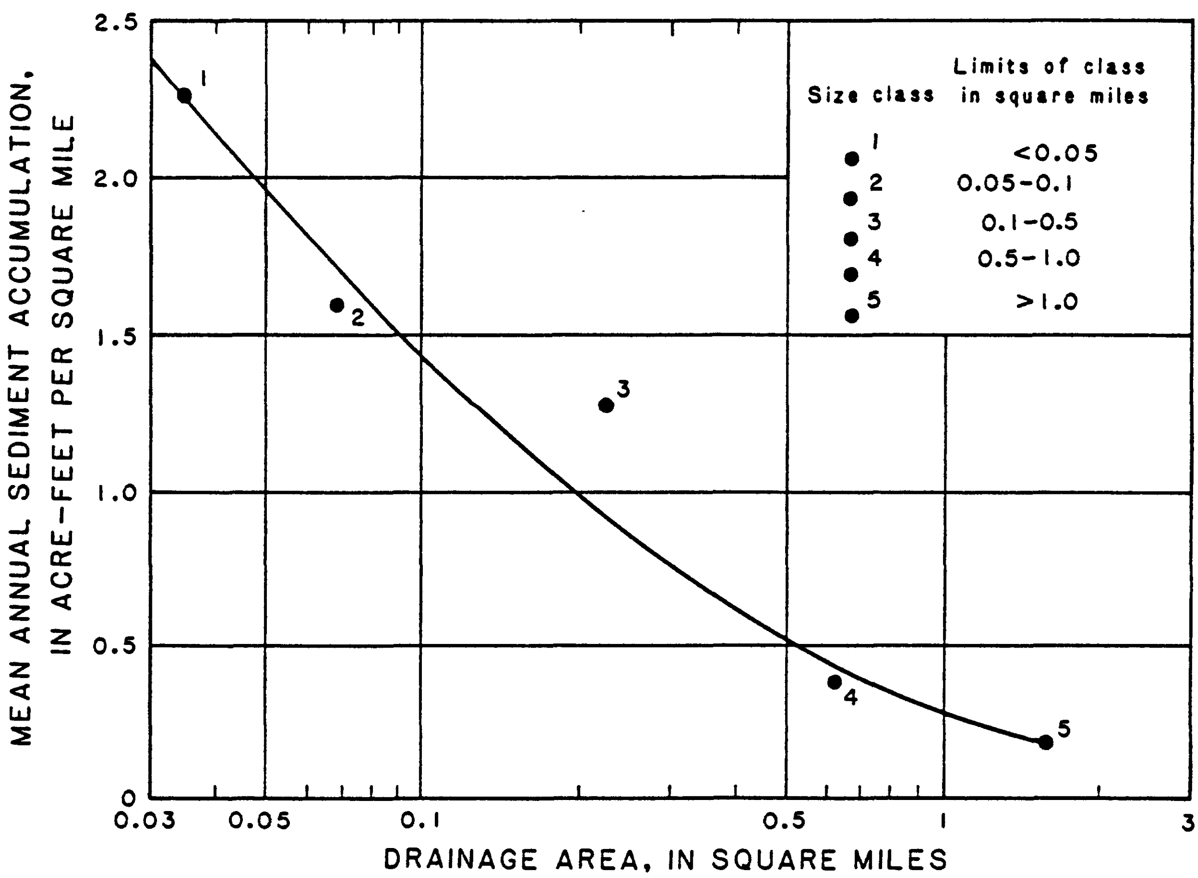


Figure 39.--Relation between sediment accumulation in reservoirs and drainage area, upper Cheyenne River basin (from Hadley and Schumm, 1961, p. 163).

If affected by mining developments, such as reservoir storage or diversion of flow, downstream appropriators having prior water rights can request release of water from the coal-mining facilities. All permits granted to coal-mining companies for stream-related developments, such as sedimentation ponds, include the State Engineer's conditions requiring a means of releasing water for downstream appropriators, after the water-quality standards are met by the settling of suspended sediment in the ponds.

Because prior water appropriators are protected by law, no significant cumulative impacts are expected to occur due to mining of either existing permitted areas or of areas of all anticipated mining.

STABILITY OF RECLAIMED DRAINAGES

Surface coal mining disturbs large areas of the land surface. About 135 mi^2 of the land surface currently (1987) are projected to be disturbed and subsequently reclaimed by existing and proposed mines in the study area; as much as 253 mi^2 potentially could be disturbed by all anticipated mining in the study area.

Flowing water is the major natural force affecting reclaimed areas. Because streams are prone to erode and transport sediment, the disturbance of large land areas has the potential to impact natural channel stability some distance upstream or downstream from mining as well as locally. Undesirable modifications of drainage networks may result in increases in erosion and sedimentation. Increased rates of erosion and sedimentation can be detrimental to reclaimed areas, adjacent areas, and downstream water quality.

The design of stable drainage basins for postmining areas is critical to the type and degree of use the land may support after reclamation. According to Bishop (1980, p. 249), the more closely postmining topography can be restored to surrounding natural conditions and approximate original contours, the greater the likelihood of stable drainage networks and successful reclamation. Natural drainage networks and stream channels have evolved during long periods, and, thus, are considered to be in equilibrium with the climatic and physical conditions of their basins. In referring to natural landscapes and stream channels, the term "stability" means "dynamic stability." Basin surfaces and channels are in a continuous state of evolution as they are subjected to forces such as tectonism, climate, and runoff, and use by humans and animals.

Regulatory Considerations

The restoration of mined land to its approximate original contour is a requirement of the Surface Mining Control and Reclamation Act of 1977. However, the relatively thick coal beds and small overburden-to-coal ratio in the study area prevent restoring the landscape to its former elevation (Keefer and Hadley, 1976, p. 15-20). As discussed by Toy and Hadley (1987, p. 276), it generally is agreed that "approximate original contour," as required by law, means that the shape of the land after mining should be about the same as it was before, but not necessarily at the same elevation.

In addition to the requirement that coal-mining companies restore the approximate original contour of the land after mining, the Surface Mining Control and Reclamation Act of 1977 also requires that spoil materials "...be shaped and graded in such a way as to prevent slides, erosion, and water pollution..." and that "adequate drainage" be provided. The Act basically requires that procedures during mining and reclamation minimize the contribution of suspended materials to areas outside the lease boundaries, control rilling and gullying, and minimize disturbance to the prevailing hydrologic balance. Surface coal mines currently (1987) in operation in the study area are exempt from the strict requirement of restoring the land to the "approximate original contour" because they are classified as having "thin overburden." This classification is applied when the thickness of the coal is large relative to the overburden. Adequate drainage is still required, but the reclaimed landscape can be more subdued than it was before mining.

The Wyoming Environmental Quality Act (Wyoming State Legislature, 1973) requires that operators of surface coal mines provide a plan to minimize disturbances to the prevailing hydrologic balance at the mine site and in adjacent areas, and to protect the quantity and quality of water in ground- and surface-water systems during and after mining. Guidelines prepared by the Wyoming Department of Environmental Quality (1980b) recommend that coal-mining companies measure various basin and channel characteristics to aid in the reclamation of surface-drainage systems. Mine plans on file with the Wyoming Department of Environmental Quality contain these data and also document the procedures used or planned for re-construction of stream channels and drainage networks. In addition, numerous studies and guidelines for design criteria have been made by hydrologists working with the coal-mining companies and State and Federal agencies. (See for example: articles by Bergstrom (1985), Harvey and others (1985), and Kearney (1985), published in proceedings of the "Second Hydrology Symposium on Surface Coal Mining in the Northern Great Plains;" Knutson (1982), Lidstone (1982), and Tarquin and Baeder (1982), published in proceedings of the "Hydrology Symposium on Surface Coal Mines in the Powder River Basin;" and Divis and Tarquin (1981)).

Method of Impact Analysis

The evaluation of whether a re-constructed landscape will be stable in relation to the prevailing hydrologic balance is a difficult task, especially for semiarid and arid regions. As noted by Lidstone (1982, p. 44), "The long-term stability of a landscape is difficult to quantify on a site-specific basis and virtually impossible to quantify on a regional basis." Runoff, which is the major natural force affecting the landscape in the semiarid study area, may be infrequent, especially within small basins. For basins of only several square miles or less, it is common to have periods of 1 year or more between substantial runoff. The adjustment of a re-constructed drainage basin that is incipiently unstable may not be noticeable until several large flows have occurred, which could take several tens of years. Although readily visible responses such as rilling and gullying may occur rapidly where all or part of the basin is unstable, it also is possible that only a gradual response would take place during several or more years until substantial runoff occurs. It is practically impossible even for an expert to look at a stream channel and tell whether the channel is presently in a period of gradual aggradation or gradual degradation (Leopold, 1962, p. 3-4).

Quantifying the degree of stability and subsequent impact of re-constructed basins on the regional landscape and sediment yield is a difficult task; however, investigators have used geomorphic analyses successfully to assess changes and assist with design of stream-related developments. For example, Patton and Schumm (1975) quantified a relation between valley-floor slope and drainage area for small drainage basins in the Piceance Creek area of Colorado, whereby a threshold slope was identified above which trenching or valley instability would occur. Dunne and Leopold (1978, p. 22-28) described the use of geomorphology and hydrology for land-use planning of the valley associated with the mobile channel of the Yakima River near Yakima, Washington. Lowham and others (1982, p. 40-45) examined severe gullying in the Salt Creek basin near Rock Springs, Wyo., and determined the causes and approximate period of occurrence.

The drainage basin is the unit most basic to reclamation of the relatively large areas being mined. The assessment of impacts of fluvial processes on landscape stability, therefore, was made by comparing fundamental geomorphic relations for natural or premining basins in the area to characteristics described for the planned postmining basins. In addition, final reclamation plans for active mines were reviewed and reclaimed areas were inspected. Steps in the procedure to analyze the stability of reclaimed drainages and to determine cumulative impacts of the mining and reclamation on regional stability and sedimentation are described below:

1. Characteristics important to the stability of drainage basins and stream channels were measured for a representative sample of natural drainage networks in or near the study area. These data were then analyzed to determine the range and average for each characteristic, and fundamental relations between the characteristics were examined and developed.

2. Characteristics of the drainage basins and stream channels for a representative sample of areas planned for reclamation were measured from maps of postmining topography prepared by the coal-mining companies as part of their final reclamation plans. Those characteristics most important to basin and channel stability were compared with those for the natural basins.

3. A review was made of the methods used in the design of re-constructed drainage networks and stream channels.

4. The stability of currently (1987) reclaimed hillslopes and stream channels was examined during visits to several mines having areas that have been mined and reclaimed.

The use of geomorphic relations derived from natural basins to determine the expected impact of re-constructed basins is based on the assumption that the natural basins currently are stable. A measure of basic geomorphic processes in relation to the prevailing hydrologic balance in drainage basins in the semiarid and arid regions of the western United States for a long period was implemented in 1962 through the Vigil Network (Leopold, 1962), whereby representative ephemeral draws, gullies, and stream channels were selected and instrumented to measure channel changes with time. Instrumentation of small tributaries was done with the intent of measuring changes resulting from climatic variation as well as those resulting from human activities.

From measurements made at eight Vigil Network sites in the semiarid and arid western United States, including several sites in the vicinity of the study area, Emmett (1974, p. 53-54) concludes that the valley trenching that began in about 1880 has now decreased, and that stream channels are stable or aggrading. Observations of stream channels in the study area since the 1960's by one of the authors of this report, H.W. Lowham, support the conclusion that the fluvial system currently (1987) is stable. Although some gullying and headcutting is occurring, the processes appear to be related to natural rejuvenation of the basins and generally are of a local nature. For example, a discontinuous gully west of Gillette, which is typical of drainages in the area, with local changes such as small, slowly advancing headcuts developing as part of a naturally changing landscape is shown in figure 40.

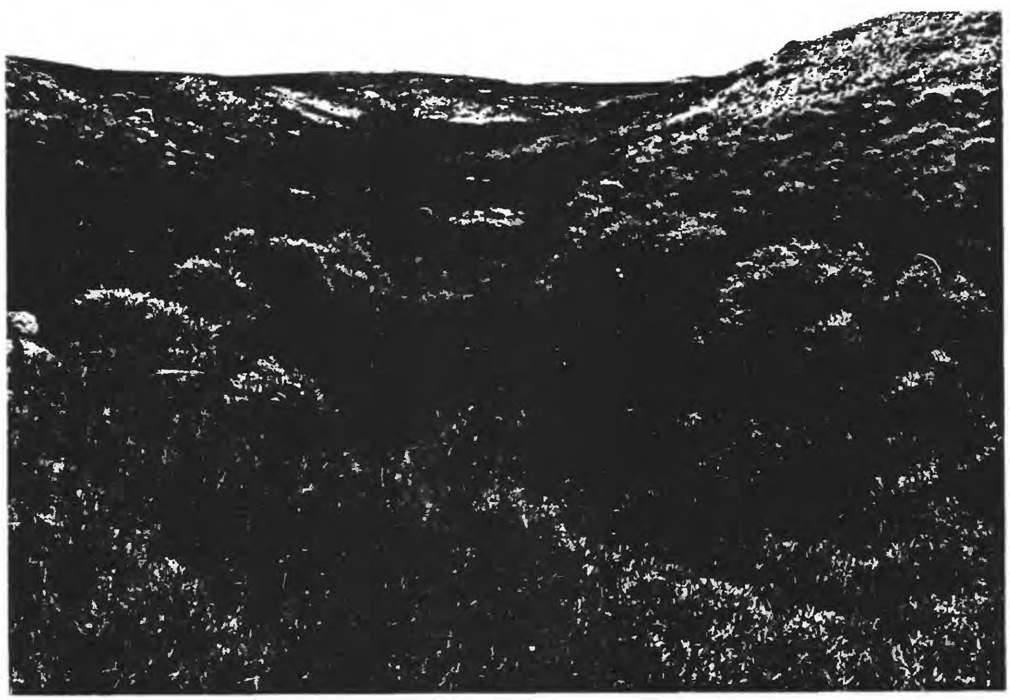


Figure 40.--Example of discontinuous gully with slowly advancing headcuts as part of a naturally changing landscape.

Characteristics of Natural Drainage Basins

A drainage basin is composed of two basic features: (1) A drainage network, and (2) hillslope and valley areas between stream channels. Stream channels and hillslopes are interrelated because what happens on the interfluve areas between streams has a dominant effect on the character of streams and on the hydrology of the basin (Chorley and others, 1984, p. 258). The stream-channel network of a drainage basin is defined as the number and form of all streams in the basin. When surface geology is fairly uniform, the network of stream channels develops in a dendritic pattern, as is shown by the example drainage basin in figure 41. Drainage networks of the study area generally are dendritic, although erosion-resistant outcrops, different lithologies, and geologic structures such as joints or faults occasionally may affect the orientation of the streams.

A quantitative description of drainage networks in the study area was made using a method commonly referred to as the Horton analysis (Horton, 1945). The fundamental aspect of the Horton analysis is the relation of certain physical characteristics, such as drainage area, stream number, and stream length, to stream order. Stream order is defined as the position of a stream within a drainage network (fig. 41). The ordering system described by Strahler (1957, p. 914) was used in this analysis. The smallest stream channels of the network are unbranched tributaries, which are designated as first-order streams. When two first-order streams join, the resulting stream channel is a second-order stream. Third-order streams receive two or more tributaries of the second order, but also may receive first-order streams, and so on. In this system, the main stream has the highest order. The order of the main stream describes the order of the drainage basin.

Stream order generally is determined by examining the drainage network of a basin on topographic maps. The map scale limits the size of the smallest stream that may be recognized. To include the smallest rills evident in the drainage basin in stream ordering, several orders of streams may have to be added to the smallest streams shown on 1:24,000-scale topographic maps (Leopold and Miller, 1956, p. 16). However, the inclusion of small rills in a drainage-net analysis is useful for only special studies. For most purposes, one may restrict consideration only to the drainage network appearing on 1:24,000-scale topographic maps (Leopold and others, 1964, p. 141).

A visit of drainage basins and stream channels in the study area was made by H.W. Lowham, who compared features observed in the field with those depicted on the topographic maps. The comparison indicated that rills, some swales, and some small stream channels are not shown on the maps; however, the drainage network and physical features shown by 1:24,000-scale topographic maps are considered adequate to define the fundamental aspects of basin stability.

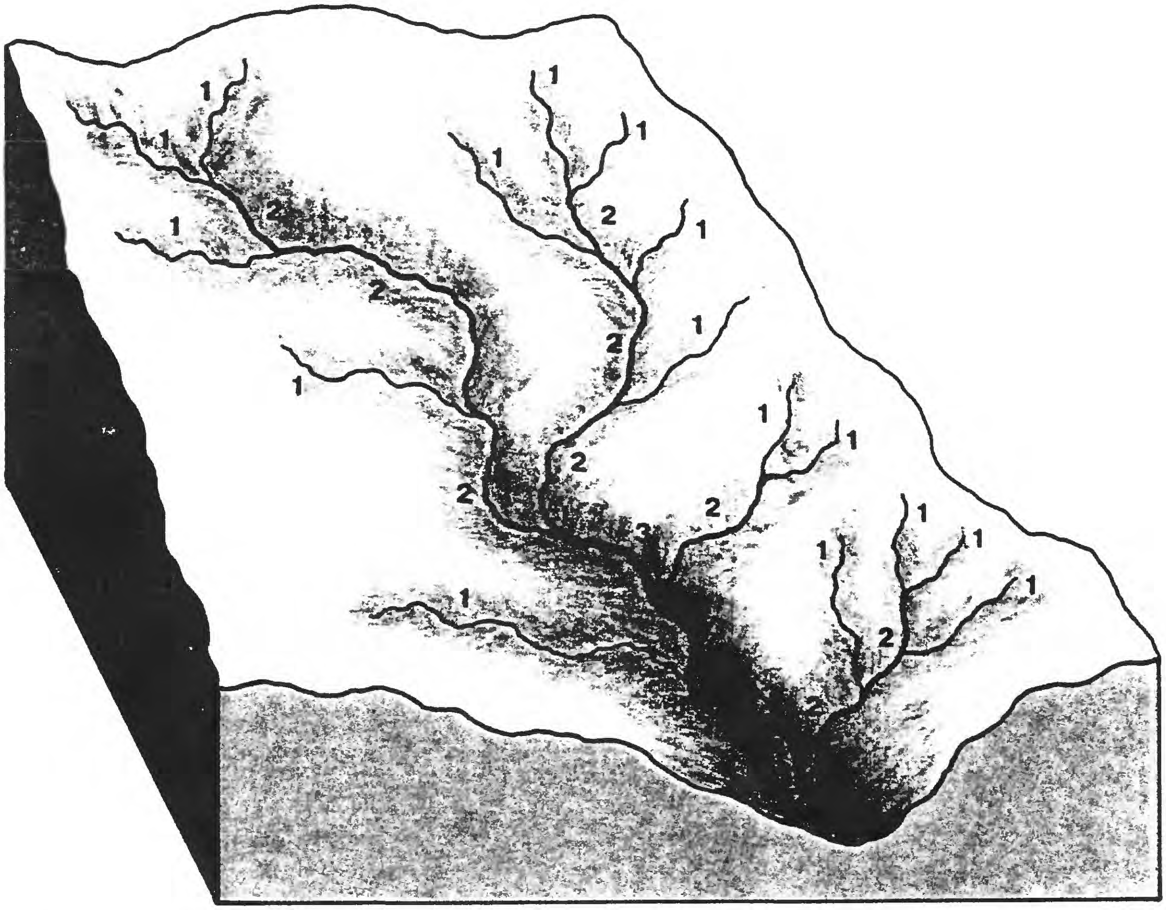


Figure 41.--Sketch of a drainage network with a dendritic pattern in a third-order drainage basin showing first-, second-, and third-order streams.

Data Used in Study

A sample of 102 first- or higher-order drainage basins was selected for determining the physical characteristics of drainage networks in the study area. The selected drainage basins are natural with insignificant controls or impacts from human activities. All of the drainage basins are located within the study area. The drainage basins were randomly selected using a mathematical procedure in conjunction with a grid overlay for topographic maps of the study area. The drainage basins were selected using the following procedure. The coal-permit areas were plotted on twenty-five 1:24,000-scale topographic maps. An overlay grid, exactly the size of one map, was divided into 150 rectangles of equal area. A mathematical procedure was used to generate a random grid number, and 51 drainage basins (fig. 42) located in the randomly selected grids were delineated for analysis. Due to the size of the grid, only second- or higher-order basins were selected using this process. A subset of 51 first-order basins was then selected from the larger basins, using a random process to select 1 first-order basin from each of the larger basins.

Twenty-one physical characteristics were measured for each of the 51 second- or higher-order drainage basins using a computerized digitizer. A description of each of the characteristics is given in table 21; the values measured for each of the 51 drainage basins are given in table 22.

Due to limitations of the map scale, some of the characteristics measured for the second- or higher-order drainage basins could not be accurately measured for the smaller first-order drainage basins. The characteristics measured for the first-order drainage basins are identified in table 21; the values are listed in table 23.

A statistical summary of the values of the physical characteristics is given in tables 24-27 for each of the drainage basin orders. The tables list the minimum and maximum values measured, the arithmetic mean, the geometric mean, and the standard deviation of the sample. The arithmetic and geometric means for each of the characteristics indicate the expected average magnitudes. The geometric mean, which is computed using logarithms of the values, generally is considered a more representative descriptor of the first moment of distributions in hydrology than the arithmetic mean, because the distributions usually are asymmetrical.

Measurements for a large sample of drainage basins within the eastern Powder River basin were used in the analysis. Similar data concerning the physical characteristics have been collected by the coal-mining companies for local areas. The data and relations determined by the coal-mining companies may vary from those of this study, depending on the scale of maps or aerial photographs used, the number of drainage basins sampled, and the local relief.

The physical characteristics of drainage networks commonly are interrelated. For example, as drainage area increases, the number of stream channels and the order of the main stream channel also increase. To determine those variables for which significant interrelations might exist, a correlation analysis was made. Results of this analysis are given in table 28.

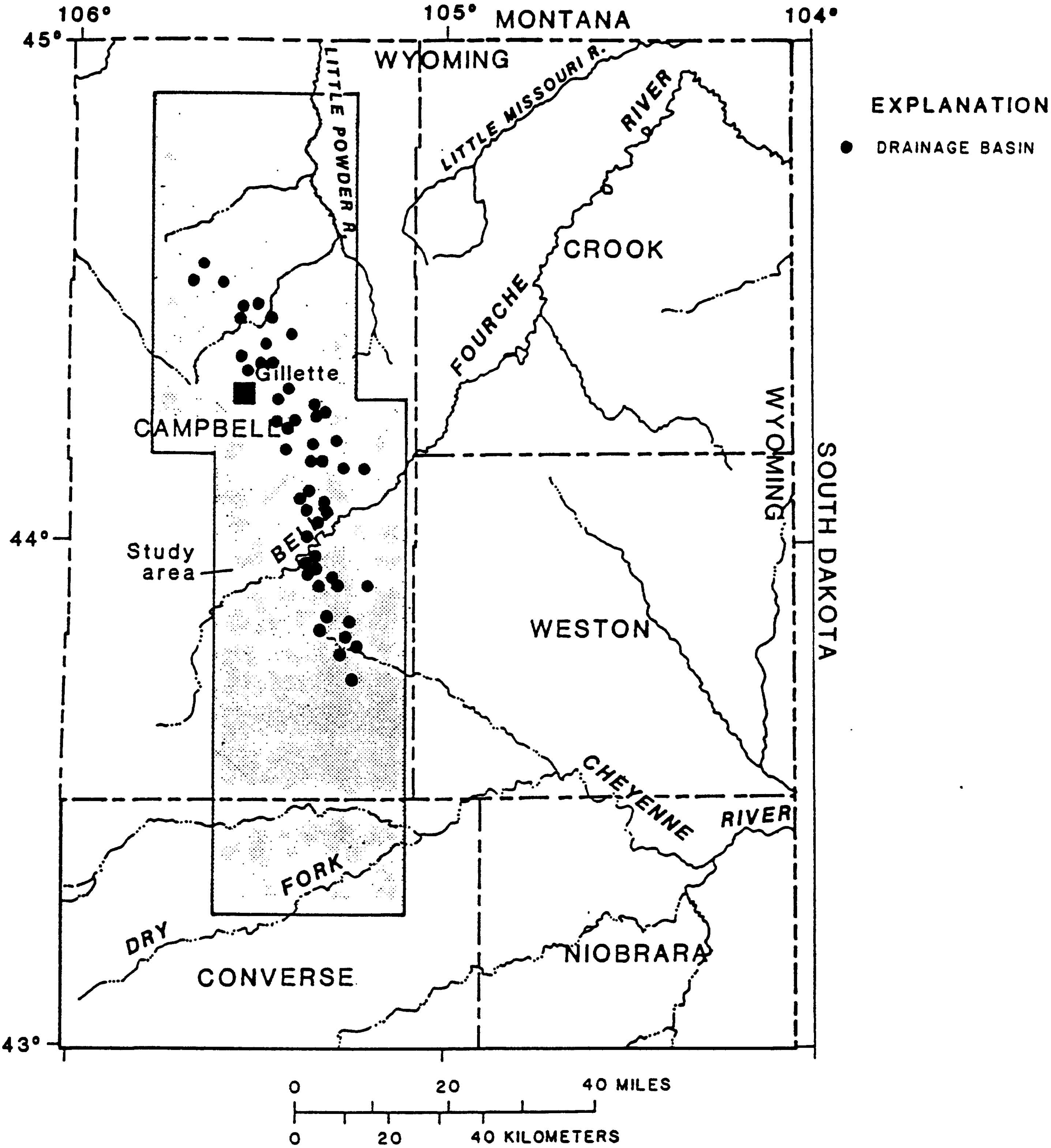


Figure 42.--Location of drainage basins used to determine physical characteristics.

Table 21.--Characteristics measured in drainage-basin-stability analysis

[*, indicates characteristics measured for first-order basins]

Characteristic	Explanation of characteristic
*Drainage area	The area, measured in a horizontal plane, from which direct surface runoff from precipitation normally drains into the stream channel upstream from the specified point, in square miles.
Number of first-order channels	Total number of stream channels in the drainage basin that are classified as first order.
Number of second-order channels	Total number of stream channels in the drainage basin that are classified as second order.
Number of third-order channels	Total number of stream channels in the drainage basin that are classified as third order.
Number of fourth-order channels	Total number of stream channels in the drainage basin that are classified as fourth order.
Length of first-order channels	Summation of lengths of all stream channels classified as first order, in miles.
Length of second-order channels	Summation of lengths of all stream channels classified as second order, in miles.
Length of third-order channels	Summation of lengths of all stream channels classified as third order, in miles.
Length of fourth-order channels	Summation of lengths of all stream channels classified as fourth order, in miles.
*Basin length	Straight-line distance across the drainage basin from the point on the drainage divide nearest the head of the dominant channel to the basin mouth, in miles.
*Basin perimeter	Perimeter of the drainage basin, in miles.
Basin width	Representative width of the drainage basin, generally measured at about the midpoint of the basin, in miles.
*Valley length	Length of the valley along the dominant stream channel, in miles.
*Channel length	Length of the dominant stream channel measured using the blue streamline shown on a 1:24,000-scale topographic map, in miles.
*Basin relief	Difference in elevation between the point on the drainage divide nearest the head of the dominant stream channel and the basin mouth, in feet.

Table 21.--Characteristics measured in drainage-basin-stability analysis--Continued

Characteristic	Explanation of characteristic
*Used relief	Difference in elevation between two points on the stream channel, channel, in feet. For the first-order basins, the points were selected at each end of the blue streamline shown on a 1:24,000-scale topographic map. For the second- and higher-order basins, the points were selected at 15 and 85 percent of the dominant stream channel length.
*Channel slope	Used relief divided by the length of stream channel between the points identified in used relief, in foot per foot. This depicts an average stream-channel slope, which should not be confused or compared with values that are measured at particular locations along stream-channels.
Basin order	Order of the stream channel at the drainage-basin mouth.
*Sinuosity	Stream-channel length divided by valley length. This depicts an average sinuosity for the stream channel, which should not be confused with values that are measured at particular locations along stream channels.
*Relief ratio	Basin relief divided by basin length.
*Total channel length	Summation of lengths of all stream channels of all orders in the drainage basin, in miles. For first-order streams, this is the same as stream-channel length.
*Drainage density	Total stream-channel length divided by the drainage area, in miles per square mile.
*Circularity ratio	Area of the drainage basin divided by the area of a circle having the same perimeter as the drainage basin.
Stream frequency	Total number of stream channels of all orders divided by the drainage area, in number of stream channels per square mile.
Maximum side-slope relief	Difference in elevation between the hilltop and the stream channel on the valley sideslope at the point of maximum difference, in feet.
Sideslope distance	Straight-line distance measured in a horizontal plane between the hilltop and the stream channel at the same point as the maximum sideslope relief was measured, in miles.
*Maximum value sideslope	Maximum value of sideslope relief divided by the sideslope distance, in foot per foot.

Table 22.--Physical characteristics for

Map name[1]	Drainage-basin sequence number	Drainage area (square miles)	For indicated order number of channel: Number of channels 1st	2nd	3rd	4th	Total length of channels, in miles 1st	2nd	3rd	4th	Basin length (miles)	Basin perimeter (miles)	Basin width (miles)	Valley length (miles)
Calf Creek	D59	0.74	5	2	1	0	1.42	1.28	0.62	0.00	1.66	4.28	0.47	1.50
Calf Creek	D58	7.73	34	11	2	1	12.01	7.60	3.31	4.14	5.29	13.03	1.97	4.97
Calf Creek	D57	.91	3	1	0	0	2.51	.48	.00	.00	1.42	3.88	.84	1.25
Calf Creek	D56	.71	5	1	0	0	1.06	1.64	.00	.00	1.67	4.05	.52	1.50
Fortin Draw	D55	.51	3	1	0	0	1.55	.95	.00	.00	1.57	3.64	.42	1.38
Rawhide School	D54	3.22	16	6	2	1	5.79	2.98	.70	1.35	2.95	7.68	1.55	2.92
Moyer Springs	D53	2.12	11	5	1	0	5.95	2.03	1.86	.00	2.37	6.94	.98	1.99
Rawhide School	D52	.88	4	1	0	0	1.36	1.69	.00	.00	1.85	5.09	.47	1.85
Rawhide School	D51	3.24	10	3	1	0	4.81	3.93	.96	.00	2.78	9.02	1.10	2.42
Rawhide School	D50	1.88	6	2	1	0	3.34	2.23	.36	.00	2.21	5.89	1.09	1.89
Gillette West	D49	3.41	8	2	1	0	5.20	1.57	2.30	.00	3.16	8.35	1.35	3.03
Gillette East	D48	.93	4	1	0	0	2.69	1.32	.00	.00	2.37	5.10	.51	2.29
Gillette West	D47	1.38	5	1	0	0	2.34	.36	.00	.00	1.71	5.10	1.02	1.68
Gillette East	D46B	8.18	13	4	2	1	7.51	5.02	6.87	.80	6.32	14.69	1.91	6.00
Gillette East	D46	2.78	6	2	1	0	4.71	2.03	2.40	.00	3.32	8.32	1.06	3.20
Gillette East	D45	1.55	5	2	0	0	2.98	1.51	.00	.00	1.26	5.92	.81	1.20
Gillette East	D44	.40	2	1	0	0	.98	.55	.00	.00	1.10	2.80	.41	1.05
Gillette East	D43	3.33	16	4	1	0	7.32	4.62	2.18	.00	3.89	9.52	1.20	3.76
Gillette East	D42	2.13	5	2	1	0	1.89	1.61	.67	.00	2.48	8.01	.70	2.16
Coyote Draw	D41	2.15	8	2	1	0	4.31	2.83	.90	.00	2.86	6.97	.87	2.58
The Gap	D40	4.16	10	3	1	0	6.55	3.25	2.28	.00	3.80	10.13	1.61	3.77
Coyote Draw	D39	4.45	15	4	2	1	8.88	2.94	1.40	1.14	4.43	12.58	1.31	3.64
The Gap	D38	1.04	3	1	0	0	1.52	1.96	.00	.00	2.12	4.96	.74	2.12
Coyote Draw	D37	1.24	8	3	1	0	3.56	1.04	1.38	.00	2.21	6.28	.56	2.17
Coyote Draw	D36	2.62	15	4	1	0	6.91	1.75	3.21	.00	3.58	8.72	.87	3.58
Coyote Draw	D35	1.36	3	1	0	0	1.81	1.59	.00	.00	2.27	5.36	.77	1.55
The Gap	D34	.96	2	1	0	0	1.26	.95	.00	.00	1.63	4.28	.67	1.63
The Gap	D33	1.08	4	1	0	0	2.29	1.25	.00	.00	2.19	5.19	.58	2.07
Coyote Draw	D32	1.24	3	1	0	0	2.50	.80	.00	.00	2.04	5.00	.72	1.74
Coyote Draw	D31	2.50	11	2	1	0	6.15	1.93	2.08	.00	3.34	7.77	.82	3.27
Saddle Horse Butte	D30	.70	5	2	1	0	1.64	1.04	.55	.00	1.50	3.82	.67	1.34
Saddle Horse Butte	D29	.40	3	1	0	0	1.25	.60	.00	.00	1.37	3.13	.44	1.03
Saddle Horse Butte	D28	1.37	4	1	0	0	2.42	2.41	.00	.00	2.83	6.35	.70	2.59
Neil Butte	D27	3.52	3	1	0	0	1.64	1.12	.00	.00	1.54	9.44	1.51	.96
Neil Butte	D26	3.70	8	1	0	0	5.86	2.35	.00	.00	2.72	10.06	1.70	2.46
Eagle Rock	D25	2.26	8	2	1	0	3.25	3.99	.92	.00	3.29	7.94	.81	3.01
Neil Butte	D24	2.14	10	2	1	0	3.22	1.48	2.61	.00	3.56	8.31	.83	3.25
Neil Butte	D23	.80	7	1	0	0	1.53	1.05	.00	.00	1.37	4.28	.58	1.18
Neil Butte	D22	.80	3	1	0	0	.71	1.80	.00	.00	2.02	4.66	.54	2.02
Neil Butte	D21	1.78	9	2	1	0	3.54	1.98	.75	.00	2.32	6.05	1.32	2.10
Neil Butte	D20	.82	4	1	0	0	.84	1.92	.00	.00	1.97	4.31	.52	1.84
Reno Reservoir	D19	8.84	41	10	3	1	15.70	6.56	6.50	5.17	6.84	14.57	1.78	6.40
Hilight	D18	1.98	6	2	1	0	2.27	2.43	.50	.00	2.29	6.66	1.27	2.21
Hilight	D17	3.72	8	2	1	0	3.37	.66	4.14	.00	4.20	9.97	1.39	3.87
Hilight	D16	1.14	6	1	0	0	1.92	2.28	.00	.00	2.15	5.08	.72	2.05
Hilight	D15	1.14	6	2	1	0	2.31	.72	1.70	.00	2.18	5.97	.65	2.05
Hilight	D14	3.26	14	3	1	0	5.21	3.24	1.74	.00	3.30	9.84	1.10	2.86
Open A Ranch	D13	1.60	6	2	1	0	3.04	1.78	.68	.00	2.51	6.75	.76	2.46
The Gap SW	D11	1.65	6	2	1	0	2.63	1.83	1.12	.00	2.58	6.49	.99	2.58
Saddle Horse Butte	D05	2.86	11	3	1	0	5.03	2.15	2.65	.00	4.19	8.27	1.09	3.11
The Gap SW	D03	3.56	3	1	0	0	2.05	3.08	.00	.00	4.40	10.17	1.13	2.85

[1] Name of U.S. Geological Survey 1:24,000-scale topographic map.

second-, third-, and fourth-order basins

Channel length (miles)	Basin relief (feet)	Used relief (feet)	Channel slope (foot per foot)	Basin order	Sinuosity	Relief ratio	Total channel length (miles)	Drainage density (miles per square mile)	Circularity ratio	Stream frequency (streams per square mile)	Maximum side-slope relief (feet)	Side-slope distance (miles)	Maximum value side-slope (foot per foot)
1.66	314	180	0.030	3	1.10	189	3.32	4.49	0.506	10.8	180	0.120	0.284
7.09	331	132	.012	4	1.42	62.6	27.06	3.50	.571	6.2	120	.092	.247
1.42	184	92	017	2	1.13	130	2.99	3.29	.757	4.4	60	.187	.060
1.72	410	122	.019	2	1.14	246	2.70	3.81	.541	8.4	180	.137	.248
1.66	375	221	.036	2	1.20	239	2.50	4.92	.481	7.8	120	.054	.420
3.20	403	220	.018	4	1.09	137	10.82	3.36	.685	7.7	120	.120	.189
2.68	433	119	.012	3	1.34	183	9.84	4.65	.551	8.0	90	.096	.177
2.01	284	135	.018	2	1.08	154	3.05	3.48	.424	5.7	130	.486	.050
2.60	276	120	.013	3	1.07	99.3	9.70	2.99	.500	4.3	140	.403	.065
2.21	461	139	.017	3	1.16	209	5.93	3.15	.680	4.7	300	.520	.109
3.87	441	130	.009	3	1.27	140	9.07	2.65	.614	3.2	140	.300	.088
2.58	232	120	.012	2	1.12	97.9	4.01	4.33	.447	5.3	180	.428	.079
1.98	194	124	.016	2	1.17	113	2.70	1.95	.666	4.3	100	.454	.041
8.44	405	148	.004	4	1.40	64.1	20.20	2.46	.476	2.4	300	1.07	.063
4.42	205	85	.005	3	1.38	61.7	9.14	3.28	.504	3.2	100	2.31	.008
1.28	205	152	.032	2	1.06	163	4.49	2.89	.555	4.5	120	.320	.071
1.12	211	140	.033	2	1.06	192	1.53	3.80	.644	7.4	120	.295	.077
4.69	312	197	.011	3	1.24	80.2	14.12	4.24	.461	6.3	141	.340	.078
2.35	190	93	.010	3	1.08	76.6	4.17	1.95	.416	3.7	170	.430	.074
3.18	241	135	.011	3	1.23	84.3	8.04	3.73	.555	5.1	100	.248	.076
4.14	443	155	.010	3	1.09	117	12.08	2.90	.509	3.3	100	.237	.079
4.41	379	152	.009	4	1.21	85.6	14.36	3.22	.353	4.9	125	.353	.067
2.38	289	98	.011	2	1.12	136	3.48	3.34	.530	3.8	160	.542	.059
2.45	283	136	.015	3	1.12	128	5.98	4.82	.394	9.6	80	.302	.050
4.70	241	106	.006	3	1.31	67	11.87	4.53	.432	7.6	202	.697	.054
2.33	176	58	.006	2	1.50	77.5	3.40	2.50	.594	2.9	80	.349	.043
1.79	231	85	.012	2	1.09	142	2.21	2.30	.657	3.1	140	.358	.074
2.18	252	78	.009	2	1.05	115	3.54	3.27	.503	4.6	192	.406	.089
2.03	329	113	.015	2	1.16	162	3.30	2.66	.622	3.2	100	.423	.044
4.01	320	164	.011	3	1.22	95.8	10.16	4.06	.520	5.6	160	.484	.062
1.40	222	116	.022	3	1.04	148	3.23	4.61	.602	11.4	80	.178	.085
1.10	200	74	.018	2	1.06	146	1.85	4.56	.519	9.8	100	.196	.099
3.10	240	135	.011	2	1.19	84.8	4.83	3.52	.426	3.6	60	.199	.057
1.38	379	95	.018	2	1.43	246	2.76	.78	.496	1.1	207	.396	.099
2.92	432	67	.006	2	1.18	159	8.21	2.21	.459	2.4	145	.393	.069
3.70	429	176	.012	3	1.22	130	8.16	3.61	.450	1.8	252	.353	.135
4.01	393	130	.008	3	1.23	110	7.31	3.41	.389	6.0	283	.540	.199
1.31	223	92	.019	2	1.11	163	2.58	3.21	.550	9.9	80	.190	.079
2.04	134	50	.006	2	1.00	66.3	2.51	3.15	.459	5.0	80	.230	.065
3.03	254	70	.006	3	1.44	109	6.27	3.52	.610	6.7	80	.232	.065
2.13	204	92	.009	2	1.15	104	2.76	3.36	.555	6.0	90	.310	.054
9.67	274	100	.002	4	1.51	40.1	33.93	3.83	.523	6.2	120	.530	.042
2.60	191	107	.011	3	1.17	83.4	5.20	2.62	.560	4.5	100	.234	.080
5.00	390	210	.011	3	1.29	92.9	8.17	2.19	.470	2.9	217	.619	.066
2.43	276	172	.019	2	1.18	128	4.20	3.68	.554	6.1	110	.509	.040
2.53	165	89	.009	3	1.23	75.7	4.73	4.14	.401	7.8	190	.267	.134
3.65	232	156	.011	3	1.27	70.3	10.19	3.12	.422	5.5	110	.425	.049
2.76	259	125	.012	3	1.12	103	5.50	3.43	.441	5.6	200	.283	.133
2.96	296	160	.014	3	1.14	115	5.58	3.38	.492	5.45	150	.280	.101
4.19	342	132	.008	3	1.34	81.6	9.88	3.45	.525	5.24	110	.065	.320
3.17	402	112	.009	2	1.11	91.4	5.13	1.44	.432	1.12	230	.820	.053

Table 23.--Physical characteristics for first-order drainage basins

Map name[1]	Drainage-basin sequence number	Drainage area (square mile)	Basin length (miles)	Basin perimeter (miles)	Valley length (miles)	Channel length (mile)	Basin relief (feet)	Used relief (feet)	Channel slope (foot per foot)	Sinuosity	Relief ratio	Drainage density (miles per square mile)	Circularity ratio	Stream frequency (streams per square mile)	Maximum value sideslope (foot per foot)
Calf Creek	D59	0.12	0.57	1.48	0.41	0.41	160	100	0.0452	1.00	279	3.52	0.676	8.40	0.100
Calf Creek	D58	.21	.56	1.83	.63	.67	125	40	.0112	1.07	223	3.25	.774	4.81	.097
Calf Creek	D57	.15	.89	2.11	.85	.93	130	110	.0224	1.09	146	6.12	.426	6.58	.071
Calf Creek	D56	.10	.58	1.35	.43	.43	290	70	.0308	.99	502	4.48	.655	10.4	.095
Fortin Draw	D55	.12	.73	1.67	.47	.49	150	70	.0268	1.04	207	3.95	.558	8.00	.133
Rawhide School	D54	.15	.67	1.85	.66	.65	160	80	.0230	.99	240	4.48	.539	6.80	.063
Moyer Springs	D53	.31	1.05	2.74	.87	.96	130	70	.0138	1.10	124	3.12	.515	3.25	.086
Rawhide School	D52	.19	.56	1.71	.43	.43	70	50	.0217	1.01	126	2.34	.799	5.38	.045
Rawhide School	D51	.24	.99	2.29	.91	.92	145	105	.0215	1.00	147	3.81	.577	4.13	.046
Rawhide School	D50	.07	.53	1.25	.47	.52	185	150	.0542	1.10	347	7.18	.583	13.7	.074
Gillette West	D49	.17	.68	1.93	.62	.73	300	160	.0414	1.18	443	4.31	.573	5.88	.074
Gillette East	D48	.43	1.20	2.88	.99	1.22	140	110	.0171	1.22	117	2.85	.646	2.34	.045
Gillette West	D47	.39	1.04	2.75	.62	.62	130	30	.0091	1.00	125	1.61	.642	2.58	.020
Gillette East	D46	.25	.67	1.95	.52	.55	100	60	.0204	1.05	150	2.21	.827	3.97	.014
Gillette East	D46B	.24	.66	2.14	.42	.49	200	40	.0152	1.17	301	2.11	.640	4.26	.049
Gillette East	D45	.14	.59	1.76	.51	.56	160	130	.0436	1.10	269	4.19	.547	7.41	.060
Gillette East	D44	.07	.68	1.50	.67	.67	170	140	.0392	1.00	252	9.66	.387	14.3	.058
Gillette East	D43	.35	1.39	3.38	1.31	1.38	180	150	.0205	1.06	130	3.94	.385	2.85	.103
Gillette East	D42	.18	.58	2.42	.49	.54	70	60	.0208	1.11	120	3.06	.381	5.59	.046
Coyote Draw	D41	.25	1.00	2.68	.72	.79	115	95	.0225	1.11	115	3.24	.430	4.07	.039
The Gap	D40	.49	1.26	3.35	.63	.67	100	40	.0112	1.06	79	1.37	.551	2.02	.033
Coyote Draw	D39	.32	1.06	2.90	.82	.93	140	60	.0121	1.13	133	2.91	.479	3.11	.076
The Gap	D38	.10	.59	1.67	.53	.56	165	65	.0219	1.06	279	5.93	.428	10.5	.046
Coyote Draw	D37	.24	.92	2.56	.65	.69	140	60	.0165	1.05	152	2.88	.458	4.17	.052
Coyote Draw	D36	.10	.63	1.43	.50	.51	80	50	.0186	1.01	128	4.86	.645	9.52	.033
Coyote Draw	D35	.10	.98	2.18	.58	.58	90	30	.0097	1.00	92	5.55	.277	9.52	.014
The Gap	D34	.04	.44	1.03	.36	.38	130	90	.0444	1.05	292	9.60	.472	25.0	.158
The Gap	D33	.34	.89	2.26	.76	.96	120	60	.0117	1.27	134	2.81	.843	2.90	.083
Coyote Draw	D32	.25	1.02	2.61	.78	.85	140	80	.0178	1.09	137	3.38	.461	3.97	.147
Coyote Draw	D31	.16	.50	2.27	.39	.44	140	50	.0211	1.13	279	2.78	.391	6.21	.078
Saddle Horse Butte	D30	.12	.43	1.40	.34	.34	120	60	.0329	1.01	278	2.92	.748	8.47	.088
Saddle Horse Butte	D29	.08	.55	1.40	.44	.47	90	70	.0279	1.06	164	5.94	.508	12.5	.081
Saddle Horse Butte	D28	.09	.62	1.49	.49	.49	100	60	.0229	1.00	160	5.29	.530	10.6	.050
Neil Butte	D27	.05	.47	1.15	.30	.30	150	80	.0505	1.00	317	6.52	.431	21.7	.074
Neil Butte	D26	.30	.96	2.40	.73	.73	215	175	.0454	1.00	224	2.42	.655	3.31	.219
Eagle Rock	D25	.08	.54	1.34	.54	.54	260	150	.0523	1.00	479	6.96	.542	12.8	.059
Neil Butte	D24	.13	.63	1.65	.47	.54	290	120	.0414	1.17	461	4.10	.614	7.46	.040
Neil Butte	D23	.07	.58	1.36	.52	.55	90	80	.0274	1.06	155	7.77	.479	14.1	.047
Neil Butte	D22	.07	.38	1.13	.29	.29	65	30	.0191	1.02	172	4.08	.709	13.7	.059
Neil Butte	D21	.16	.72	2.00	.68	.72	70	60	.0158	1.04	97.0	4.50	.502	6.25	.037
Neil Butte	D20	.04	.32	.85	.21	.21	60	40	.0349	1.00	185	4.93	.765	22.7	.077
Reno Reservoir	D19	.25	1.12	2.65	.81	.95	110	80	.0159	1.17	98.0	3.78	.449	3.97	.293
Hilight	D18	.16	.49	1.67	.45	.45	115	35	.0146	1.00	236	2.89	.700	6.37	.075
Hilight	D17	.22	.69	2.15	.61	.61	200	150	.0461	1.00	290	2.75	.605	4.46	.165
Hilight	D16	.12	.96	2.15	.77	.84	210	110	.0246	1.09	218	6.99	.328	8.26	.025
Hilight	D15	.11	.53	1.33	.43	.49	45	25	.0096	1.12	85.2	4.63	.747	9.43	.081
Hilight	D14	.25	1.09	2.56	.70	.78	80	40	.0096	1.11	73.2	3.14	.476	4.00	.015
Open A Ranch	D13	.13	.66	1.92	.66	.66	130	120	.0343	1.00	196	5.18	.432	7.81	.263
The Gap SW	D11	.22	.84	2.42	.78	.81	160	120	.0280	1.03	191	3.78	.460	4.65	.104
Saddle Horse Butte	D05	.13	.81	1.87	.61	.65	170	130	.0376	1.06	210	4.92	.477	7.52	.174
The Gap SW	D03	.46	1.32	3.80	.95	.96	75	53	.0104	1.01	56.6	2.08	.400	2.16	.042

[1] U.S. Geological Survey 1:24,000-scale topographic map

Table 24.--Statistical properties for first-order drainage basins

[Number of basins in sample = 51]

Characteristic	Minimum	Maximum	Arithmetic mean	Geometric mean	Standard deviation of geometric mean, in percent	
					Minus	Plus
Drainage area (square miles)	0.04	0.49	0.19	0.16	46.7	87.7
Basin length (miles)	.32	1.39	.76	.72	28.8	40.5
Basin perimeter (miles)	.85	3.81	2.02	1.92	27.8	38.6
Valley length (miles)	.22	1.31	.61	.58	29.1	41.1
Channel length (miles)	.22	1.38	.65	.61	30.6	44.0
Basin relief (feet)	45.0	300	140	129	34.3	51.9
Used relief (feet)	25.0	175	82.2	72.8	39.8	66.2
Channel slope (foot per foot)	.009	.054	.026	.023	50.6	102
Sinuosity	1.00	1.28	1.06	1.06	5.9	6.26
Relief ratio	56.6	502	204	180	39.6	66.0
Total channel length (miles)	.22	1.38	.65	.61	30.6	44.0
Drainage density (miles per square mile)	1.37	9.66	4.26	3.90	34.7	52.9
Circularity ratio	.277	.843	.551	.535	21.2	28.5
Maximum value sideslope (foot per foot)	.014	.293	.081	.065	49.1	96.6

Table 25.--Statistical properties for second-order drainage basins

[Number of basins in sample = 22]

Characteristic	Minimum	Maximum	Arithmetic mean	Geometric mean	Standard deviation of geometric mean, in percent	
					Minus	Plus
Drainage area (square miles)	0.04	3.70	1.32	1.09	45.5	83.3
Basin length (miles)	1.10	4.40	1.98	1.89	26.7	36.4
Basin perimeter (miles)	2.80	10.2	5.36	5.06	28.3	39.5
Basin width (miles)	.41	1.70	.74	.69	32.1	47.3
Valley length (miles)	.96	2.85	1.74	1.66	26.9	36.7
Channel length (miles)	1.10	3.17	2.00	1.91	26.9	36.9
Basin relief (feet)	134	432	266	254	27.0	37.0
Used relief (feet)	50.0	124	116	107	33.1	49.4
Channel slope (foot per foot)	.006	.037	.016	.015	39.3	64.7
Sinuosity	1.01	1.50	1.16	1.15	8.81	9.65
Relief ratio	66.3	246	143	135	30.3	43.5
Total channel length (miles)	1.53	8.21	3.40	3.17	30.6	44.2
Drainage density (miles per square mile)	.784	4.92	3.12	2.92	33.5	50.6
Circularity ratio	.424	.757	.540	.533	14.8	17.3
Stream frequency (streams per square mile)	1.12	9.96	5.06	4.41	44.3	79.6
Maximum sideslope relief (feet)	60.0	230	127	118	31.7	46.5
Sideslope distance (miles)	.054	.820	.349	.306	43.8	78.0
Maximum value sideslope (foot per foot)	.041	.421	.090	.073	42.5	74.0
Average channel length for first-order basins (miles)	.210	.84	.511	.471	35.6	55.4
Average channel length for second-order basins (miles)	.360	3.08	1.40	1.21	44.0	78.5

Table 26.--Statistical properties for third-order drainage basins

[Number of basins in sample = 24]

Characteristic	Minimum	Maximum	Arithmetic mean	Geometric mean	Standard deviation of geometric mean, in percent: Minus	Plus
Drainage area (square miles)	0.70	4.16	2.31	2.11	37.3	59.4
Basin length (miles)	1.50	4.20	2.90	2.80	24.1	31.8
Basin perimeter (miles)	3.82	10.1	7.51	7.31	21.9	28.1
Basin width (miles)	.47	1.61	.98	.94	26.3	35.8
Valley length (miles)	1.34	3.87	2.67	2.58	24.9	33.1
Channel length (miles)	1.40	5.00	3.28	3.13	28.2	39.2
Basin relief (feet)	165	461	306	292	26.2	35.5
Used relief (feet)	70.0	210	135	130	23.8	31.2
Channel slope (foot per foot)	.005	.303	.012	.011	31.8	46.6
Sinuosity	1.04	1.44	1.22	1.21	8.24	8.98
Relief ratio	61.7	209	110	104	28.3	39.4
Total channel length (miles)	3.23	14.1	7.82	7.27	33.0	49.4
Drainage density (miles per square mile)	1.96	4.82	3.54	3.45	21.0	26.6
Circularity ratio	.389	.681	.501	.495	13.1	16.5
Stream frequency (streams per square mile)	2.96	11.4	5.93	5.53	31.3	45.4
Maximum sideslope relief (feet)	80.0	300	153	141	33.4	50.1
Sideslope distance (miles)	.065	2.31	.415	.316	50.8	103
Maximum value sideslope (foot per foot)	.008	.320	.108	.087	51.1	104
Average channel length for first-order basins (miles)	.284	.785	.467	.453	21.5	27.3
Average channel length for second-order basins (miles)	.330	2.00	.884	.797	38.3	62.1
Average channel length for third-order basins (miles)	.360	4.14	1.61	1.32	48.8	95.4

Table 27.--Statistical properties for fourth-order drainage basins

[Number of basins in sample = 5]

Characteristic	Minimum	Maximum	Arithmetic mean	Geometric mean	Standard deviation of geometric mean, in percent	
					Minus	Plus
Drainage area (square miles)	3.22	8.84	6.48	6.04	35.8	55.8
Basin length (miles)	2.95	6.84	5.17	4.96	28.5	39.8
Basin perimeter (miles)	7.68	14.7	12.51	12.21	23.4	30.6
Basin width (miles)	1.31	1.97	1.70	1.68	15.5	18.3
Valley length (miles)	2.92	6.40	4.79	4.59	28.4	39.7
Channel length (miles)	3.20	9.67	6.56	6.06	37.1	59.1
Basin relief (feet)	274	405	358	355	15.3	18.0
Used relief (feet)	100	220	150	146	24.7	32.9
Channel slope (foot per foot)	.003	.019	.010	.008	53.3	114
Sinuosity	1.10	1.51	1.33	1.32	12.4	14.2
Relief ratio	40.0	137	77.8	71.6	36.4	57.1
Total channel length (miles)	10.8	33.9	21.3	19.6	36.9	58.5
Drainage density (miles per square mile)	2.47	3.83	3.28	3.24	15.3	18.0
Circularity ratio	.353	.680	.522	.510	21.8	27.8
Stream frequency (streams per square mile)	2.44	7.76	5.52	5.15	36.0	56.2
Maximum sideslope relief (feet)	120	300	157	145	33.3	50.0
Sideslope distance (miles)	.092	1.07	.433	.294	64.1	179
Maximum value sideslope (foot per foot)	.043	.247	.121	.097	53.2	113
Average channel length for first-order basins (miles)	.353	.592	.454	.441	22.8	29.5
Average channel length for second-order basins (miles)	.497	1.26	.77	.730	28.7	40.2
Average channel length for third-order basins (miles)	.350	3.44	1.66	1.25	60.0	150
Average channel length for fourth-order basins (miles)	.800	5.17	2.52	1.92	56.3	128

Table 28.--Summary of correlation analysis of physical characteristics for drainage basins

[Values listed are correlation coefficients; analysis made using logarithms of characteristics]

	Drainage area	Basin length	Basin perimeter	Basin width	Valley length	Channel length	Basin relief	Used relief	Channel slope	Sinuosity ratio	Relief ratio	Total channel length	Drainage density	Circularity ratio	Stream frequency	Maximum sideslope relief	Sideslope distance	Maximum value sideslope
Drainage area	1.00																	
Basin length	.96	1.00																
Basin perimeter	.99	.97	1.00															
Basin width	.92	.70	.85	1.00														
Valley length	.95	.98	.96	.65	1.00													
Channel length	.95	.98	.96	.70	.99	1.00												
Basin relief	.71	.72	.71	.44	.73	.73	1.00											
Used relief	.47	.51	.48	.14	.57	.55	.73	1.00										
Channel slope	-.70	-.71	-.70	-.51	-.68	-.69	-.20	.18	1.00									
Sinuosity ratio	.71	.69	.70	.57	.67	.73	.51	.30	-.60	1.00								
Relief ratio	-.62	-.68	-.64	-.38	-.65	-.65	.02	.04	.81	-.46	1.00							
Total channel length	.96	.97	.97	.78	.98	.98	.75	.56	-.65	.72	-.60	1.00						
Drainage density	-.50	-.33	-.45	-.42	-.25	-.26	-.16	.11	.41	-.26	.30	-.24	1.00					
Circularity ratio	-.12	-.27	-.26	.06	-.26	-.24	-.14	-.19	.15	-.05	.25	-.20	-.22	1.00				
Stream frequency	-.53	-.45	-.52	-.47	-.40	-.41	-.23	-.04	.50	-.34	.41	-.33	.84	.00	1.00			
Maximum sideslope relief	.29	.31	.34	.16	.29	.27	.49	.23	-.08	.06	.06	.20	-.23	-.33	-.26	1.00		
Sideslope distance	.30	.29	.33	.20	.30	.29	-.06	-.13	-.45	.12	-.35	.16	-.35	-.23	-.50	.38	1.00	
Maximum value sideslope	.10	.10	.09	-.10	.12	.12	.34	.39	.25	.06	.22	.15	.13	.03	.17	.27	-.78	1.00

These correlations were used as a guide to develop graphs (figs. 43-45) and regression relations (table 29) for the physical characteristics that are significantly related and that are considered important in assessing drainage-basin stability. These relations were then used to compare the physical characteristics from postmining plans to those existing for natural drainage basins of the area.

Illustrative Example

An example of how the previously described graphs and relations quantify physical characteristics of natural drainage basins follows, using a headwater drainage basin of 1.9 mi^2. The data and relation of drainage-basin order to drainage area in figure 43 indicate that, on the average for the data base in this study, a drainage-basin order of 2.8 is necessary to drain an area of 1.9 mi^2. The figure 2.8 rounds to the whole number 3, indicating the main stream channel at the mouth of the drainage basin needs to be a third-order stream channel. On the basis of the relative numbers of stream channels in various orders for the study sample, the relations in figure 44 indicate that for a drainage area of 1.9 mi^2, 12 first-order, 3 second-order, and 1 third-order stream channels also are necessary to complete the drainage network. The average slope of first- to fourth-order stream channels is shown by the relation in figure 45, which illustrates that lower-order stream channels and valleys have relatively steeper gradients than do higher-order stream channels and valleys. Valley slope, which has not previously been defined in the report, is computed by either: (1) Multiplying stream-channel slope by sinuosity, or (2) dividing used relief by the length of valley between the points identified in used relief. As shown in the example (fig. 45), a second-order stream channel will have a slope of 0.016 ft/ft, on the average. The physical characteristics of the example drainage basin are summarized in table 30.

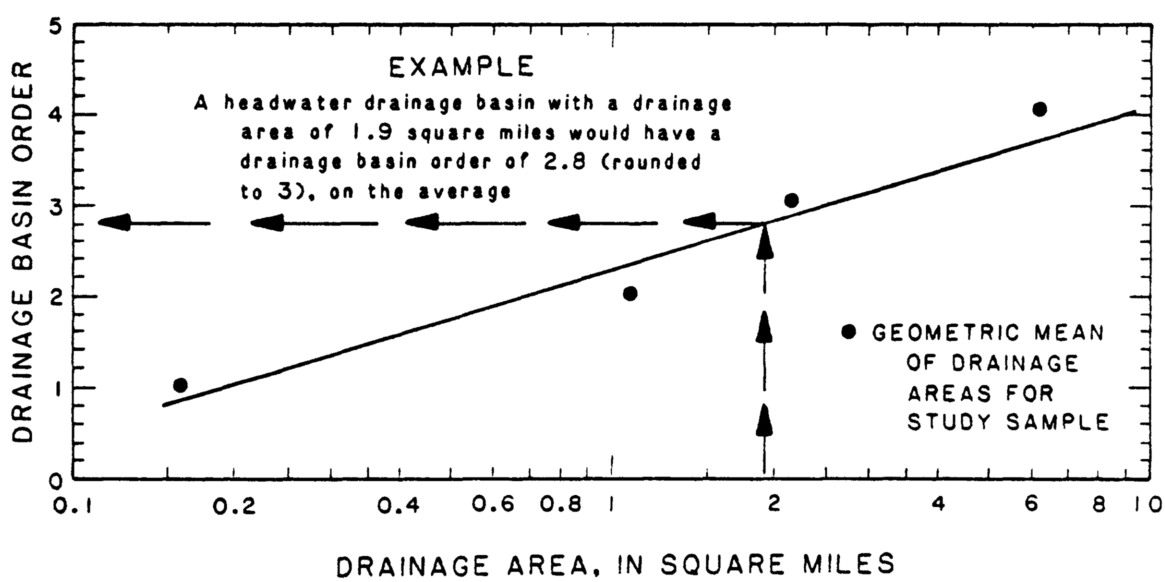


Figure 43.--Relation of drainage-basin order to drainage area.

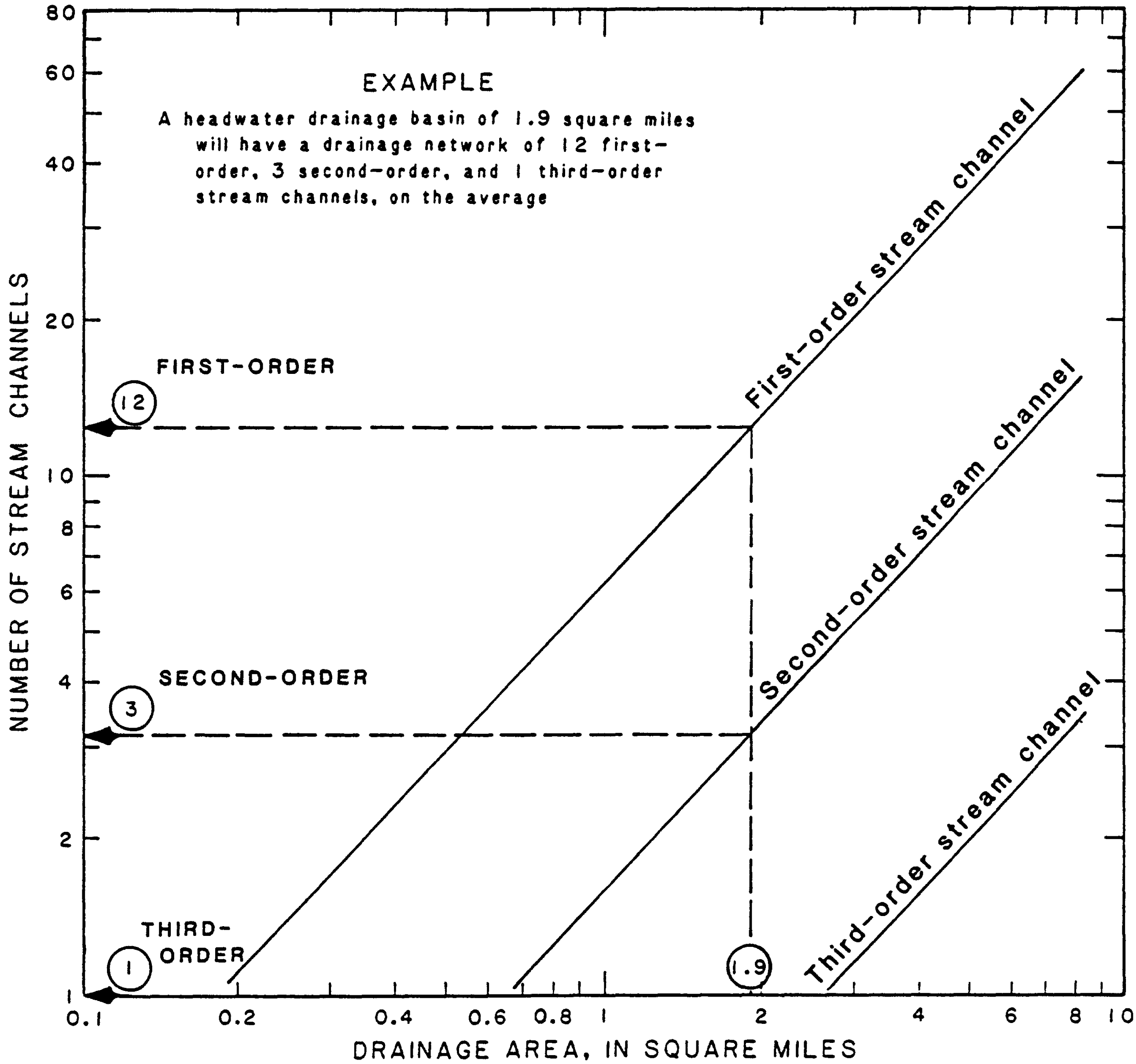


Figure 44.--Relation of number of stream channels to drainage area.

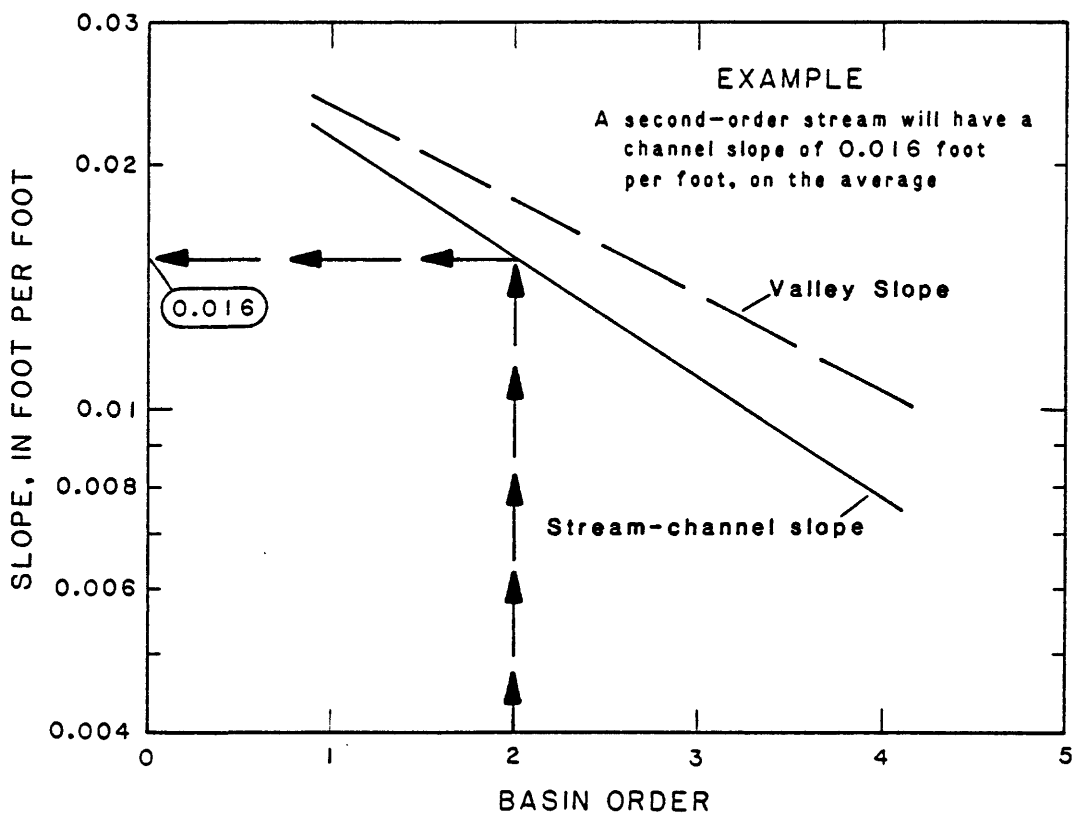


Figure 45.--Relations of stream-channel and valley slopes to drainage-basin order.

Table 29.--Summary of regression analysis

[BL, basin length, in miles; AREA, drainage area, in square miles; RELIEF, basin relief, in feet; UR, used relief, in feet; CHAN-L, length of main stream channel, in miles; CHAN-S, average slope of main stream channel, in foot per foot; and CL-TOTAL, total length of stream channels, in miles]

Regression equation	Correlation coefficient (R)	Standard error of estimate (SE)		
		Log units	Average	Percent
$BL = 1.85\ AREA^{0.51}$	0.96	0.091	-18.9	+23.3
$RELIEF = 227\ AREA^{0.28}$	.71	.164	-31.5	+23.3
$RELIEF = 163\ BL^{0.52}$	.72	.163	-31.3	-45.5
$UR = 2.56\ RELIEF^{0.69}$	.73	.144	-28.2	+39.3
$CHAN\text{-}L = 0.92\ BL^{1.16}$	.98	.066	-14.1	+16.4
$CHAN\text{-}S = 0.00036\ BL^{-0.89}UR^{0.90}$	.96	.072	-15.3	+18.0
$CL\text{-}TOTAL = 3.22\ AREA^{0.86}$	.96	.147	-28.7	+40.3

Table 30.--Physical characteristics for example drainage basin

[BL, basin length, in miles; AREA, drainage area, in square miles; RELIEF, basin relief, in feet; UR, used relief, in feet; CHAN-L, length of main stream channel, in miles; CHAN-S, average slope of main stream channel, in foot per foot; and CL-TOTAL, total length of stream channels, in miles]

Basin area = 1.9 mi^2

Characteristics from relations of figures 43 to 45

Average slope of first-order stream channels = 0.022 foot per foot

Average slope of second-order stream channels = 0.016 foot per foot

Average slope of the third-order stream channels = 0.011 foot per foot

Characteristics from regression relations in table 29

Basin length = BL = $1.85\ AREA^{0.51} = 1.85(1.9)^{0.51}$ = 2.6 miles

Basin relief = RELIEF = $227\ AREA^{0.28} = 227(1.9)^{0.28}$ = 270 feet

Used relief = UR = $2.56\ RELIEF^{0.69} = 2.56(270)^{0.69}$ = 120 feet

Length of main stream channel = CHAN-L = $0.92\ BL^{1.16} = 0.92(2.6)^{1.16}$
= 2.8 miles

Average slope of main stream channel = CHAN-S = $0.00036\ BL^{-0.89}UR^{0.90}$
= $0.00036(2.6)^{-0.89}(120)^{0.90}$
= 0.0114 foot per foot

Total length of stream channels = CL-TOTAL = $3.22\ AREA^{0.86}$
= $3.22(1.9)^{0.86}$
= 5.6 miles

Erosional Development

The results of a hypsometric analysis evaluating the stability of natural drainage basins can be used to determine how well re-constructed drainage basins compare with natural drainage basins. Hypsometric analysis provides a quantitative description of the distribution of material within a drainage basin from the base, or low point of the basin, to the top, or high point of the basin (Strahler, 1952, 1964). A hypsometric analysis was made for second- and higher-order drainage basins in the data base of the study sample. The average hypsometric curve for the respective drainage-basin order is shown in figures 46-48. The curves indicate the relative area that exists at various heights within the drainage basin from measurements of the area between successive land-surface contours on a topographic map. The square in which each of the curves are plotted may be visualized as a vertical section through the mass of material that will be removed as the drainage basin evolves (Schumm, 1977, p. 68-69).

The shape of a hypsometric curve provides a representation of the erosional development of a drainage basin in time. During erosion of a drainage basin, the shape of the hypsometric curve will change from convex upward to virtually straight and then to concave upward (Schumm, 1977, p. 70). Such changes indicate that the zone of maximum erosion migrates with time toward the head of the drainage basin. The concave shape of the hypsometric curves for all three drainage-basin orders indicates the basins have reached a state in their geomorphic development where further development will be slow.

A review of the means and standard deviations of the hypsometric sample data indicates that the variability of material distribution decreases with increasing stream order. That is, the standard deviation of the data for fourth-order drainage basins is less than that for third-order drainage basins, and so forth. This is because: (1) The larger drainage basins are older and have had more time to develop than many of the smaller headwater basins, and (2) the larger drainage basins have the magnitude of streamflow and associated energy necessary to attain a base level of equilibrium despite erosion-resistant outcrops and inequalities in surface structure.

Impacts of Surface Coal Mining on Drainage-Basin Stability

As discussed in detail earlier, the method used for determining the cumulative impact of surface coal mining and reclamation on drainage-basin stability involved: (1) Comparison of characteristics for premining and postmining drainage basins, (2) review of the methods used for design of the re-constructed drainage networks and stream channels, and (3) visits of areas that have already been reclaimed.

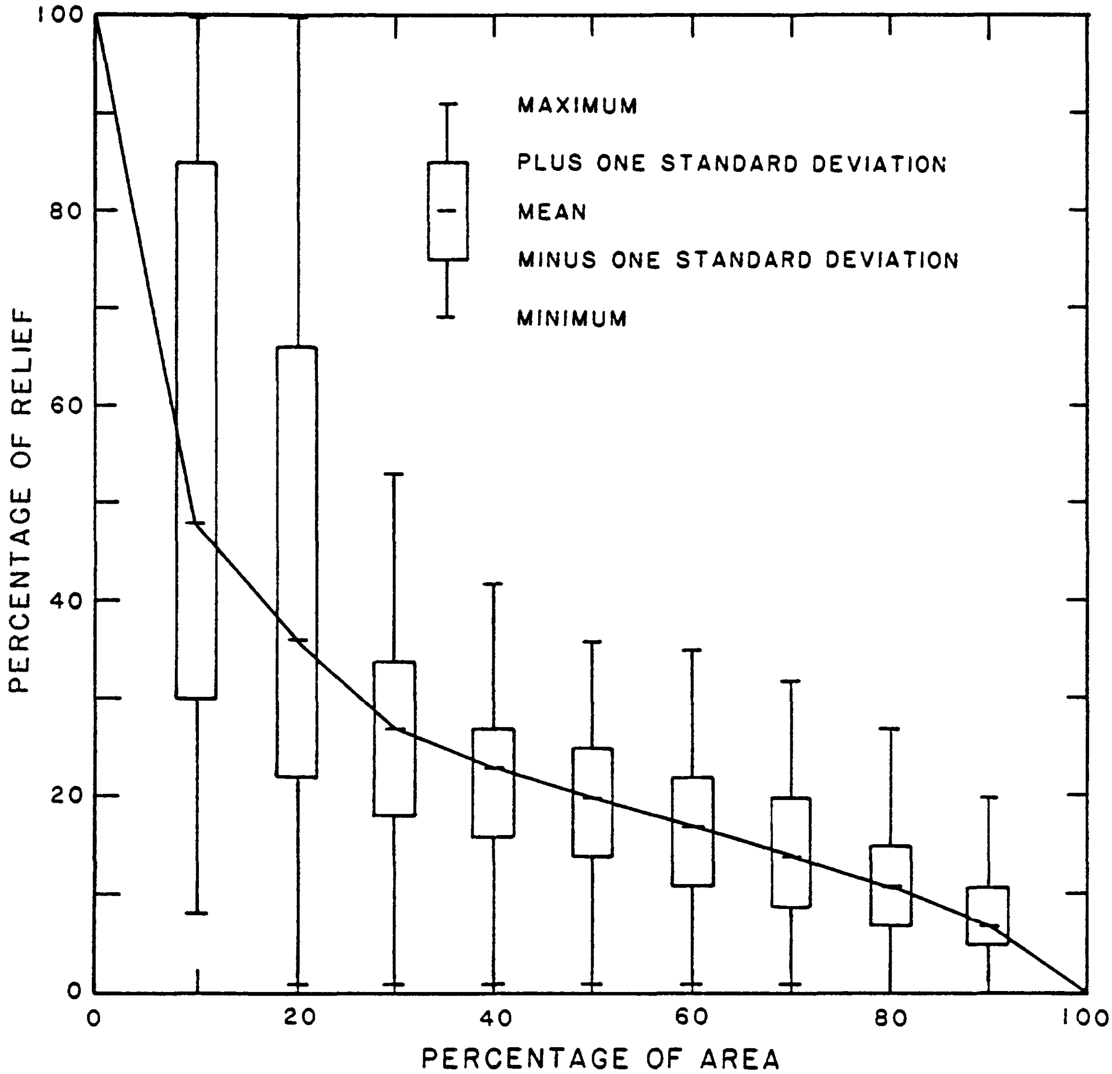


Figure 46.--Average hypsometric curve for second-order drainage basins (represents 22 basins).

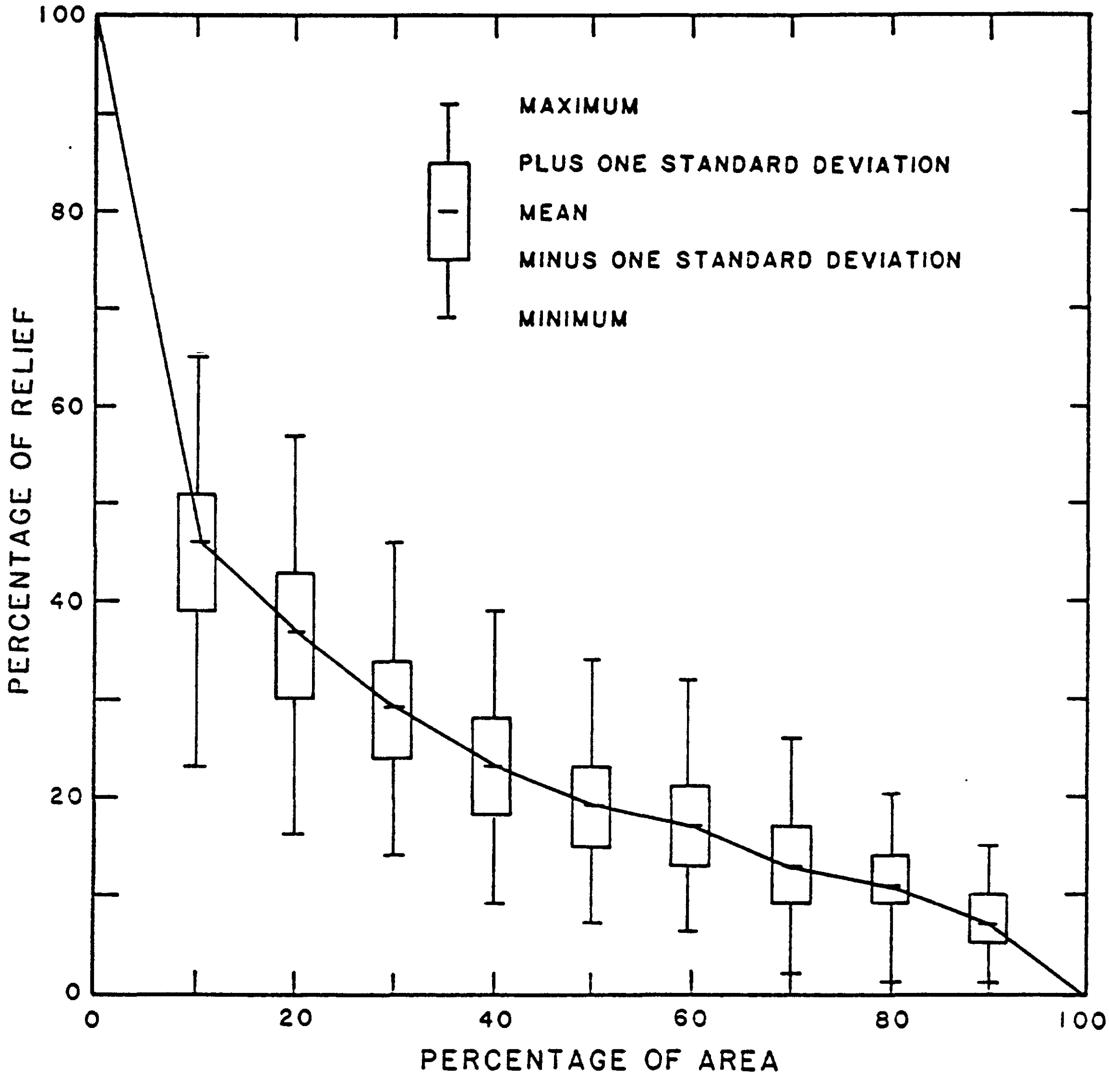


Figure 47.--Average hypsometric curve for third-order drainage basins (represents 24 basins).

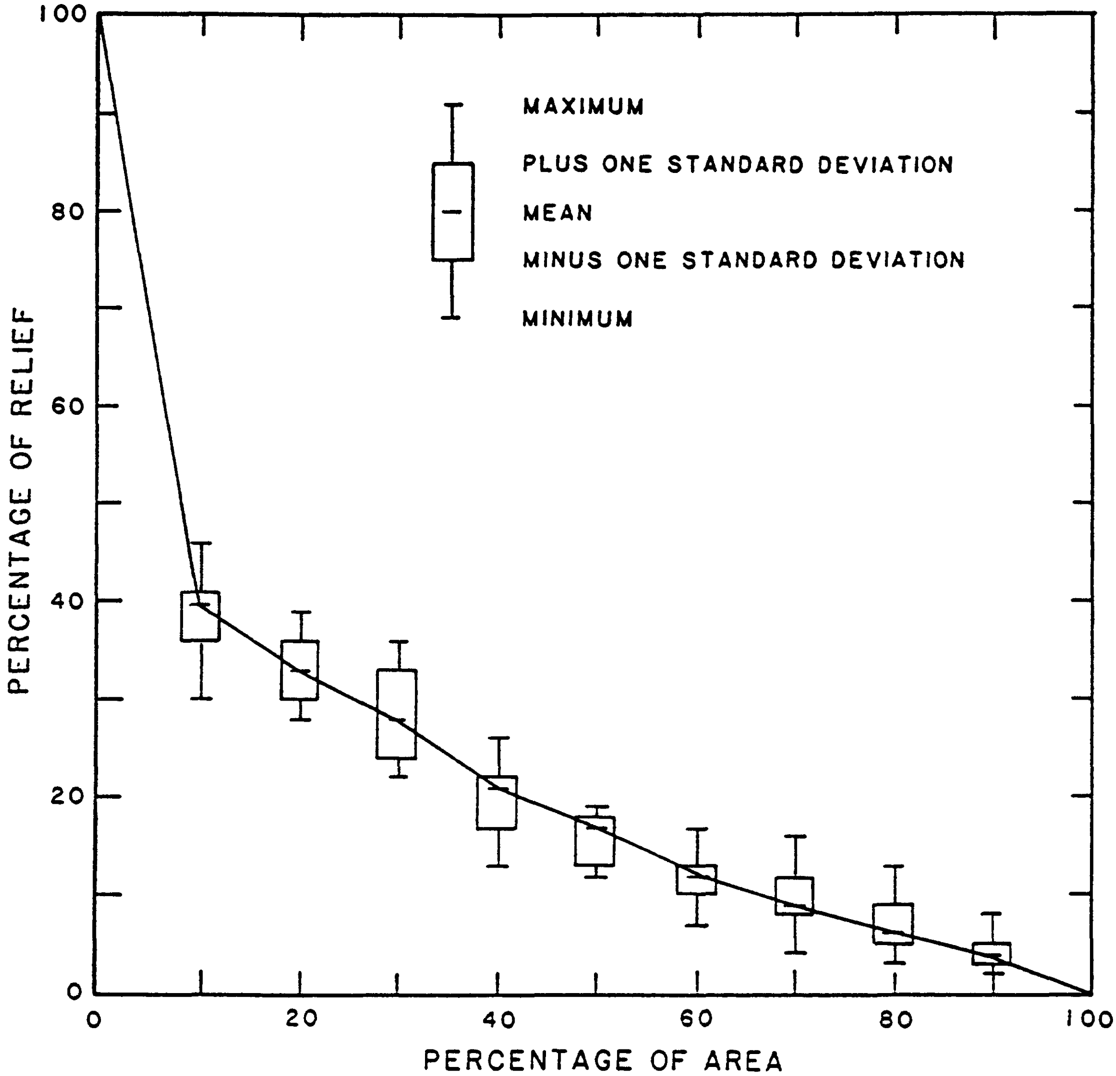


Figure 48.--Average hypsometric curve for fourth-order drainage basins (represents five basins).

Characteristics of Postmining Drainage Basins

The plans for postmining topography and drainage were reviewed for each of the existing mines. A sample of 33 drainage basins planned for re-construction was randomly selected, using at least one drainage basin for each mine. Drainage area, drainage-basin order, channel length, used relief, and stream-channel and valley slopes were determined for each drainage basin from maps of the postmining topography and drainage (table 31). Assuming re-vegetation of interfluve areas is successful, stream-channel slope, valley slope, and drainage density are among the most important characteristics to drainage-basin stability.

Stream-channel slope

The slope of a stream stream channel affects stability. Unstable stream channels resulting from rapid velocities and erosion of streambeds and banks are most likely to occur in reaches with steep gradients. A plot of stream-channel slopes for the sample of postmining drainage basins in comparison to the average relation determined for natural drainage basins is shown in figure 49. The slopes measured for the sample of postmining stream channels are consistent with the range of slopes for the sample of natural drainage basins. Data for only one postmining stream channel plots above the line depicting the maximum slopes measured for the sample of natural stream channels. Slopes for most postmining stream channels plot close to the average relation for the natural drainage basins.

The drainage-basin orders used for plotting the postmining stream-channel slopes in figure 49 were calculated using figure 43, rather than using the actual drainage-basin order shown on the postmining maps. This was done to afford comparability between the 1:24,000-scale topographic maps used for determining the natural characteristics and the topographic maps of 1:4,800 to 1:12,000 scale used for postmining plans.

Valley slope

The sinuosity and slope of a stream channel are affected by valley slope (Schumm, 1977, p. 137-149). In addition to the control imposed by surface geology, variation of valley slope can be caused by changes in rates of colluvium deposition from hillslopes and increases in sediment loads from tributaries. Sinuosity of a re-constructed stream channel could be shown on a postmining plan to dictate appropriate stream-channel distance and slope to achieve nonerosive velocity. However, re-constructed stream channels can be modified by subsequent high flows; valley slope is a more suitable indicator than stream-channel slope of drainage-basin stability.

A comparison of valley slopes for the natural and postmining drainage basins is shown in figure 50. With the exception of one valley with a relatively steep slope, the valley slopes for the sample of postmining drainage basins plot near or below the average relation of valley slope for the sample of natural drainage basins.

Table 31.--Physical characteristics for sample of postmining drainage basins

[--, not determined]

Drainage area (square miles)	Basin order	Basin order computed from figure 42	Total channel length (miles)	Used relief (feet)	Channel length (miles)	Channel slope (foot per foot)	Valley length (miles)	Valley slope (foot per foot)
0.08	1	1	0.41	55	0.41	0.026	0.39	0.027
.09	1	1	.68	41	.68	.016	.62	.018
.11	1	1	.41	75	.41	.035	.40	.036
.11	2	1	1.13	60	.53	.031	.50	.032
.13	1	1	.50	46	.50	.025	.48	.031
.15	1	1	.61	80	.61	.025	.59	.026
.15	1	1	.54	60	.54	.021	.51	.022
.16	1	1	.46	40	.46	.017	.43	.018
.18	1	1	.49	42	.49	.016	.47	.017
.18	1	1	.68	37	.68	.015	.63	.016
.21	1	1	.51	51	.51	.027	.44	.031
.24	1	1	.46	60	.46	.025	.44	.026
.25	2	1	1.53	65	.89	.020	.87	.020
.29	1	1	.72	65	.72	.024	.69	.025
.35	1	1	.72	154	.72	.058	.68	.061
.37	1	1	.73	40	.73	.010	.70	.010
.38	1	1	1.30	95	1.30	.020	1.22	.021
.38	2	1	1.20	77	.83	.026	.80	.027
.40	1	2	.70	34	.70	.013	.69	.013
.42	1	2	.87	31	.87	.010	.79	.010
.46	1	2	.92	70	.92	.021	--	--
.48	1	2	1.62	85	1.62	.014	1.50	.015
.53	1	2	1.41	55	1.41	.011	1.18	.013
.57	1	2	1.40	42	1.40	.008	1.25	.009
.78	1	2	1.85	152	1.85	.022	1.21	.024
.83	3	2	3.98	64	1.47	.012	1.40	.013
.88	--	2	--	85	1.15	.019	1.13	.019
1.08	1	2	1.40	51	1.40	.010	1.36	.010
1.12	3	2	6.54	133	2.58	.014	2.39	.015
2.48	3	3	10.1	170	3.75	.012	3.40	.013
4.39	2	3	4.58	125	3.35	.007	2.59	.009
5.80	2	4	6.50	69	2.91	.006	2.77	.007
18.1	4	4	77.3	220	10.3	.006	8.07	.008

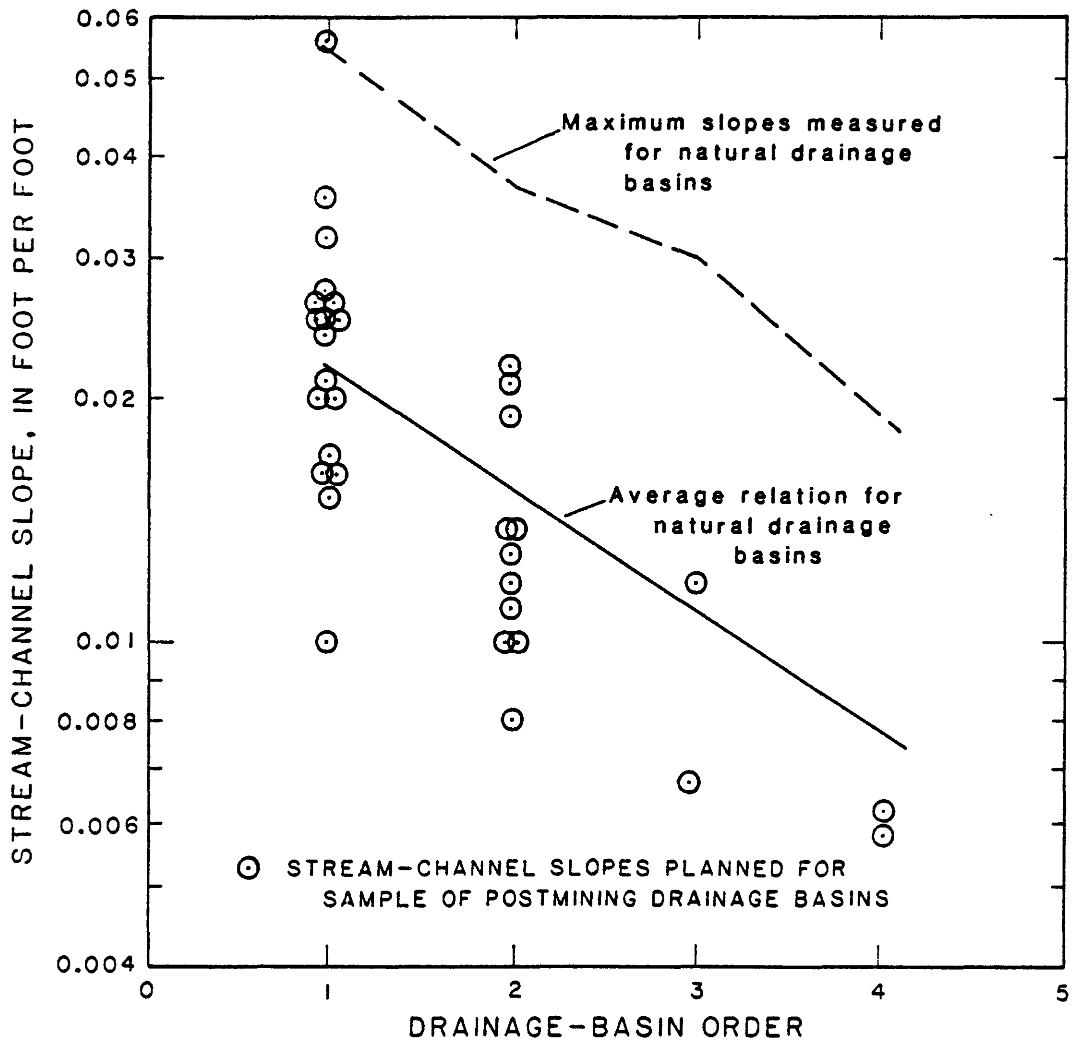


Figure 49.--Comparison of stream-channel slopes for natural and postmining drainage basins.

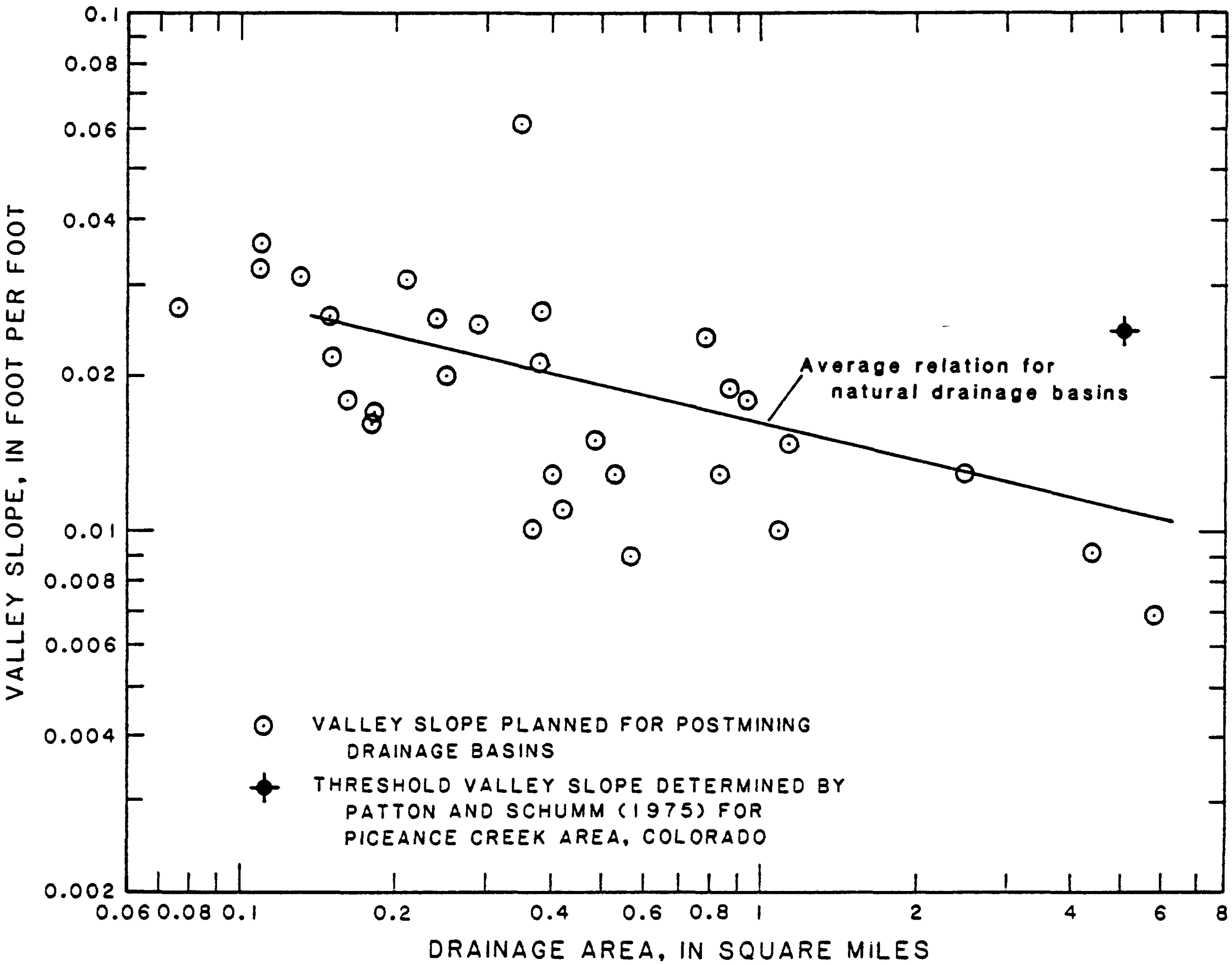


Figure 50.--Comparison of valley slopes for natural and postmining drainage basins.

A threshold value of valley slope, above which instability of the stream occurs, has been examined for arid and semiarid regions by several investigators. For example, studies by Schumm and Hadley (1957) in semiarid valleys of Arizona, Colorado, New Mexico, and Wyoming indicated that discontinuous gullies can be related to slope of the valley. Patton and Schumm (1975) examined measurements of valley slope for drainage basins in the Piceance Creek area of Colorado, and defined a relation of threshold slope with drainage area, above which trenching or valley instability will occur. The relation was considered not to pertain to drainage basins smaller than about 5 mi^2, perhaps because vegetative cover becomes more dominant in small drainage basins and because local differences in vegetation prevent clear recognition of a critical threshold slope. The threshold slope at 5 mi^2 was determined to be about 0.024 ft/ft for the Piceance Creek area. This value is shown on figure 50 as a comparison to the data summarized in this study.

An investigation of areas containing reclaimed surface coal mines in Colorado currently (1987) is being conducted by the U.S. Geological Survey. According to John Elliot (U.S. Geological Survey, written commun., 1987), surveys of 10 first- and second-order drainage basins that were reclaimed 3 years ago indicate that a threshold valley slope does appear to be in effect. However, additional surveys are being conducted, and the threshold relation has not been quantified yet (1987).

In summary, relations for defining specific threshold slopes of stream channels and valleys in the study area are not available; however, the slopes for the sample of postmining drainage basins are similar to those of the natural drainage basins. Assuming the valleys and stream channels are constructed as planned, no substantial impacts either on or offsite are expected in relation to the postmining slopes.

Drainage density

A review of the drainage-basin orders listed in table 31 indicates that for many of the stream channels designated as second order by the relation in figure 43, only a first-order stream channel was shown on the postmining maps. In addition, even though the 1:4,800- to 1:12,000-scale postmining topographic maps are larger and more detailed than the 1:24,000-scale topographic maps used for measuring the natural characteristics, fewer stream channels per unit area are shown for postmining drainage basins than occur for natural drainage basins. In general, the coal-mining companies are designing postmining topography with a lesser drainage density than occurs naturally in the area.

A comprehensive study of the determination of drainage density for surface-mine reclamation in the western United States has been made by Gregory and others (1985). Their study included the measurement of drainage density for 69 natural drainage basins near the Dave Johnston and Jim Bridger Coal Mines in Wyoming, and the McKinley Coal Mine in New Mexico. They note that drainage density is a geomorphic variable that integrates effects of other basin characteristics and they suggest that if the optimum density is restored, the initial adjustment of a reclaimed area should be minimal. Gregory and others (1985, p. 1) conclude "There is a characteristic drainage density for each location, and when this is identified, it should be used in reclamation design." However, they also note that surface coal mining and reclamation will change properties of the natural drainage basin that will affect drainage density, that characteristic drainage densities will require adjustment as a result of such changes, and that additional research is needed in order to refine estimates of drainage density.

Schaefer and others (1979) suggested that postmining drainage density could be estimated using measurements of premining drainage basins and aerial photographs, and then the drainage density could be increased to account for the effects of disruption. Conversely, Stiller and others (1980) note that reclaiming a drainage basin with a greater drainage density than the natural drainage density could create additional impacts such as increased magnitude of flood peaks. They suggest reclaiming with a drainage density at least equal to the premining drainage density.

A well-developed drainage density promotes efficient drainage, resulting in shorter runoff time with correspondingly higher peak flows. Due to the interrelations of various drainage-basin features on drainage density, the design of the optimum density that will result in the most stable landscape is complex. For example, because the dendritic drainage pattern is efficient, it also may be the most erosive. Zimpfer and others (1982, p. 3) describe studies conducted at the Rainfall-Erosion Facility (REF) that was built at Colorado State University to examine the erosional development of drainage patterns and other phenomena of drainage-basin evolution. On the basis of results of studies using the REF, Zimpfer and others (1982, p. 11) concluded that it may not be necessary to re-establish first-order stream channels on a reclaimed surface. They determined that first-order stream channels would eventually form, but that sediment yields from a drainage basin with only the larger-order stream channels would be less than yields from a fully re-constructed drainage basin with first-order stream channels.

As discussed by Chorley and others (1984, p. 257-258), drainage density is interrelated with the angle and length of hillslopes. As shown in figure 51, the greater the drainage density, the more closely streams are spaced and the steeper the hillslopes will be. Steep hillslopes usually contribute a large quantity of sediment to stream channels; stream channels also must be steep to transport the sediment.

Although headcuts and gullys characterize stream channels where erosion is occurring, surface erosion on unrilled slopes yielded 98 percent of the total sediment in a semiarid area of New Mexico (Leopold and others, 1966, p. 239). Likewise, Rankl (1987, p. 15) made detailed measurements of a tributary of Dugout Creek, a semiarid basin in Wyoming with active headcuts. He determined that sediment contribution of the headcuts was a relatively minor part of the total sediment yield from the drainage basin. Because steep hillslopes have overland flows with rapid velocities, which contribute to sediment yield, then re-constructed drainage basins with lesser drainage densities and correspondingly flatter hillslopes may yield smaller sediment yields.

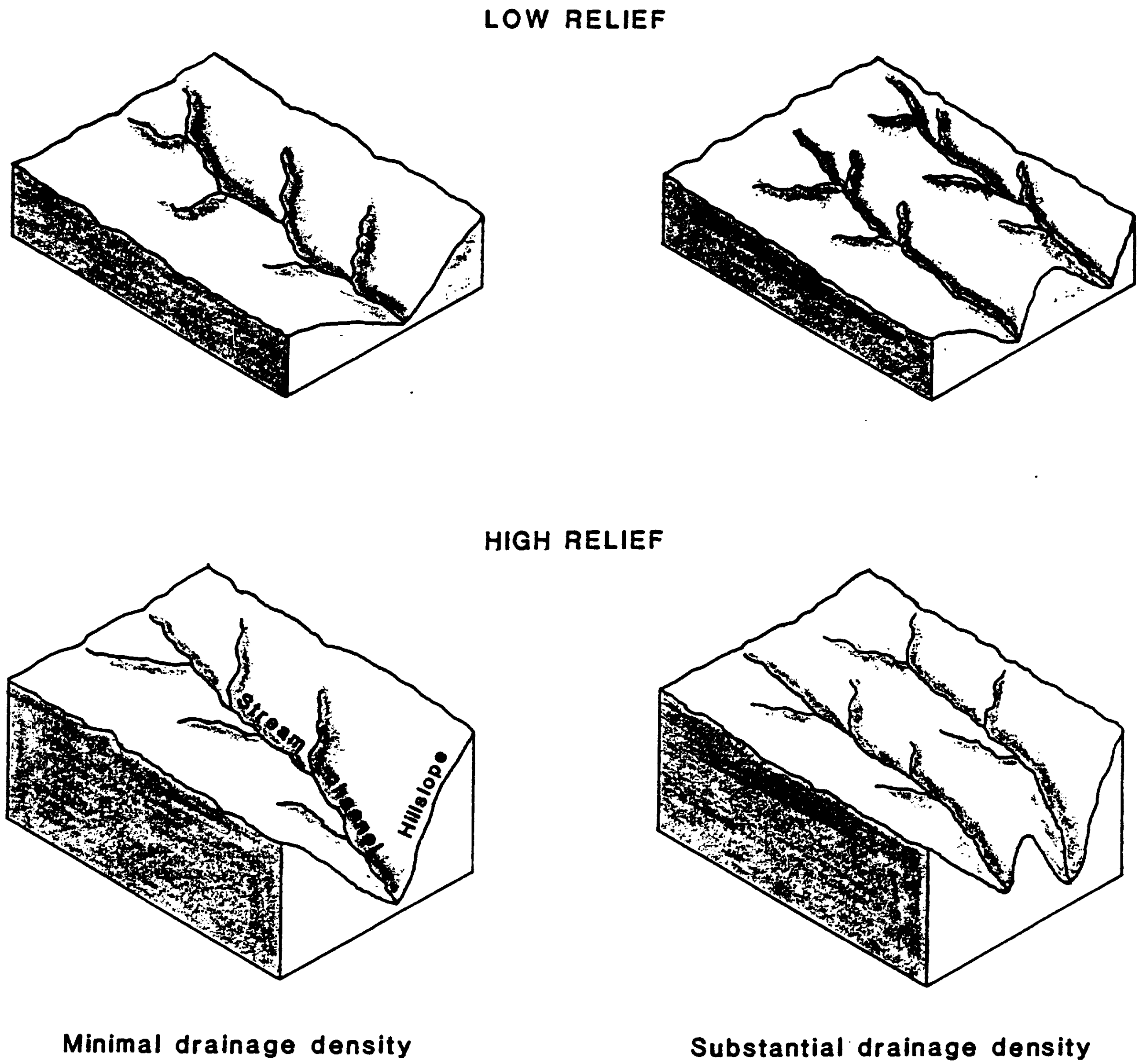


Figure 51.--Effects of drainage density and relief on hillslope inclination and length.

In summary, reclamation procedures using somewhat lesser drainage densities than occur naturally may improve re-vegetation success and decrease sedimentation problems. However, this conclusion is based on limited laboratory data and on onsite studies of natural drainage basins; additional laboratory studies of re-constructed drainage basins and onsite studies of reclaimed drainage basins are needed to verify optimum drainage patterns and densities.

Hypsometric analysis

Mine plans indicate that many of the coal-mining companies analyzed hypsometric curves for the premining drainage basins and also developed curves for the postmining drainage basins. Most of the postmining hypsometric curves have less concavity (indicating an early state of erosional development) than depicted for the sample of natural drainage basins in figures 46-48. Hypsometric curves with lines that are convex upward or straight do not necessarily mean faster rates of erosion and greater sediment load will occur in drainage basins than in basins with hypsometric curves that are concave upward. Parker (1977) reported that drainage density of a basin increases toward the headwater areas as a drainage basin evolves. If drainage basins are reclaimed with only the second- and higher-order stream channels re-constructed, they will be similar to natural drainage basins in an early stage of development, and further stream-channel development is likely to occur. However, this does not necessarily indicate faster rates of erosion in or greater sediment load from the drainage basin will occur.

As was noted earlier, in the discussion of drainage density, stream-channel reaches where erosion and deposition occur are readily visible. Erosion of topsoil, increased sediment loads, and destruction of vegetation will occur locally as first-order stream channels are established and as the drainage network evolves. However, reclamation of drainage basins to simulate an early state of erosional development may improve overall re-vegetation success and result in lesser annual sediment yield from the drainage basin.

Review of Design Methods

Two basic approaches, geomorphic and engineering, exist for the design of drainage networks and steam channels. As discussed by Toy and Hadley (1987), numerous problems are encountered with each approach. The geomorphic approach advocates re-construction of drainage basins to premining conditions; however, few onsite studies document the successful use of geomorphic principles for large mined areas in the arid and semiarid western United States. The engineering approach uses estimates of water and sediment discharges that the drainage network and stream channels must transport; however, these values generally need to be estimated and, consequently, are approximate.

The application of geomorphic relations derived from natural or premining drainage basins to the design of postmining drainage basins is based on the assumption that postmining drainage basins will have runoff, lithology, soil, and vegetative cover similar to premining drainage basins. As described in the section concerning impacts on surface water, infiltration and runoff are expected to return to normal after about 6 years. Reclamation is directed toward the re-establishment of soil and vegetative cover. However, lithology cannot be re-established. Many of the first- and second-order stream channels for natural drainage basins have steep slopes that are supported by outcrops of erosion-resistant rocks. If such outcrops are not present in the postmining drainage basins, then slopes indicated by the geomorphic relations may be steeper than the reclaimed areas of spoil material can actually support. As surface coal mining progresses, documentation of successes and failures in the re-establishment of drainage basins will be necessary to the refinement of design methods.

The engineering approach to design of fluvial systems generally relies on estimates of streamflow and sediment loads; engineering design of stable stream channels also requires estimates of roughness factors. Many estimates are being made in such designs, and it is likely that some stream channels will be misdesigned. Local sedimentation and erosion will occur as misdesigned stream channels adjust to the actual surrounding conditions.

The ideal procedure for reclaiming mined areas is to construct a drainage network that would optimize overall stability and immediately minimize erosion and sediment transport. However, the realities of the state-of-the-art regarding drainage-basin and stream-channel design, as well as construction techniques, make this impossible. For example, even if the perfect drainage-basin and stream-channel design were implemented, unpredictable differential settling of the spoil material is likely to occur that would affect the hydrologic function of the drainage basin.

The design for at least one reclaimed area (Wyodak Mine) contains plans for a large depression to be left as a permanent feature, with a major stream routed around the depression. The bank and terrace between the stream and depression are to be stabilized against erosion, and the stream-channel capacity is designed to convey maximum expected floodflows. During a long period, this stream or others might possibly meander and intercept the depression. This would cause some erosion and sedimentation as the stream channel adjusted to the steep slope entering the depression; however, the depression would eventually fill with water and sediment. An occurrence such as this could have substantial local impact on the stream channel as it would result in a change in downstream hydrologic conditions, including: (1) Loss of water available to downstream water users, (2) degraded water quality due to less flow available for dilution of dissolved solids, and (3) possible lowered ground-water levels near the stream channel due to less water available for recharge. For such problems in reclamation, provisions for a long-term maintenance program may be needed.

Re-Constructed Drainage Basins

In June 1987, H.W. Lowham visited several mines that have been operating since the 1970's. Reclaimed areas were toured, and re-construction methods were discussed with company representatives for the Eagle Butte, Belle Ayr, Black Thunder, Cordero, and Antelope Mines. The following observations were noted:

1. Stream channels of third and higher order have been given a great deal of attention in design, because it is realized that flow in these stream channels can be large and such flow can occur frequently enough to be of immediate concern. A combination of engineering- and geomorphic-design methods generally has been used in the re-construction of these streams.

2. When stabilizing temporary storage piles or finishing off the highwall at the mined-area boundary, the general practice is to construct steep-sloped areas to maximize runoff as sheet flow and to avoid forming stream channels until absolutely necessary. Much effort is given to achieving re-vegetation with dense stands of grasses and shrubs in order to retard runoff and erosion.

3. The areas reclaimed to date (1987) generally appear to be stable. However, it is difficult to assess long-term stability from observations of the existing reclaimed areas because erosion damage, such as rilling and gullying, generally is immediately repaired.

4. Company representatives are concerned about the procedures that will be used for reclamation of the end-of-mine highwalls. Small drainage basins located just outside the highwall perimeter, but draining into the mined area, have potential to cause some of the greatest problems. For example, two small drainage basins that need to be re-constructed are shown in figure 52. If the stream channels are constructed without artificial structures or other innovative features, such as construction of storage and recharge areas to capture flow from the small drainage basins, then a great quantity of material will have to be moved to achieve stable stream-channel slopes in the vicinity of the highwall. Because thick coal beds are being removed, at most surface coal mines there will be an insufficient volume of overburden to accomplish the re-construction, and material may have to be borrowed from unmined areas. In addition to being extremely expensive, the disturbance of an unmined area for the purposes of borrowing soil material may be environmentally questionable.

In summary, the reclaimed areas appear to be stable, but they have been in existence for only a short time relative to the semiarid climate and infrequent nature of runoff in the study area. Rills that might develop on reclaimed areas are immediately repaired. Therefore, information obtained from the inspection was inconclusive in determining long-term stability of the reclaimed basins.

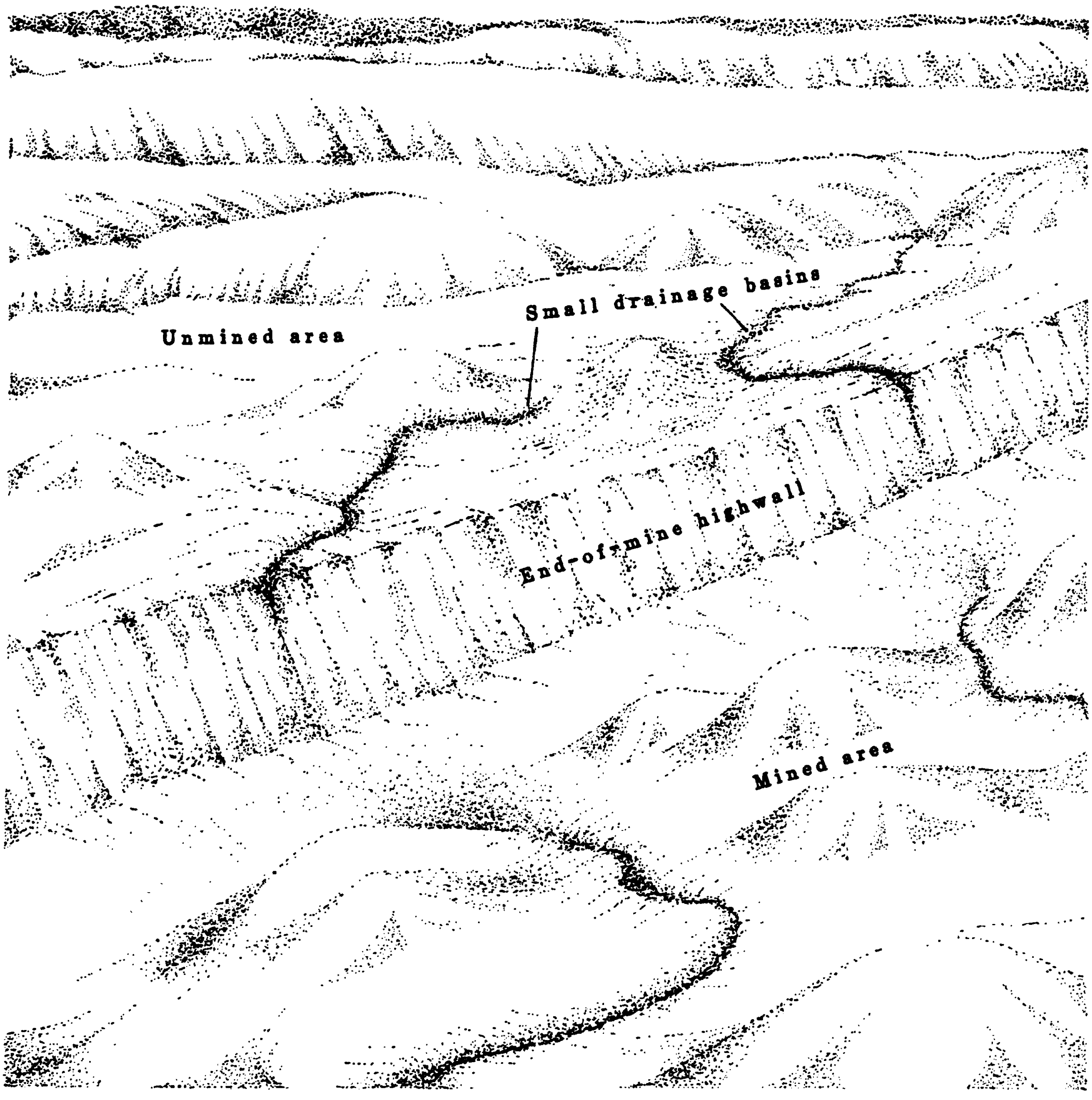


Figure 52.--End-of-mine reclamation problem resulting from shortage of material to re-construct small drainage basins.

NEEDS FOR ADDITIONAL STUDY

Ground Water

Evaluation of recent ground-water-level data indicates that the predictions of water-level declines likely have overestimated the magnitude and areal extent of water-level declines in the Wyodak coal aquifer. In addition, some backfilled spoils are being re-saturated more rapidly than was predicted by the models. If these conditions are accurate indicators of future trends, the effects of surface coal mining on water levels and ground-water use would be greatly decreased. Coal-mining companies will contribute toward more realistic predictions of water-level declines as ground-water models are recalibrated using the results of continued monitoring of water levels in the Wyodak coal aquifer. A more realistic assessment of the duration of water-level declines is needed to determine whether additional mining in the eastern Powder River basin would affect future water availability.

Monitoring wells need to be established in the Wyodak coal aquifer downgradient from the mining operations to document long-term water-level changes. These wells need to be located sufficiently distant from active mining operations to detect the maximum cumulative extent of water-level declines resulting from mining. There are several monitoring wells located on land owned by the State (school sections) that would suit this purpose. The wells, drilled in 1976 and 1977, are completed in the Wyodak coal aquifer and are located in sections 16 and 36 of several townships extending from north of Gillette to northwest of the North Antelope Mine. Water levels in these wells have not been monitored since 1985.

The recharge rate and source of recharge water for the spoil aquifers need to be investigated. Determination of the recharge rate is needed to evaluate the duration of impacts on the ground-water system. The source of recharge water is important in determining appropriate placement of acid-forming material in the spoil.

Geochemistry

Additional study is needed to determine overburden suitability for aquifer restoration, water-quality changes associated with selective placement of overburden material, and long-term changes in postmining water quality. On the basis of column-leaching data presented, additional information is needed about the geochemistry of selected chemical constituents in the overburden to adequately predict concentrations of these constituents in the postmining ground water. For example, overburden with extractable-selenium concentrations less than the detection limit has produced water from column-leaching tests with selenium concentrations exceeding the State standard for livestock.

Without additional information on the source or sources of recharge to the spoil aquifers, appropriate disposal of toxic and acid-forming spoil material cannot be guaranteed. For example, if a substantial part of recharge to the spoil aquifer is from infiltration of precipitation and leakage from ephemeral streams, perhaps acid-forming material would be better placed at depths below the postmining water table, where seasonal wet-dry cycles would not continue to oxidize the acid-forming material.

At some time in the future, the postmining potentiometric surface in the spoil aquifer will begin re-equilibrate such that water from the spoil aquifer will begin to move offsite into the adjacent Wasatch aquifer and Wyodak coal aquifer. Although changes in offsite postmining water quality resulting from this offsite ground-water movement have been simulated and examined during this study, additional information is needed. Additional study is needed to determine the sulfate-reducing potential of aquifers and to determine site-specific, water-quality changes that occur as water from the spoil aquifer moves offsite into the Wasatch aquifer and Wyodak coal aquifer.

Surface Water

Infiltration values need to be more accurately defined. The study would involve collecting rainfall and runoff data on small, paired basins (less than 3 mi^2) consisting of natural basins and reclaimed basins. The data collected would be used to simulate the infiltration rates, which in turn can be used to predict long-term cumulative impacts for larger basins. Continuous sediment-concentration data need to be collected in conjunction with the rainfall and runoff data for additional evaluation of the erosion and sedimentation process in relation to reclaimed soil materials.

The analysis of cumulative impacts on surface-water flow is based on the analysis of available infiltrometer data from rainfall-simulation tests and on the assumption that the change in infiltration will result in an inverse change in runoff. A network of streamflow-gaging stations needs to be re-established on streams draining the mine areas in order to verify the relation between infiltration and runoff. These gaging stations need to be established downstream from the mine areas where large areas have been disturbed by surface mining and need to be operated for the duration of mining, but they do not need to include large undisturbed areas or areas disturbed by other activities. The network of gaging stations operated by coal-mining companies and methods of record collection need to be evaluated so that: (1) A coordinated and efficient effort of data collection is maintained, (2) data are collected with proper quality assurance and control, (3) a centralized computer file is developed and maintained to facilitate retrievals and statistical summaries, and (4) future cumulative-impact evaluations will have data suitable to analyze hydrologic properties such as peak-flow yields, average runoff, and surface-water/ground-water relations.

Stream channels in the major drainage basins in the study area need to be monumented and documented to study erosion and sedimentation in mine areas. The information can be used for future reference in understanding the erosion and sedimentation processes in a semiarid climate with large areas disturbed by mining.

Stability of Reclaimed Drainage Basins

Reclamation of large land areas in the arid and semiarid West has only been done for a few years; much needs to be learned concerning long-term processes affecting re-constructed drainage basins. Although much literature exists regarding fluvial processes in natural drainage basins, there is a paucity of literature reporting case histories of fluvial processes in reclaimed basins. There is a need to establish a network of reclaimed basins similar to the Vigil Network (Leopold, 1962) that exists for natural basins. Instrumentation for the network needs to include streamflow-gaging stations and monumented stream channel cross sections as discussed earlier; it also needs to include precipitation gages and erosion grids for hillslopes.

Due to the nature of the semiarid climate and resulting infrequent runoff in the study area, it may take as much as 10 years of data collection before results are achieved from the network described above. In the meantime, additional onsite and laboratory studies are needed whereby actual data are accurately and systematically collected to define geomorphic thresholds, such as basin and channel slopes, and to define optimum drainage patterns and densities for re-constructed basins.

CONCLUSIONS

1. Mining and reclamation will result in the replacement of the Wasatch aquifer and Wyodak coal aquifer with unconsolidated backfilled spoil materials. The resulting spoil aquifer is estimated to have approximately the same hydraulic conductivity as did the Wasatch aquifer and Wyodak coal aquifer.

   On the basis of data currently (1987) available, it appears that postmining recharge, movement, and discharge of water in the Wasatch aquifer and Wyodak coal aquifer will not be substantially different from premining conditions. Recharge rates and mechanisms will not change substantially. Because hydraulic conductivity of the spoil aquifer will be approximately the same as in the Wasatch aquifer and the Wyodak coal aquifer, water will move from recharge areas where clinker is present east of mine areas through the spoil aquifer to the undisturbed Wasatch aquifer and the Wyodak coal aquifer to the west.

   Coal-mining companies predict water-level declines of 5 ft or more in the Wasatch aquifer to extend from about 1,000 to about 2,000 ft beyond the mine pits. The predicted 5-ft water-level decline in the Wyodak coal aquifer generally extends 4 to 8 mi westward beyond the lease areas.

   Cumulative water-level declines are not expected to be substantial in the Wasatch aquifer because water-level declines due to individual coal-mining operations generally will not extend more than 2,000 ft beyond the mine pits. The extent of water-level declines in the Wasatch aquifer will be restricted because the ground-water system consists of discontinuous sandstone lenses that have limited hydraulic connection. Therefore, there will be few areas where water-level declines from individual mines will overlap to create cumulative impacts. In areas where a cumulative impact may occur, the impacts will be localized because of the discontinuous, lenticular nature of the sandstone lenses comprising the Wasatch aquifer.

Water-level declines in the Wyodak coal aquifer are predicted to extend beyond the area affected by individual coal mines because of the cumulative effect of adjacent coal-mining operations. The extent of cumulative water-level declines generally was determined by superposition of predicted water-level declines for individual coal mines. The area of cumulative impacts for existing and proposed coal-lease areas was determined by compositing information from mine-permit applications for the entire study area. Within the area of cumulative water-level declines that result from existing and proposed surface coal mining, water-level declines are predicted to range from 5 to 80 ft, depending on the proximity to coal-mining operations. Differences in transmissivity resulting from the variable degree and density of fracturing, variable thickness, and division of coal beds may affect the predicted declines locally.

In order to determine which water-supply wells may be affected by water-level declines resulting from all anticipated coal mining, the area of the potential cumulative 5-ft or more water-level decline in the Wyodak coal aquifer resulting from all anticipated coal mining was approximated. The area of potential cumulative water-level declines from all anticipated coal mining is defined, in this report, as extending from the outcrop of the Wyodak coal bed to about 8 mi from areas of all anticipated mining.

About 3,000 wells are in the area of potential cumulative water-level declines resulting from all anticipated coal mining. Of these 3,000 wells, about 1,200 are outside the areas of anticipated coal mining: about 1,000 wells supply water for domestic or livestock uses; and about 200 wells supply water for municipal, industrial, irrigation, and miscellaneous uses. The approximately 1,800 remaining wells are used by coal-mining companies.

In order to determine the effects of water-level declines on the 1,200 water-supply wells outside the areas of all anticipated coal mining, the aquifer in which the well is completed had to be determined. According to well logs and completion reports for these wells, about 580 wells are completed in the Wasatch aquifer, about 100 in the Wyodak coal aquifer, and about 280 in aquifers below the Wyodak coal bed. Stratigraphic location of the completion interval could not be determined for about 260 wells because of lack of information on the well-completion report.

The effect of water-level declines on wells outside coal-mining areas will depend on the magnitude of decline that occurs in the individual wells, which in turn is related to the proximity of a well to coal-mining operations. Other factors important in determining the effect on individual wells include the depth of the well, the depth and number of perforated intervals, depth to water, and the yield required from the well to maintain it as a useable source of water. If the water level in any of the wells is lowered such that production is seriously decreased, the well can be deepened or replaced with a well completed in the underlying aquifers.

The most important factor in determining if the water level in a well will be affected by coal-mining operations is the stratigraphic location of the perforated interval of the well and, consequently, the aquifer in which the well is completed. In the approximately 580 wells completed in the Wasatch aquifer in the area of anticipated water-level declines, water levels will decline only if the wells are about 2,000 ft or less from a coal-mine pit.

However, wells completed in the Wyodak coal aquifer may be affected as far away as 8 mi from coal-mine pits. Water-level declines in those wells are predicted to range from less than 5 ft in wells far away from coal-mining operations to more than 80 ft in wells near coal-mining operations. Wells completed in the underlying aquifers will not be affected by dewatering of the coal-mine pits; however, the yields of wells located near wells supplying facilities at the coal mines may be affected by water-level declines near the pumped wells.

2. Alternative sources of water supplies for wells markedly impacted by coal-mining operations are the Tongue River-Lebo aquifer (Paleocene Fort Union Formation) for domestic and livestock supplies, and the Tullock (Paleocene Fort Union Formation) aquifer or Lance-Fox Hills (Upper Cretaceous) aquifer for uses requiring a larger yield. Water quality in aquifers in the Fort Union Formation is variable and appears to correlate with the permeability of the water-yielding sandstone and proximity to the recharge area. Dissolved-solids concentrations range from about 200 to more than 3,000 mg/L but commonly range between 500 and 1,500 mg/L.

   In order to provide a brief overview of the water quality from aquifers in Upper Cretaceous formations, the concentration ranges of dissolved solids, fluoride, and selenium in water from these aquifers were summarized. Because of a lack of water-quality data for the Lance-Fox Hills aquifer in the study area, water-quality data from wells completed in aquifers in Upper Cretaceous formations in the entire Powder River structural basin were assumed to approximate the water quality in the Lance-Fox Hills aquifer. Dissolved-solids concentrations in 130 ground-water samples ranged from 240 to 2,800 mg/L. Dissolved-fluoride concentrations in 124 ground-water samples ranged from less than 0.1 to 6.0 mg/L.

   Dissolved-selenium concentrations in 70 ground-water samples ranged from less than 0.001 to 0.1 mg/L. Although the quality of water from these alternative sources does not always meet the State standard for domestic supplies, it is approximately the same as the quality of water currently (1987) being used for such supplies.

3. On the basis of the compiled premining (Wasatch aquifer and Wyodak coal aquifer) and postmining (spoil aquifers) water-quality data, current (1986) and future postmining water quality generally will meet the State standard for livestock. The primary chemical constituents that exceed the State standard for livestock in selected wells include dissolved solids, sulfate, nitrate, chromium, and selenium. Except for the consistent decrease in nitrate and selenium concentrations with time, data for the other constituents of concern (dissolved solids, sulfate, and chromium) do not indicate consistent decreases in concentration with time. Future surface coal mining in the study area is expected to produce postmining ground water of similar quality to that currently (1987) present. Because only 10 of the 16 active coal mines in the study area currently (1987) have saturated spoil, additional mining at these 16 active and 6 proposed mines will expand the areal extent of the most recent (through 1986) detected effects of surface coal mining on water quality.

   On the basis of analysis-of-variance results, current and future ground-water-quality-monitoring needs for spoil aquifers are listed. Future sampling efforts need to focus on collecting a few samples from numerous wells completed in spoil aquifers rather than collecting a large number of samples from only a few wells. For maximum sampling effectiveness and usefulness of existing and future monitoring data, different sampling densities need to be investigated for different chemical constituents depending on the distribution of variance for each constituent.

4. Batch-mixing experiments that use water and spoil material from the Cordero Mine in a water-to-spoil material ratio of 2:1 (by weight), resulted in smaller major-ion concentrations compared to the water quality in the spoil aquifer at the mine. Column-leaching-test results compiled from three mines in the study area were variable depending on the type of water used in the columns (deionized as opposed to actual ground water) and the chemical composition of the overburden materials. The median dissolved-solids and nitrate concentrations based on all postmining water analyses in the study area generally were exceeded until at least 1 pore volume of water leached through the columns. Decreases in the concentrations of dissolved solids, nitrate, and selenium in future postmining water are predicted by the column-leaching-test results. Water samples from selected wells in the study area indicate that actual postmining nitrate and selenium concentrations are currently (1987) decreasing.

5. Geochemical data collected at the Cordero and Dave Johnston Mines were used to predict future ground-water-quality changes and to identify reclamation methods that could minimize future postmining water-quality degradation. Because of differences in the method of mining and hydrologic and geochemical conditions present at the Cordero and Dave Johnston Mines, these predictions may not apply to all the mines within the study area. On the basis of the geochemical conditions in the postmining spoil aquifer at the Cordero Mine, it is unlikely that the dissolved-solids concentrations will

increase further. Substantial decreases in dissolved-solids concentration in postmining water in the spoil aquifer at the Cordero Mine should not occur until at least 1 pore volume of water has leached the spoil. Leaching of 1 pore volume through the spoil could take from tens to hundreds of years. Isolation of overburden material with large soluble-salt contents to areas above the postmining ground-water table in conjunction with decreasing the rates of infiltration of precipitation and runoff in the spoil aquifer could minimize increases in dissolved-solids concentrations in future reclaimed areas. Furthermore, isolation of spoil material with large soluble-salt contents from clay-rich and organic-rich strata during backfilling also could minimize increases in dissolved-solids concentrations in postmining ground water.

Movement of postmining ground water from the spoil aquifer into the adjacent School coal aquifer at the Dave Johnston Mine indicated substantial mixing resulting in a net increase in the dissolved-solids concentration in water from the School coal aquifer. This increase in dissolved-solids concentration in water within the School coal aquifer probably will be temporary. As the soluble salts continue to leach from the spoil material, future postmining water that enters the coal aquifer will decrease in dissolved-solids concentration until a postmining equilibrium condition is attained. On the basis of small tritium concentrations in the School coal aquifer downgradient from the coal outcrop at the Dave Johnston Mine, movement of postmining water within the School coal aquifer will be slow, possibly minimizing the extent of water-quality degradation to offsite areas.

6. Results of geochemical modeling of hypothetical reaction paths indicated the potential for marked improvements in postmining water quality as a postmining ground water with a large dissolved-solids concentration (3,540 mg/L) moves into a coal aquifer containing water with a relatively small dissolved-solids concentration (910 mg/L). Results of the geochemical modeling indicate geochemical conditions that are most ideal for large decreases in dissolved-solids concentrations in coal aquifers receiving recharge from a spoil aquifer. These conditions include: (1) The presence of sulfate-reducing bacteria populations, (2) organic-carbon sources that can be utilized by the sulfate-reducing bacteria, and (3) a source of iron within the coal aquifer that will facilitate the removal, by mineral precipitation, of the sulfide produced by sulfate reduction. On the basis of indirect geochemical evidence, sulfate-reducing bacteria and organic-carbon sources probably are present in at least a few spoil aquifers within the study area.

7. Simulated-rainfall studies indicated that reclaimed soils have, on the average, a 29-percent slower infiltration rate than do undisturbed soils. Statistical analysis of the infiltrometer data indicates that the decrease in infiltration rates is not significant for individual studies, but average values of all the studies would be useful for evaluating cumulative hydrologic impacts. In addition, the data indicated a trend for the infiltration rates to increase to premining rates. For the purpose of computing the

effective change in infiltration, it was assumed that runoff had an inverse corresponding value. The projected maximum areas to be disturbed during surface coal mining were computed for the major basins draining the study area. A computation of increase in runoff indicated that the increase in runoff at the mouth of the basins will be less than 5 percent. The disturbed areas for all anticipated coal mining (projected maximum disturbed areas of existing and proposed coal mines, and Selected Coal Tracts and areas with Preference Right Lease Applications) were compiled for all the major drainage basins. The computation of runoff using disturbed areas for all anticipated coal mining is a worst-case condition and indicated a maximum increase in runoff of 7.6 percent for Coal Creek and 5.3 percent for Little Thunder Creek. The remainder of the drainage basins analyzed for the worst-case condition would have increases in runoff of less than 5 percent.

A graphical analysis of storm runoff from the Coal Creek drainage basin indicated an insignificant change on the recession of the flow hydrograph. Coal Creek has the largest percentage of projected maximum disturbed area of all basins studied; therefore, the change in flow due to surface coal mining will be less for the remaining basins.

8. Analysis of changes in sediment yield are limited due to a lack of data; therefore, predictions of cumulative changes in sediment yield are subjective. Sediment yield from reclaimed-soil plots was 436 percent greater than sediment yield from natural-soil plots. The reclaimed-soil plots had less vegetation cover and slightly steeper slopes than the natural-soil plots. The larger sediment yield from reclaimed soils are not expected to be conveyed to the mouth of the basins due to sediment deposition as a result of slope decrease from hillsides to stream channels, and sediment deposition in settling ponds. The larger sediment yield indicated by the reclaimed-soil plots will have a minor impact on the major drainages because: (1) Sediment yield decreases as drainage area increases and, (2) the dilution effect caused by the small percentage of disturbed area in relation to total drainage area. Soil erodibility and steep land slopes, such as those in the Coal Creek drainage basin, account for sediment yields that are 8 times greater than those in the upland areas of the Belle Fourche River basin. The variability in natural sediment yields mask any increases in sediment yield resulting from surface coal mining.

9. The design and re-construction of stable drainage basins is critical to successful land use after reclamation. In addition, stable drainage networks and stream channels are needed to avoid adverse impacts in offsite streams due to increases in erosion and sedimentation. Postmining drainage networks and stream channels have been and are being designed with attention to existing geomorphic conditions and accepted engineering principles. In general, stream-channel and valley slopes are consistent with natural conditions for the area; however, re-constructed drainage basins have lesser drainage densities than exist for natural drainage basins. Although additional first-order stream channels

likely will form in the reclaimed drainage basins, the practice of re-constructing only higher-order major stream channels is believed to have advantages of: (1) Smaller hillside slopes with resulting greater re-vegetation success, and (2) providing smaller sediment yields than if drainage networks were fully re-constructed to premining densities.

On the basis of the limited data and literature available for the study area and similar semiarid regions, no adverse cumulative impacts are expected due to instability of postmining drainage networks and stream channels. Some visible changes likely will occur on a local scale as the postmining drainage networks adjust to a new state of dynamic equilibrium. A maintenance program would be warranted for occasional severe adjustments and failures.

SELECTED REFERENCES

Armentrout, G.W., and Wilson, J.F., Jr., 1987, An assessment of low flows in streams in northeastern Wyoming: U.S. Geological Survey Water-Resources Investigations Report 85-4246, 21 p.

Bergstrom, F.W., 1985, Determination of longitudinal profile for stream channel reclamation, in Second Hydrology Symposium on Surface Coal Mines in the Northern Great Plains, Gillette, Wyoming, Proceedings: Gillette Area Groundwater Monitoring Organization, Colorado Ground-Water Association, and Wyoming Water Research Center, p. 29-60.

Bishop, M.B., 1980, Geomorphic concepts and their application to ephemeral stream channel reclamation, in Second Wyoming Mining Hydrology Symposium, Laramie, Wyoming, Proceedings: University of Wyoming, p. 249-261.

Bloyd, R.M., Daddow, P.B., Jordan, P.R., and Lowham, H.W., 1986, Investigation of possible effects of surface coal mining on hydrology and landscape stability in part of the Powder River structural basin, northeastern Wyoming: U.S. Geological Survey Water-Resources Investigations Report 86-4329, 101 p.

Breckenridge, R.M., Glass, G.B., Root, F.K., and Wendell, W.G., 1974, Campbell County Wyoming; Geologic Map Atlas and Summary of Land, Water and Mineral Resources: Laramie, Wyo., The Geological Survey of Wyoming County Resource Series No. 3, 9 sheets.

Chatham, J.R., Wanty, R.B., and Langmuir, Donald, 1981, Groundwater prospecting for sandstone-type uranium deposits--The merits of mineral-solution equilibria versus single element tracer methods: U.S. Department of Energy National Uranium Resource Evaluation Report GJO 79-360-E, 197 p.

Chorley, R.J., Schumm, S.A., and Sugden, D.E., 1984, Geomorphology: New York, Methuen and Co., 607 p.

Craig, G.S., Jr., and Rankl, J.G., 1978, Analysis of runoff from small drainage basins in Wyoming: U.S. Geological Survey Water-Supply Paper 2056, 70 p.

Daddow, P.B., 1986, Potentiometric-surface map of the Wyodak-Anderson coal bed, Powder River structural basin, Wyoming, 1973-84: U.S. Geological Survey Water-Resources Investigations Report 85-4305, scale 1:250,000.

Davis, R.E., 1984, Geochemistry and geohydrology of the West Decker and Big Sky coal-mining areas, southeastern Montana: U.S. Geological Survey Water-Resources Investigations Report 83-4225, 109 p.

Davis, R.E., and Dodge, K.A., 1986, Results of experiments related to contact of mine-spoils water with coal, West Decker and Big Sky Mines, southeastern Montana: U.S. Geological Survey Water-Resources Investigations Report 86-4002, 16 p.

Dean, W.E., Ringrose, C.D., and Klusman, R.W., 1979, Geochemical variation in soils in the Piceance Creek Basin, western Colorado: U.S. Geological Survey Bulletin 1479, 47 p.

Denson, N.M., Dover, J.H., and Osmonson, L.M., 1978, Lower Tertiary coal bed distribution and coal resources of the Reno Junction-Antelope Creek Area, in Campbell, Converse, Niobrara, and Weston Counties, Wyoming: U.S. Geological Survey Miscellaneous Field Studies Map MF-960, scale 1:250,000.

Divis, S.A., and Tarquin, P.A., 1981, The geohydrologic regime of the Powder River Basin: Wheat Ridge, Colo., Environmental Science Associates, January 1981 (revised), 109 p.

Drever, J.I., 1982, The geochemistry of natural waters: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 388 p.

Druse, S.A., Dodge, K.A., and Hotchkiss, W.R., 1981, Base flow and chemical quality of streams in the Northern Great Plains area, Montana and Wyoming: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-692, 60 p.

Druse S.A., Glass, W.R., McCollam, P.B., and Kennedy, H.I., 1987, Water resources data Wyoming, water year 1986: U.S. Geological Survey Water-Data Report WY-86-1, 474 p.

Dunne, Thomas, and Leopold, L.B., 1978, Water in environmental planning: San Francisco, W.H. Freeman and Co., 818 p.

Ebens, R.J., and Shacklette, H.T., 1982, Geochemistry of some rocks, mine spoils, stream sediments, soils, plants, and waters in the western energy region of the conterminous United States: U.S. Geological Survey Professional Paper 1237, 173 p.

Emmett, W.W., 1974, Channel aggradation in western United States as indicated by observations at Vigil Network sites: Zeitschrift Für Geomorphologic Suppl., v. 21, December 1974, p. 52-62.

Everett, L.G., ed., 1979, Ground-water quality monitoring of western coal strip mining: U.S. Environmental Protection Agency report, 239 p.

Feathers, K.R., Libra, Robert, and Stephenson, T.R., 1981, Occurrence and characteristics of ground water in the Powder River Basin, Wyoming: Laramie, University of Wyoming, Water Resources Research Institute Report, 171 p.

Fogg, J.L., Martin, M.W., Daddow, P.B., in press, Geohydrology and potential effects of coal mining in 12 coal-lease areas, Powder River structural basin, northeastern Wyoming: U.S. Geological Survey Water-Resources Investigations Report 87-4102.

Garrett, R.G., and Goss, T.I., 1980, UANOVA; A FORTRAN IV program for unbalanced nested analysis of variance: Computers and Geosciences, v. 6, p. 35-60.

Gat, J.R., 1980, The isotopes of oxygen and hydrogen in precipitation, in Fritz, Peter, and Fontes, J.C., eds., Handbook of environmental isotope geochemistry, part A--The terrestrial environment: New York, American Elsevier Publishing Co., p. 21-47.

Gifford, G.F., 1982, A long-term infiltrometer study in Southern Idaho, U.S.A.: Journal of Hydrology, v. 58, p. 367-374.

----- 1983, Rainfall simulator studies--1983: Gillette, Wyo., Amax Coal Co. report, no pagination.

Gillette Area Groundwater Monitoring Organization, 1987, GAGMO annual report: Gillette, Wyo., no pagination.

Glass, G.B., 1986a [1987], Coal [Geology], in Hydrology of area 50, Northern Great Plains and Rocky Mountain coal provinces, Wyoming and Montana: U.S. Geological Survey Water-Resources Investigations Open-File Report 83-545, p. 26-27.

----- 1986b [1987], Coal [Economic development], in Hydrology of area 50, Northern Great Plains and Rocky Mountain coal provinces, Wyoming and Montana: U.S. Geological Survey Water-Resources Investigations Open-File Report 83-545, p. 34-35.

Glassey, T.W., Dunnewald, T.J., Brock, John, Irving, H.H., Tippetts, Neff, and Rohrer, Conrad, 1955, Soil survey (reconnaissance) of Campbell County, Wyoming: U.S. Department of Agriculture, Soil Conservation Service, Series 1939, No. 22, 67 p.

Gregory, D.I., Schumm, S.A., Watson, C.C., 1985, Determination of drainage density for surface mine reclamation in the western U.S.: Fort Collins, Colo., Water Engineering and Technology, Inc., Final report to U.S. Office of Surface Mining, 59 p.

Groenewold, G.H., 1979, Hydrologic and hydrogeochemical characteristics of selected strip mine spoils in western North Dakota, in Wali, M.D., ed., Ecology and Coal Resource Development Symposium, Proceedings: New York, Pergamon Press, p. 685-692.

Groenewold, G.H., Koob, R.D., McCarthy, G.J., Rehm, B.W., and Peterson, W.M., 1983, Geologic and geochemical controls on the chemical evolution of subsurface water in undisturbed and surface-mined landscapes in western North Dakota: North Dakota Geological Survey Report of Investigation No. 79, 151 p.

Hackley, K.C., and Anderson, T.F., 1986, Sulfur isotopic variations in low-sulfur coals from the Rocky Mountain region: Geochemica et Cosmochimica Acta, v. 50, p. 1703-1713.

Hadley, R.F., and Keefer, W.R., 1975, Map showing some potential effects of surface mining of the Wyodak-Anderson coal, Gillette area, Campbell County, Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I-848-F, scale 1:125,000.

Hadley, R.F., and Schumm, S.A., 1961, Sediment sources and drainage-basin characteristics in upper Cheyenne River basin: U.S. Geological Survey Water-Supply Paper 1531-B, p. 137-198.

Harvey, M.D., Watson, C.C., and Schumm, S.A., 1985, Stream channel restoration criteria, in Second Hydrology Symposium on Surface Coal Mines in the Northern Great Plains, Gillette, Wyoming, Proceedings: Gillette Area Groundwater Monitoring Organization, Colorado Ground-Water Association, and Wyoming Water Research Center, p. 61-73.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water (3rd ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Henderson, Thomas, 1984, Geochemistry of ground-water in two sandstone aquifer systems in the Northern Great Plains in parts of Montana and Wyoming: U.S. Geological Survey Professional Paper 1402-C, 84 p.

Hodson, W.G., Pearl, R.H., and Druse, S.A., 1973 [1974], Water resources of the Powder River Basin and adjacent areas, northeastern Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-465, 4 sheets.

Horton, R.E., 1945, Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology: Geological Society of America Bulletin, v. 56, p. 275-370.

Houghton, R.L., Koob, R.D., and Groenewold, G.H., 1985, Progress report on the geochemistry of the sulfur cycle in Northern Great Plains Coal mines: U.S. Geological Survey Water-Resources Investigations Report 85-4016, 70 p.

Houghton, R.L., Thorstenson, D.L., Fisher, D.W., and Groenewold, G.H., 1987, Hydrogeochemistry of the upper part of the Fort Union Group in the Gascoyne lignite strip-mining area, North Dakota: U.S. Geological Survey Professional Paper 1340, 104 p.

Hounslow, Arthur, Fitzpatrick, Joan, Cerrillo, Lawrence, and Freeland, Michael, 1978, Overburden mineralogy as related to ground-water chemical changes in coal strip mining: U.S. Environmental Protection Agency Report EPA-600/7-78-156, 156 p.

Hutten, N.G., and Gifford, G.F., 1984, Survey of interrill erosion and infiltration rates on natural and reclaimed lands: Gillette, Wyo., Amax Coal Company report, 33 p.

Kearney, W.F., 1985, Channel reconstruction efforts to date in Wyoming, in Second Hydrology Symposium on Surface Coal Mines in the Northern Great Plains, Gillette, Wyoming, Proceedings: Gillette Area Groundwater Monitoring Organization, Colorado Ground-Water Association, and Wyoming Water Research Center, p. 74-75.

Keefer, W.R., and Hadley, R.F., 1976, Land and natural resource information and some potential environmental effects of surface mining of coal in the Gillette area, Wyoming: U.S. Geological Survey Circular 743, 27 p.

Kent, B.H., Berlage, L.J., Boucher, E.M., 1980, Stratigraphic framework of coal beds underlying the western part of the Recluse 1° x 1/2° quadrangle, Campbell County, Wyoming: U.S. Geological Survey Coal Investigations Map C-81-C, scale 1:100,000, 2 sheets.

Klusman, R.W., Ringrose, C.D., Candito, R.J., Zuccaro, Bruce, Rutherford, D.W., and Dean, W.E., 1980, Sampling designs for geochemical baseline studies in the Colorado Oil Shale region: U.S. Department of Energy Report DOE/EV/10298-2, 180 p.

Knutson, Kent, 1982, Regional comparison of drainage basin morphometry--Eastern Powder River Basin, Wyoming, in Hydrology Symposium on Surface Coal Mines in the Powder River Basin of Wyoming, Gillette, Wyoming, Proceedure: Gillette Area Groundwater Monitoring Organization and American Institute of Mining Engineers, p. 157-172.

Koch, Donald, Ringrose, C.D., Moore, R.C., and Brooks, D.L., 1982, Monitoring and modeling the shallow ground-water systems in the Powder River Basin: Englewood, Colo., Hittman Associates, Inc., Report to U.S. Bureau of Mines, 359 p. (appendicies A through U, separate volume).

Larson, L.R., 1984, Ground-water quality in Wyoming: U.S. Geological Survey Water-Resources Investigations Report 84-4034, 71 p.

----- 1986a [1987], pH [Surface water], in Hydrology of area 50, Northern Great Plains and Rocky Mountain coal provinces, Wyoming and Montana: U.S. Geological Survey Water-Resources Investigations Open-File Report 83-545, p. 62-63.

----- 1986b [1987], Total phosphorous [Surface water], in Hydrology of area 50, Northern Great Plains and Rocky Mountain coal provinces, Wyoming and Montana: U.S. Geological Survey Water-Resources Investigations Open-File Report 83-545, p. 66-67.

----- 1986c [1987], Trace metals [Ground water], in Hydrology of area 50, Northern Great Plains and Rocky Mountain coal provinces, Wyoming and Montana: U.S. Geological Survey Water-Resources Investigations Open-File Report 83-545, p. 96-97.

Larson, L.R., and Daddow, R.L., 1984, Ground-water quality data from the Powder River structural basin and adjacent areas, northeastern Wyoming: U.S. Geological Survey Open-File Report 83-939, 56 p.

Leopold, L.B., 1962, The man and the hill: U.S. Geological Survey Circular 460-A, 5 p.

Leopold, L.B., Emmett, W.W., and Myrick, R.M., 1966, Channel and hillslope processes in a semiarid area, New Mexico: U.S. Geological Survey Professional Paper 352, p. 193-253.

Leopold, L.B., and Miller, J.P., 1956, Ephemeral streams--Hydraulic factors and their relation to the drainage net: U.S. Geological Survey Professional Paper 282-A, p. 1-37.

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1964, Fluvial processes in geomorphology: San Francisco, W.H. Freeman and Co., 522 p.

Lewis, B.D., and Hotchkiss, W.R., 1981, Thickness, percent sand, and configuration of shallow hydrogeologic units in the Powder River Basin, Montana and Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I-1317, scale 1:1,000,000, 6 sheets.

Lidstone, C.D., 1982, Stream channel reconstruction and drainage basin stability, in Hydrology symposium on surface coal mines in the Powder River Basin of Wyoming, Gillette, Wyoming, Proceedings: Gillette Area Groundwater Monitoring Organization and American Institute of Mining Engineers, p. 43-58.

Love, J.D., and Christiansen, A.C., 1985, Geologic map of Wyoming: Laramie, Geological Survey of Wyoming, scale 1:500,000.

Lowham, H.W., 1976, Techniques for estimating flow characteristics of Wyoming streams: U.S. Geological Survey Water-Resources Investigations Report 76-112, 83 p.

----- 1986 [1987], Climate, in Hydrology of area 50, Northern Great Plains and Rocky Mountain coal provinces, Wyoming and Montana: U.S. Geological Survey Water-Resources Investigations Open-File Report 83-545, p. 12-13.

Lowham, H.W., DeLong, L.L., Collier, K.R., and Zimmerman, E.A., 1982, Hydrology of Salt Wells Creek--A plains stream in southwestern Wyoming: U.S. Geological Survey Water-Resources Investigations Report 81-62, 52 p.

Lowry, M.E., 1986 [1987], Availability [Ground water], in Hydrology of area 50, Northern Great Plains and Rocky Mountain coal provinces, Wyoming and Montana: U.S. Geological Survey Water-Resources Investigations Open-File Report 83-545, p. 90-91.

Lowry, M.E., and Rankl, J.G., 1987, Hydrology of the White Tail Butte area, northern Campbell County, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 82-4117, 47 p.

Lowry, M.E., Wilson, J.F., Jr., and others, 1986 [1987], Hydrology of Area 50, Northern Great Plains and Rocky Mountain coal provinces, Wyoming and Montana: U.S. Geological Survey Water-Resources Investigations Open-File Report 83-545, 137 p.

Lusby, G.C., and Toy, T.J., 1976, An evaluation of surface-mine spoils area restoration in Wyoming using rainfall simulation: Earth Surface Processes, v. 1, p. 375-386.

McWhorter, D.B., and Landers, R.A., 1985, Prediction of post-mining water quality with column tests and overburden chemistry: Proceedings of the 1985 American Society for Surface Mining and Reclamation National Meeting, October 8-10, 1985, p. 1-28.

Miesch, A.T., 1967, Methods of computation for estimating geochemical abundance: U.S. Geological Survey Professional Paper 574-B, 15 p.

----- 1976, Geochemical survey of Missouri--Methods of sampling, laboratory analysis, and statistical reduction of data, with sections on Laboratory methods, by P.R. Barnett and others: U.S. Geological Survey Professional Paper 954-A, 39 p.

Naftz, D.L., in press, Geochemistry of batch-extract waters derived from spoil material collected at the Cordero coal mine, Powder River Basin, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 87-4200.

Parker, R.S., 1977, Experimental study of basin evolution and its hydrologic implications: Fort Collins, Colo., Colorado State University, unpublished dissertation.

Parkhurst, D.L., Plummer, L.N., and Thorstenson, D.C., 1982a, BALANCE--A computer program for calculating mass transfer for geochemical reactions in ground water: U.S. Geological Survey Water-Resources Investigations Report 82-14, 29 p.

Parkhurst, D.L., Thorstenson, D.C., and Plummer, L.N., 1982b, PHREEQE--A computer program for geochemical calculations: U.S. Geological Survey Water-Resources Investigations Report 80-96, 210 p.

Patton, P.C., and Schumm, S.A., 1975, Gully erosion, northern Colorado, a threshold phenomena: Geology, v. 3, p. 88-90.

Peterson, D.A., 1986 [1987], Vegetation, in Hydrology of area 50, Northern Great Plains and Rocky Mountain coal provinces, Wyoming and Montana: U.S. Geological Survey Water-Resources Investigations Open-File Report 83-545, p. 20-21.

----- in press, Streamflow characteristics of the Missouri River basin, Wyoming, through 1984: U.S. Geological Survey Water-Resources Investigations Report 87-4018.

Plummer, L.N., Jones, B.F., and Truesdell, A.H., 1978, WATEQF--A FORTRAN IV version of WATEQ, a computer program for calculating chemical equilibrium of natural waters: U.S. Geological Survey Water-Resources Investigations Report 76-13, 63 p.

Plummer, L.N., Parkhurst, D.L., and Thorstenson, D.C., 1983, Development of reaction models for ground-water systems: Geochimica Cosmochimica Acta, v. 47, p. 665-686.

Powell, J.D., and Larson, J.D., 1985, Relation between ground-water quality and mineralogy in the coal-producing Norton Formation of Buchanan County, Virginia: U.S. Geological Survey Water-Supply Paper 2274, 30 p.

Rahn, P.H., 1976, Potential of coal strip-mine spoils as aquifers in the Powder River Basin: Rapid City, South Dakota School of Mines and Technology, Project completion report prepared for Old West Regional Committee, Project No. 10470025, 108 p.

Rankl, J.G., 1982, An empirical method for determining average soil infiltration rates and runoff, Powder River structural basin, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 81-76, 38 p.

----- 1986a, Drainage, _in_ Hydrology of area 50, Northern Great Plains and Rocky Mountain coal provinces, Wyoming and Montana: U.S. Geological Survey Water-Resources Investigations Open-File Report 83-545, p. 16-17.

----- 1986b, Soils, _in_ Hydrology of area 50, Northern Great Plains and Rocky Mountain coal provinces, Wyoming and Montana: U.S. Geological Survey Water-Resources Investigations Open-File Report 83-545, p. 18-19.

----- 1987, Analysis of sediment production from two small semiarid basins in Wyoming: U.S. Geological Survey Water-Resources Investigations Report 85-4314, 27 p.

Rankl, J.G. and Lowry, M.E., in press, Regional ground-water flow in the Powder River structural basin, Wyoming and Montana: U.S. Geological Survey Water-Resources Investigations Report 85-4229.

Rehm, B.W., Groenewold, G.H., and Morin, K.A., 1980, Hydraulic properties of coal and related materials, Northern Great Plains: Ground Water, v. 18, no. 6, p. 551-561.

Schaefer, Melvin, Elifrits, Dale, and Barr, D.J., 1979, Sculpturing reclaimed land to decrease erosion: Lexington, University of Kentucky, Symposium on Surface Mining Hydrology, Sedimentology and Reclamation, December 4-7, p. 99-109.

Schumm, S.A., 1977, The fluvial system: New York, John Wiley and Sons, 338 p.

Schumm, S.A., and Hadley, R.F., 1957, Arroyos and the semiarid cycle of erosion: American Journal of Science, v. 255, p. 161-174.

Stiller, D.M., Zimpfer, G.L., and Bishop, M.B., 1980, Application of geomorphic principles to surface mine reclamation: Journal of Soil and Water Conservation, v. 35, p. 274-277.

Strahler, A.N., 1952, Hypsometric (area-altitude) analysis of erosional topography: Geological Society of America Bulletin, v. 63, p. 1117-1142.

----- 1957, Quantitative analysis of watershed geomorphology: American Geophysical Union Transactions, v. 38, p. 913-920.

----- 1964, Quantitative geomorphology of drainage basins and channel networks, in Chow, V.T., ed., Handbook of applied hydrology: New York, McGraw-Hill, p. 4-39 to 4-76.

Surface Mining Control and Reclamation Act of 1977--Public Law 95-87: 95th Congress of the United States, August 3, 1977, U.S. Statutes at Large, p. 445-532.

Tarquin, P.A., and Baeder, L.D., 1982, Stream channel reconstruction--The problem of designing lower order streams, in Hydrology Symposium on Surface Coal Mines in the Powder River Basin of Wyoming, Gillette, Wyoming, Proceedings: Gillette Area Groundwater Monitoring Organization and American Institute of Mining Engineers, p. 257-270.

Thompson, K.A., and Van Voast, W.A., 1983, Update on mined land ground water research in southeastern Montana: Casper, Wyo., Symposium on Soils and Overburden in Arid/Semiarid Mined Land Reclamation.

Thorstenson, D.C., Fisher, D.W., and Croft, M.G., 1979, The geochemistry of the Fox Hills-basal Hell Creek aquifer in southwestern North Dakota and northwestern South Dakota: Water Resources Research, v. 15, no. 6, p. 1479-1498.

Toy, T.J., and Hadley, R.F., 1987, Geomorphology and reclamation of disturbed lands: Orlando, Fla., Academic Press, Inc., 480 p.

U.S. Department of the Interior, U.S. Department of Agriculture, and U.S. Interstate Commerce Commission, 1974, Proposed development of coal resources in the eastern Powder River coal basin of Wyoming: Cheyenne, Wyo., U.S. Department of the Interior, Bureau of Land Management (lead agency), Final Environmental Impact Statement, 6 volumes.

U.S. Environmental Protection Agency, 1986a, Maximum contaminant levels (subpart B of part 141, National interim primary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised as of July 1, 1986, p. 524-528.

----- 1986b, Secondary maximum contaminant levels (section 143.3 of part 143, National secondary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised as of July 1, 1986, p. 587-590.

U.S. Geological Survey, 1975, Geochemical survey of the western coal regions, 2nd Annual Progress Report: U.S. Geological Survey Open-File Report 75-436, 132 p.

----- 1977, Geochemical survey of the western coal regions, 4th Annual Progress Report: U.S. Geological Survey Open-File Report 77-872, 207 p.

----- 1980, Water resources data for Wyoming, water year 1979, volume 1, Missouri River Basin: U.S. Geological Survey Water-Data Report WY-79-1, 647 p.

Van Voast, W.A., Hedges, B., and McDermott, J.J., 1976, Strip coal mining and mined land reclamation in hydrologic systems, southeastern Montana, Appendix D in Williams, T.T., Koob, R.L., and Rechard, P.A., Surface and groundwater problems associated with potential strip mine sites: Draft final report for EPA Grant R-303727, 122 p.

Wyoming Department of Environmental Quality, 1980a, Quality standards for Wyoming groundwaters: Cheyenne, Wyo., Water Quality Rules and Regulations, Chapter VIII, 13 p.

----- 1980b, Hydrology: Cheyenne Wyo., Land Quality Division Guideline No. 8, 25 p.

----- 1984, Topsoil and overburden: Cheyenne, Wyo., Land Quality Division Guideline No. 1, 34 p.

----- 1986, Rules and regulations: Cheyenne, Wyo., Land Quality Division, 230 p.

Wyoming Geological Association, 1958, Guidebook--13th Annual Field Conference, Powder River Basin: Casper, Wyo., Wyoming Geological Association, 341 p.

Wyoming State Legislature, 1973, Wyoming Environmental Quality Act: Cheyenne, Wyoming Department of Environmental Quality, statutes 35-502.1 to 35-502.56, 32 p.

Wyoming Water Planning Program, 1972, Water and related land resources of northeastern Wyoming: Cheyenne, Office of the State Engineer, Wyoming Water Planning Program Report No. 10, 209 p.

Yurtsever, Y., 1975, Worldwide survey of stable isotopes in precipitation, in Environmental isotope data no. 5--World survey of isotope concentration in precipitation (1970-1971): Vienna, International Atomic Energy Agency, Technical Report Series No. 165, 40 p.

Zimpfer, G.L., O'Brien, Michael, and Schumm, S.A., 1982, Design of stable drainage networks for mined land reclamation: Final report to Colorado Commission on Higher Education, December 1982, 26 p.

SUPPLEMENTAL DATA

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines

[Permit number, Wyoming State Engineer's Office permit number; Use of Water: COM, commercial; DOM, domestic; IND, industrial; IRR, irrigation; MIS, miscellaneous; MUN, municipal; RAI, railroad; RES, residential; STO, stock. Location is by township, range, section, and quarter-quarter; gal/min, gallons per minute; Hydrogeologic unit: WAS, Wasatch aquifer; COL, Wyodak coal aquifer; TTL, Tongue River-Lebo, Tullock, or Lance-Fox Hills aquifers; UNK, unknown; --, no data]

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P45325W	Lester, Mayne	DOM STO	56 73 29 SE NE	0	224	164	224	YES	COL
P58355W	Oedekoven, Donald L. and Barbara	DOM STO	56 73 30 SW NW	4	112	75	109	YES	COL
P33069W	Oedekoven, Donald L. and Barbara	STO	56 73 30 SW SW	25	8	--	--	NO	UNK
P26184W	McClure, Duane	DOM	56 73 33 SE SE	5	346	295	346	YES	COL
P55893W	Brug Land and Livestock Co., Inc.	STO	56 74 36 NE SE	8	195	--	--	NO	UNK
P3508P	Tyree, Edward P.	DOM STO	55 72 21 SW NE	4	150	--	--	NO	UNK
P42041W	Davis Oil Co.	IND	55 73 00	27	1,100	8	840	YES	TTL
P55891W	Brug Land and Livestock Co., Inc.	STO	55 73 03 NW SE	8	230	--	--	NO	UNK
P24680W	Amoco Production Co.	IND	55 73 03 NW SW	15	--	--	--	NO	UNK
P55889W	Brug Land and Livestock Co., Inc.	STO	55 73 05 SW NW	4	121	--	--	NO	UNK
P62017W	Heald, Robert	STO	55 73 07 SW SE	5	244	195	230	YES	WAS
P55879W	Brug Land and Livestock Co., Inc.	STO	55 73 08 NW NE	4	225	--	--	YES	COL
P5140W	Elliott, Curtis C.	STO	55 73 09 SW SE	3	200	135	190	YES	COL
P13341P	Elliott, Curtis C.	STO	55 73 10 NW SE	7	--	--	--	NO	UNK
P24681W	Amoco Production Co.	IND	55 73 10 SE NW	45	--	--	--	NO	UNK
P13435W	Elliott, Curtis C.	DOM STO	55 73 11 NW SE	10	546	470	500	YES	TTL
P13340P	Elliott, Curtis C.	STO	55 73 11 SE NE	3	148	--	--	NO	UNK
P55894W	Brug Land and Livestock Co., Inc.	STO	55 73 17 NW NW	8	120	--	--	NO	UNK
P15098P	Oedekoven, Henry H.	STO	55 73 19 NE SW	25	99	88	99	YES	WAS
P56803W	U.S. Bureau of Land Management	STO	55 73 26 SE NE	4	465	370	383	YES	TTL
P15096P	Oedekoven, Henry H.	STO	55 73 29 NW NE	25	--	85	89	YES	UNK
P19954P	Oedekoven, Leon L.	STO	55 73 29 NW SE	2	225	180	215	YES	WAS
P19952P	Oedekoven, Leon L.	STO	55 73 30 SE NE	3	220	196	220	YES	WAS
P19953P	Oedekoven, Leon L.	STO	55 73 30 SE NW	3	100	75	100	YES	WAS
P7714P	Wolff, James A.	STO	55 73 32 SW NE	7	120	--	--	NO	UNK
P15097P	Oedekoven, Henry H.	STO	55 74 24 NW SE	7	15	12	15	YES	WAS
P19957P	Oedekoven, Leon L.	DOM	55 74 24 NW SE	10	100	72	94	YES	WAS
P19958P	Oedekoven, Leon L.	DOM	55 74 24 NW SE	10	240	197	231	YES	WAS
P19956P	Oedekoven, Leon L.	STO	55 74 24 SE SE	2	160	142	160	YES	WAS
P18796P	Collins, John P.	STO	54 72 30 NE SW	7	140	90	140	NO	UNK
P5442P	Norfolk, Ted S.	STO	54 73 03 SE NW	6	566	--	--	YES	UNK
P9672P	Floyd, Fred, Jr.	DOM	54 73 05 NW NE	7	270	--	--	NO	UNK
P12267P	Norfolk, Ted S. and Mary E.	STO	54 73 16 SW SW	25	125	60	124	YES	WAS
P5439P	Norfolk, Ted S.	STO	54 73 29 NW NE	10	125	--	--	YES	COL
P2379W	Heinrich, Cassie B. and W.R.	STO	54 73 30 SE SE	20	105	44	65	YES	COL
P51976W	Scott, Harold W.	STO	54 73 31 SE SW	10	333	283	333	YES	WAS
P49486W	Heinrich, Cassie B.	STO	54 73 33 SE SW	5	404	330	385	YES	TTL
P3266P	Hall, Dean W.	STO	54 73 36 SW SW	5	110	--	--	NO	UNK
P7708P	Wolff, James A.	STO	54 74 01 SE SW	7	220	180	220	YES	TTL
P9930P	Oedekoven, Walter	DOM STO	54 74 12 NE NW	5	443	--	--	NO	UNK
P51447W	Fjelseth, David and Karen K.	DOM	54 74 13 NW NW	8	188	140	152	YES	WAS
P4206P	Carson, Dan W.	STO	54 74 13 SE NW	7	115	--	--	YES	TTL
P21669P	Reed, Louis C., Jr.	STO	54 74 14 SW NE	4	110	91	108	YES	WAS
P4207P	Carson, Dan W.	STO	54 74 15 NE NE	7	101	--	--	NO	WAS

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P29570W	Edwards, James A. and Kathryn D.	DOM STO	54 74 23 NE NE	25	485	--	--	YES	TTL
P21670P	Reed, Louis C., Jr.	DOM STO	54 74 23 SW NE	17	210	--	--	NO	UNK
P63343W	Heinrich and Company	STO	54 74 24 SW SW	5	166	157	166	YES	WAS
P2379W	Heinrich, Cassie B. and W.R.	STO	54 74 25 NE NE	5	94	76	86	YES	WAS
P3044W	Heinrich, Cassie B.	IND STO	54 74 25 SE SW	45	20	--	--	YES	WAS
P58404W	Heinrich, Cassie B.	STO	54 74 25 SW NE	5	100	80	100	YES	WAS
P2513W	Butcher, Clarence	IND STO	54 74 27 SE NE	20	250	185	195	YES	COL
P22128P	Scott, Harold	STO	54 74 36 SE NW	4	143	--	--	NO	WAS
P10234P	Landeck, William A.	DOM STO	53 72 19 NW SE	5	282	--	--	NO	UNK
P3193P	60 Bar Ranch	STO	53 72 26 NE SW	3	20	--	--	NO	UNK
P18186P	Oedekoven, Gilbert	STO	53 72 28 NW NW	3	250	--	--	NO	UNK
P18184P	Oedekoven, Gilbert	DOM STO	53 72 32 SE NE	8	220	--	--	NO	UNK
P18188P	Oedekoven, Gilbert	STO	53 72 32 SW SE	8	150	--	--	NO	UNK
P18185P	Oedekoven, Gilbert	STO	53 72 33 NE NW	3	180	--	--	NO	UNK
P27251W	Oedekoven, Gilbert	DOM STO	53 72 33 SW NW	15	315	260	285	YES	TTL
P61232W	Oedekoven, Gilbert	DOM STO	53 72 33 SW NW	20	800	--	--	YES	TTL
P2377W	Heinrich, Cassie B. and W.R.	STO	53 73 04 SW SE	10	340	280	335	YES	TTL
P68719W	Heinrich and Company	STO	53 73 05 NE NW	10	355	278	350	YES	TTL
P14809W	Heinrich, W.R.	DOM	53 73 05 NW NE	10	420	285	420	YES	TTL
P2384W	Butcher, Clarence	MIS STO	53 73 07 SE SE	10	200	160	180	NO	WAS
P23430P	Schiermeister, Milton O.	STO	53 73 09 SE SW	7	150	--	--	NO	UNK
P3263P	Hall, Dean W.	STO	53 73 14 SW NW	6	80	--	--	NO	UNK
P3265P	Hall, Dean W.	STO	53 73 15 SE SE	7	110	--	--	NO	UNK
P2389W	Butcher, Clarence	MIS STO	53 73 18 SW SW	15	210	120	170	YES	COL
P2387W	Butcher, Clarence	DOM STO	53 73 20 NW NW	15	350	310	330	NO	UNK
P3822W	Butcher, Clarence S.	STO	53 73 20 SE NW	150	407	302	380	YES	TTL
P4055P	Scott, Harold W.	STO	53 73 20 SE SE	5	127	--	--	YES	WAS
P22125P	Scott, Harold and Marion	STO	53 73 21 SW SE	2	100	--	--	NO	UNK
P3261P	Hall, Dean W.	STO	53 73 22 NE NE	6	220	--	--	NO	UNK
P3264P	Hall, Dean W.	DOM	53 73 22 NW NE	6	213	--	--	YES	COL
P19956P	Oedekoven, Leon L.	STO	55 74 24 SE SE	2	160	142	160	YES	WAS
P2385W	Butcher, Clarence	IRR STO	53 73 22 SE SW	20	220	180	200	NO	UNK
P3260P	Hall, Dean W.	STO	53 73 23 NW SE	7	115	--	--	NO	UNK
P52285W	Barbour, Ralph E.	STO	53 73 25 SE SE	15	330	306	330	YES	TTL
P2635W	Hall, Dean W. and Eldee	STO	53 73 26 NW SW	3	112	65	105	YES	WAS
P66546W	Scott, Marion H.	DOM STO	53 73 33 NE SW	10	390	340	390	YES	TTL
P22123P	Scott, Harold and Marion	STO	53 73 33 NW SE	5	10	--	--	YES	WAS
P22124P	Scott, Harold and Marion	STO	53 73 34 NW NW	3	130	--	--	NO	UNK
P3262P	Hall, Dean W.	STO	53 73 36 SW SW	2	110	--	--	NO	UNK
P4918P	Scott, Harold W.	STO	53 74 01 NE SW	5	121	--	--	NO	WAS
P4916P	Scott, Harold W.	DOM STO	53 74 13 SW SE	8	265	--	--	YES	WAS
P4920P	Scott, Harold W.	STO	53 74 24 NW SE	2	238	--	--	YES	WAS
P18187P	Oedekoven, Gilbert	STO	52 72 05 NE NE	7	140	--	--	NO	UNK
P42484W	Oedekoven, Gilbert	STO	52 72 05 NE NW	10	225	150	225	YES	COL
P61486W	Oedekoven, Charles R.	STO	52 72 19 SE SE	25	100	75	85	YES	WAS
P21101P	Oedekoven, Charles R.	DOM	52 72 19 SW SW	10	93	25	85	YES	WAS
P21105P	Oedekoven, Charles R.	STO	52 72 19 SW SW	5	25	--	--	NO	UNK
P21106P	Oedekoven, Charles R.	STO	52 72 30 NE NE	10	60	--	--	NO	WAS
P10236P	Landeck, William A.	DOM STO	52 73 04 SE SW	3	226	--	--	NO	UNK

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P67072W	Twenty Mile Land Co.	STO	52 73 09 NE NW	10	340	198	251	YES	COL
P10235P	Landeck, William A.	STO	52 73 10 NW NW	3	209	--	--	NO	UNK
P67024W	Ray, Darrell	DOM	52 73 13 NE SW	25	296	276	296	YES	WAS
P67063W	Petersen, Kerry L.	DOM	52 73 13 NE SW	25	250	90	250	YES	WAS
P33812W	Cook, Cecle L.	DOM STO	52 73 13 SE NE	25	130	--	--	YES	UNK
P8545P	Morel, Maurice	STO	52 73 14 NE NW	2	4	--	--	NO	WAS
P15860W	Parnell, Reginald	STO	52 73 14 NE SE	60	102	70	97	YES	WAS
P8543P	Morel, Maurice	DOM STO	52 73 14 NW NW	3	185	--	--	NO	WAS
P8412W	Morel, Maurice	STO	52 73 14 SE NW	4	84	25	70	YES	WAS
P8544P	Morel, Maurice	STO	52 73 15 SE NE	3	120	80	100	YES	WAS
P52382W	Daly Livestock Co.	STO	52 73 16 NW NW	15	184	100	137	YES	WAS
P21099P	Oedekoven, Charles R.	STO	52 73 23 SE SE	5	370	310	360	YES	WAS
P21102P	Oedekoven, Charles R.	STO	52 73 24 SE SE	15	140	70	140	YES	WAS
P21104P	Oedekoven, Charles R.	DOM STO	52 73 24 SE SW	10	210	--	--	NO	WAS
P69602W	Sullivan, Charles P.	DOM	52 73 25 NW NW		820	740	815	NO	TTL
P55199W	Bruski, Lawrence	DOM	52 73 25 NW SW	20	330	145	310	YES	WAS
P59551W	Connolly, Jack P. and Victoria L.	DOM	52 73 25 NW SW	25	800	676	779	YES	TTL
P51185W	Hull, Harlan A.	DOM	52 73 25 SE NW	20	660	--	--	YES	WAS
P21103P	Oedekoven, Charles R.	STO	52 73 25 SE SE	10	210	160	210	YES	COL
P41579W	Bredthauer, Charles E.	DOM	52 73 25 SW NW	11	705	645	705	YES	TTL
P56385W	Hafling, Helen	DOM STO	52 73 25 SW NW	20	785	610	785	YES	TTL
P65773W	Bredthauer, Charles E.	MIS	52 73 25 SW NW	25	705	645	705	YES	TTL
P34782W	Barbour, Steven R. and Georgia L.	DOM STO	52 73 25 SW SE	12	200	100	160	YES	WAS
P66876W	Barbour, Steven R. and Georgia L.	DOM	52 73 25 SW SE	20	717	606	640	YES	TTL
P21100P	Oedekoven, Charles R.	STO	52 73 26 NE NE	10	141	110	127	YES	WAS
P65774W	Bredthauer-West Home Owners	MIS	52 73 26 NE SE	40	710	605	690	YES	TTL
P36583W	Podenski, Raymond	DOM STO	52 73 26 NE SW	5	580	520	580	YES	WAS
P57369W	Holden, Orvil L.	DOM STO	52 73 26 NW NE	9	625	550	625	YES	TTL
P38967W	Johnson, Bob Leroy, Mr. and Mrs.	DOM	52 73 26 NW SW	7	260	220	261	YES	WAS
P43866W	Eldridge, Edward W. and Linda K.	DOM STO	52 73 26 SW NE	12	325	235	305	YES	WAS
P43864W	Collins, Horace Ray	DOM STO	52 73 26 SW SE	10	442	--	--	YES	WAS
P65156W	Butcher, Duane	DOM	52 73 26 SW SE	10	790	--	--	NO	TTL
P67074W	Twenty Mile Land Co.	STO	52 73 29 NW SE	15	320	212	254	YES	COL
P6251W	Taylor, Ralph D.	STO	52 73 31 NE NE	4	273	210	273	YES	WAS
P67073W	Twenty Mile Land Co.	STO	52 73 35 NW NE	15	250	30	200	YES	WAS
P6523P	Groves, Glenn M.	STO	51 71 31 SW SE	2	180	--	--	NO	UNK
P6525P	Ryan, Jean	STO	51 71 31 SW SW	10	19	--	--	NO	UNK
P2267W	Groves, Glenn M.	DOM STO	51 71 32 SW SW	18	738	643	700	YES	TTL
P6524P	Groves, Glenn M.	STO	51 71 32 SW SW	2	311	--	--	YES	UNK
P18183P	Oedekoven, Gilbert	DOM STO	51 72 05 SE NE	10	450	--	--	NO	UNK
P25835W	Campbell County School District	MIS	51 72 07 NE NE	60	126	126	--	YES	WAS
P27230W	Hardy, W.E.	MIS	51 72 17 SE SW	20	490	255	292	YES	UNK
P69873W	Jones, Terry and Lori	DOM	51 72 17 SE SW	--	617	578	587	NO	TTL
P16553W	Hardy, W.E.	DOM	51 72 17 SW SW	7	127	95	127	YES	WAS
P34920W	Meadowlark Farm, Inc.	MIS	51 72 17 SW SW	100	1,100	775	876	YES	TTL
P49324W	Sagebrush Development, Inc.	MIS	51 72 20 NE SE	100	1,097	886	990	YES	TTL
P23445P	Vandekoppel, Tony, Mr. and Mrs.	STO	51 72 20 NW SW	7	50	--	--	NO	WAS
P8896W	Coulter, Milton	DOM	51 72 20 SE NE	25	245	15	60	YES	WAS
P23443W	Vandekoppel, Tony, Mr. and Mrs.	DOM STO	51 72 20 SE NW	6	60	50	56	YES	WAS

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P23444P	Vandekoppel, Tony, Mr. and Mrs.	DOM STO	51 72 20 SE NW	6	50	--	--	NO	UNK
P22762W	Wandler, Leon E.	DOM	51 72 20 SW NE	25	118	40	100	YES	WAS
P7932W	Hladky, E.E.	STO	51 72 20 SW SE	100	10	--	--	YES	WAS
P15800P	Grams, Lewis E. and Fern V.	STO	51 72 28 NE SW	5	273	220	273	YES	COL
P15236W	Hladky, E.E.	STO	51 72 29 NW SE	20	444	280	300	YES	WAS
P16599W	Barbour, Ralph E.	STO	51 72 30 SW NW	6	254	214	254	YES	WAS
P63913W	Gillette-Campbell County Airport	MIS	51 72 32 SE SE	150	1,130	690	1,130	YES	TTL
P18094P	Fulkerson, James T.	STO	51 72 32 SW SW	10	450	--	--	NO	UNK
P18752P	Grams, Mary H.	STO	51 72 33 NE NW	8	290	--	--	NO	WAS
P69335W	Meadowlark Farms, Inc.	MIS STO	51 72 33 NW SE	25	340	225	321	YES	COL
P10083P	Jones, Gerald W.	DOM	51 72 33 NW SW	12	320	230	315	YES	COL
P2757W	Davis, C.H.	STO	51 72 33 SE SE	25	276	--	--	YES	COL
P18750P	Grams, Mary H.	DOM STO	51 72 33 SW NE	6	158	--	--	NO	WAS
P68084W	Davis-Schiermiester Ranch	STO	51 72 34 SE SW	20	280	249	280	YES	COL
P18751P	Grams, Mary H.	STO	51 72 34 SW NW	6	162	--	--	NO	WAS
P52307W	Daly Livestock, Inc. and Twenty	DOM STO	51 73 02 SW SE	25	800	710	800	YES	TTL
P6982W	McCulloch Oil Corporation	DOM	51 73 03 NW SW	20	235	150	215	YES	WAS
P57900W	Twenty Mile Land Co.	STO	51 73 04 NW SE	20	223	150	210	YES	WAS
P58094W	Twenty Mile Land Co.	STO	51 73 08 SE NW	10	405	--	--	YES	WAS
P9682W	Bridwell, Perry	STO	51 73 35 NW SW	10	189	103	179	YES	WAS
P22987P	Springen, Phyllis A.	STO	50 71 04 SE NW	15	90	--	--	NO	UNK
P21677P	Burkhardt, Arthur J. and Edna E.	STO	50 71 05 NW SW	4	100	--	--	NO	UNK
P6536W	Burkhardt, Arthur J.	STO	50 71 05 NW SW	3	744	654	720	YES	TTL
P40362W	Burkhardt, Arthur	STO	50 71 05 SE NW	10	300	145	300	YES	TTL
P21674P	Burkhardt, Arthur J. and Edna E.	STO	50 71 05 SW NW	10	80	--	--	NO	UNK
P21676P	Burkhardt, Arthur J. and Edna E.	DOM STO	50 71 05 SW NW	15	60	--	--	NO	UNK
P24359W	Ryan, Jean M.	STO	50 71 06 NE NW	5	50	12	30	YES	TTL
P31460W	Kawulok, Joe	DOM STO	50 71 06 SE NE	20	700	--	--	YES	UNK
P24663P	Kawulok, Joe	STO	50 71 06 SE SE	3	240	--	--	NO	UNK
P24662P	Kawulok, Joe	STO	50 71 06 SW NE	10	250	--	--	NO	UNK
P24664P	Kawulok, Joe	STO	50 71 06 SW SE	2	80	--	--	NO	UNK
P69919W	Countryside Water Users, Inc.	MIS	50 71 18 NE SW	120	1,256	714	826	YES	TTL
P9787W	Gillette Stock Car Racing Association	MIS	50 71 18 SE SW	25	380	345	360	YES	UNK
P21638P	Kenitzer, Charles S.	DOM STO	50 71 18 SW NW	25	206	--	--	NO	UNK
P24605W	Countryside Water Users Co.	MIS	50 71 18 SW NW	150	1,190	1,050	1,150	YES	TTL
P41246W	Countryside Water Users Co.	MIS	50 71 18 SW NW	10	320	--	--	NO	UNK
P56727W	Lemaster Enterprises	STO	50 71 18 SW SE	20	380	340	364	YES	TTL
P28855W	Dodd, Houston L.	DOM	50 71 19 NW NW	6	199	--	--	YES	WAS
P62177W	Kinnear, Lindsay J. and Denice	MIS	50 71 19 NW NW	75	1,073	768	806	YES	TTL
P20572W	Lemaster, Henry	DOM	50 71 19 NW SW	15	162	127	162	YES	WAS
P41471W	Lemaster, Henry	DOM	50 71 19 SW NW	12	169	60	135	YES	WAS
P32002W	Collins, Clarence E.	DOM MIS	50 71 19 SW SE	20	1,234	1,200	1,225	NO	TTL
P32003W	Collins, Clarence E.	MIS	50 71 19 SW SE	100	1,050	938	973	NO	TTL
P22627P	Homestake Mining Co.	DOM STO	50 71 20 NE SW	25	80	--	--	NO	UNK
P20829W	Wyoming State Highway Department	STO	50 71 20 NW SW	25	180	50	170	YES	WAS
P30794W	Shepherd, Roy S. or Carmen	DOM STO	50 71 20 NW SW	5	73	55	73	YES	WAS
P55161W	Shepherd, Roy S.	STO	50 71 20 NW SW	10	50	30	50	YES	WAS
P42771W	Harrod and Potter	STO	50 71 20 SW SW	25	20	--	--	YES	WAS
P53139W	Werts, Vernon R.	DOM STO	50 71 20 SW SW	18	83	70	83	NO	UNK

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P11699W	Wellen, Merle E. and Maryls J.	STO	50 71 29 NW NW	25	86	65	86	YES	WAS
P41460W	Roesler, Donald E. or Wanda I.	DOM	50 71 29 NW NW	12	90	--	--	YES	WAS
P19788P	Gillette Ag. Substation	STO	50 71 29 NW SW	1	15	--	--	NO	UNK
P19787P	Gillette Ag. Substation	STO	50 71 29 SW SW	5	183	125	180	YES	COL
P60751W	Sullivan, Jesse E. and Gwendolyn	MIS	50 71 30 NE NE	50	775	660	768	YES	TTL
P61519W	Mader, Kelly	MIS	50 71 30 NE NW	40	926	590	910	YES	TTL
P19786P	Gillette Ag. Substation	STO	50 71 30 NE SW	5	135	--	--	NO	UNK
P62439W	Arrow Trucking, Inc.	MIS	50 71 30 SE NW	20	759	--	--	NO	TTL
P39502W	Bassett, Clark	DOM STO	50 71 31 NE NE	20	450	--	--	NO	UNK
P37959W	Drum Coulter Partnership	MIS	50 71 31 NW NE	300	1,775	1,100	1,775	YES	TTL
P28934P	Pickrel Land and Cattle Co.	STO	50 71 33 NE NW	5	80	60	75	YES	WAS
P69111W	Pickrel Land and Cattle Co.	STO	50 71 33 NW SE	12	485	420	450	YES	TTL
P47569W	Pickrel Land and Cattle Co.	STO	50 71 33 SE NE	25	247	191	228	YES	TTL
P2634W	Pickrel, I.A.	STO	50 71 34 NW NW	7	125	35	115	YES	COL
P28947P	Pickrel Land and Cattle Co.	STO	50 71 34 SE NW	5	200	--	--	NO	UNK
P28937P	Pickrel Land and Cattle Co.	STO	50 71 35 NW NW	5	86	56	86	YES	COL
P53297W	McGee, John	STO	50 71 35 SE NE	25	583	365	415	YES	WAS
P10017P	Chamberlain, Daniel R.	STO	50 71 35 SE SW	6	80	--	--	NO	UNK
P32391W	Hoy, Philip	DOM	50 72 04 NE SW	8	480	--	--	NO	UNK
P21172P	Meadowlark Farms, Inc.	DOM	50 72 04 NW NE	20	904	715	820	YES	TTL
P68195W	Meadowlark Farms, Inc.	STO	50 72 04 NW NE	20	904	715	820	YES	TTL
P13354W	Fleck, Martin and Paulette	DOM STO	50 72 04 NW SE	30	340	--	--	YES	WAS
P14241W	Knutson, Roy E.	DOM	50 72 04 NW SW	5	268	225	239	YES	WAS
P46512W	National Tank Company	MIS	50 72 04 NW SW	20	363	242	342	YES	COL
P14239W	Paul's Truck and Tractor Service	DOM	50 72 04 SE NW	1	328	206	268	YES	WAS
P21171P	Davis, Clifford H.	STO	50 72 04 SW NE	10	250	--	--	NO	UNK
P18092P	Fulkerson, James T.	STO	50 72 05 NE SE	5	25	--	--	NO	WAS
P18095P	Fulkerson, James T.	DOM STO	50 72 05 NE SE	25	370	270	370	YES	COL
P23947W	Gillette-Campbell County Airport	MIS	50 72 05 NW NE	15	1,230	940	960	YES	TTL
P18748P	Grams, Raymond	STO	50 72 07 SW SE	8	198	140	198	YES	WAS
P56012W	The Western Company of North	MIS	50 72 08 NE NE	100	1,450	790	1,420	YES	TTL
P6430W	Apache Corporation	DOM MIS	50 72 08 NE SE	25	1,374	964	980	YES	TTL
P65507W	Grams, Lewis E.	STO	50 72 08 NE SE	4	294	228	298	YES	COL
P26423W	Barbour, Ralph E. and Georgia L.	MIS	50 72 08 SE SE	25	400	300	390	YES	COL
P62976W	Campbell Agri-Center, Inc.	MIS	50 72 08 SE SW	15	464	330	440	YES	COL
P29099W	Steel-Built, Inc.	MIS	50 72 09 NE SW	15	340	250	320	YES	COL
P18093P	Fulkerson, James T.	STO	50 72 09 NW NW	20	110	--	--	NO	WAS
P44836W	Barnes, John K. and Rita J.	DOM	50 72 09 NW SE	4	360	245	235	YES	COL
P27645W	McGee, John E.	DOM	50 72 09 NW SW	15	403	340	385	YES	TTL
P30042W	Zentner, Frank	MIS	50 72 09 NW SW	25	432	--	--	YES	WAS
P37682W	Ary, Ronnie L.	MIS	50 72 09 NW SW	20	586	454	586	YES	TTL
P26529W	Dolcater, Robert A. and Betty L.	DOM	50 72 09 SE NE	20	400	295	390	YES	COL
P29735W	Coltrane, Brad	DOM	50 72 09 SE NE	20	910	--	--	YES	TTL
P44280W	Curry, Albert Willis	DOM	50 72 09 SE NE	10	850	--	--	YES	TTL
P70226W	Means, Monte	DOM	50 72 09 SE NE	25	905	800	890	NO	TTL
P49493W	S and M Construction, Inc.	MIS	50 72 09 SE NW	10	305	240	305	YES	COL
P24602W	Bargmann, Richard and Clarice	DOM	50 72 09 SE SE	15	360	240	355	YES	COL
P48013W	Means, Glen and Kathleen	DOM IRR	50 72 09 SE SE	25	1,030	--	--	NO	TTL
P52819W	Means, Glen E.	MIS	50 72 09 SE SE	70	1,075	--	--	YES	TTL

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P30149W	Webb, Ray L.	MIS	50 72 09 SE SW	23	408	163	210	YES	WAS
P40764W	Donald Cross Distributing	MIS	50 72 09 SE SW	5	470	380	470	NO	UNK
P33261W	Overhead Door of Gillette, Inc.	IND	50 72 09 SW NW	13	360	235	345	YES	COL
P34512W	Nannemann Brothers Automotive	MIS	50 72 09 SW NW	20	110	80	100	YES	WAS
P54873W	Oil Well Perforators, Inc.	MIS	50 72 09 SW NW	56	1,705	1,355	1,374	YES	TTL
P24492P	Carter, Wilma and Clarence C.	STO	50 72 09 SW SE	10	320	--	--	NO	UNK
P34001W	Means, Glen E.	DOM STO	50 72 09 SW SE	25	1,250	999	1,092	YES	TTL
P37062W	Campbell County Concrete, Inc.	IND	50 72 09 SW SE	8	1,031	830	980	YES	TTL
P40765W	Dudley's, Inc.	MIS	50 72 09 SW SW	20	432	330	360	YES	COL
P11322W	Harrod, Mary	STO	50 72 10 NW NE	25	339	245	305	YES	COL
P62986W	Integrity Oil and Gas Company	IND	50 72 10 SW NE	190	4,150	2,453	4,026	YES	TTL
P63396W	Integrity Oil and Gas Company	IND	50 72 10 SW NE	355	4,140	2,453	4,026	YES	TTL
P20319W	Wright, William	DOM	50 72 11 SW SE	17	420	360	420	YES	COL
P34327W	Wright, William A. and Cheryl J.	DOM	50 72 11 SW SE	20	168	100	168	NO	WAS
P66935W	Cash, Wally and Georgia	DOM	50 72 11 SW SE	24	1,228	--	--	NO	TTL
P70505W	Cash, Wally and Georgia	STO	50 72 11 SW SE	0	1,228	--	--	NO	TTL
P69546W	Gladson, Terry and Bonnie	DOM	50 72 11 SW SW	10	638	564	630	YES	TTL
P25069W	Kluver, John M.	DOM STO	50 72 13 NE SW	3	140	108	121	YES	WAS
P41890W	Austin, Roy and or Joann	DOM	50 72 14 NE NW	25	30	12	18	YES	WAS
P41682W	McGee, Paul and Patty	MIS	50 72 14 NE SE	45	970	840	950	YES	TTL
P69075W	McGee, Paul and Patty	MIS	50 72 14 NE SE	75	1,040	776	926	YES	TTL
P33294W	Heritage Village Water and Sewer	MIS	50 72 14 NE SW	50	1,002	--	--	YES	TTL
P57954W	Heritage Village Water and Sewer	MIS	50 72 14 NE SW	150	1,545	1,488	1,522	YES	TTL
P20536W	Jodozi, Peter Wayne	DOM	50 72 14 NW NE	20	290	200	290	YES	WAS
P27917W	McKenney Subdivision Homeowners	DOM	50 72 14 NW NE	25	900	325	425	YES	COL
P30792W	Parnell, Gene	DOM	50 72 14 NW NE	20	314	290	400	YES	COL
P15589W	Vandervoort, David and Inga	DOM STO	50 72 14 NW NW	10	278	200	265	YES	WAS
P60141W	Northland Village Mobile Home	MIS	50 72 14 NW SE	80	1,363	816	1,131	YES	TTL
P23590W	Knighten, Daniel C.	DOM	50 72 14 NW SW	2	280	250	280	YES	WAS
P20321W	Vaughn, James A. and Dorthy E.	DOM	50 72 14 SE NW	25	500	--	--	NO	UNK
P13513W	Williams, Milton B.	STO	50 72 14 SE SW	20	318	245	315	YES	COL
P33293W	Heritage Village Water and Sewer	MIS	50 72 14 SE SW	50	1,000	--	--	YES	TTL
P29097W	Buckskin Club	MIS	50 72 14 SW SW	25	1,035	925	990	YES	TTL
P23960W	Carpenter, Howard L. and Kathryne	DOM	50 72 15 NE NE	10	330	--	--	NO	UNK
P61910W	Williams, L.T.	DOM	50 72 15 NE SE	25	600	570	595	YES	TTL
P20038P	Lubken, Willie E. and Rita M.	DOM	50 72 15 SE NE	4	350	--	--	NO	UNK
P28249W	Lubken, Willie E. and Rita M.	DOM STO	50 72 15 SE NE	25	176	--	--	YES	WAS
P32855W	Morris, Willis	MIS	50 72 17 NE NE	15	425	322	390	NO	UNK
P18747P	Grams, Raymond	STO	50 72 17 NE NW	8	135	--	--	NO	WAS
P6857W	Gillette Diesel Service	MIS STO	50 72 17 NE SE	580	131	--	--	NO	WAS
P18749P	Grams, Raymond	DOM STO	50 72 17 NW NW	12	340	160	325	YES	WAS
P65493W	Butler, Lawrence G. and Noreen J.	DOM	50 72 17 SE NE	25	1,172	887	1,153	YES	TTL
P62965W	Grams, Raymond	DOM STO	50 72 17 SE NW	25	373	90	373	YES	WAS
P65804W	Big Horn Construction Company	MIS	50 72 17 SW NE	100	1,225	970	1,160	YES	TTL
P39875W	Grams, Ray	STO	50 72 18 NE SW	2	6	--	4	NO	WAS
P39876W	Grams, Ray	STO	50 72 18 SE NW	2	6	6	--	YES	WAS
P24751W	Flint Engineering and Construction Co.	MIS	50 72 19 NE SE	20	346	240	340	YES	WAS
P34323W	Webb Resources	DOM MIS	50 72 19 NW SE	18	1,084	1,067	1,087	NO	UNK
P42985W	City of Gillette	MUN	50 72 19 SE NE	160	2,429	1,140	2,354	YES	TTL

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P18670P	Newton, Lee	STO	50 72 19 SE SE	7	150	--	--	NO	WAS
P3013P	Barlow, Henry L.	STO	50 72 19 SW SW	10	280	--	--	YES	WAS
P10177W	Producers Chemical Service Co.	IND	50 72 20 NE SE	70	165	118	165	YES	WAS
P3460W	Edwards, Robert E.	MIS	50 72 20 NE SE	40	294	195	294	YES	WAS
P200W	Littleton, E.E.	DOM IRR RES STO	50 72 20 NE SW	225	364	200	--	YES	WAS
P38071W	Dickinson, Gerald F. and Jessie	DOM MIS	50 72 20 NE SW	70	1,255	960	--	YES	TTL
P2219W	Reeves, C.A.	DOM IND	50 72 20 NW SE	30	1,045	750	1,045	YES	TTL
P25106W	Western Oil Transportation Co.	IND	50 72 20 NW SW	40	1,100	--	--	YES	COL
P27226W	Pacific Power and Light Co.	MIS	50 72 20 SW NE	250	380	255	365	YES	WAS
P6351W	Tarver, Bernice Irma	DOM	50 72 21 NE NW	10	168	125	168	YES	WAS
P41991W	City of Gillette	MUN	50 72 21 NE SE	94	222	--	--	YES	WAS
P42005W	City of Gillette	MUN	50 72 21 NE SE	170	2,350	--	--	NO	TTL
P90C	Chicago Burlington and Quincy Railroad	RAI	50 72 21 NE SE	50	850	798	850	YES	TTL
P14223W	Bay, Eldred B.	DOM MIS	50 72 21 NE SW	30	210	100	210	YES	WAS
P26308P	Shepherd, Roy S.	DOM	50 72 21 NE SW	10	150	--	--	NO	WAS
P1222W	City of Gillette	MUN	50 72 21 NW NE	60	930	800	--	NO	TTL
P1233W	City of Gillette	MUN	50 72 21 SE NE	125	1,143	575	--	YES	TTL
P41987W	City of Gillette	MUN	50 72 21 SE NE	40	175	--	--	NO	WAS
P41992W	City of Gillette	MUN	50 72 21 SE NE	52	222	--	--	YES	WAS
P21944W	Butcher, Arley	DOM	50 72 21 SE SW	10	180	124	180	YES	WAS
P35191W	McManamen, James T.	DOM	50 72 21 SE SW	12	210	--	--	NO	WAS
P5109P	Butcher, Arley C.	DOM	50 72 21 SE SW	15	140	--	--	NO	WAS
P1229W	City of Gillette	MUN	50 72 21 SW NE	60	1,060	--	--	NO	TTL
P1232W	City of Gillette	MUN	50 72 21 SW NE	125	3,479	2,805	--	NO	TTL
P30005W	City of Gillette	IND MUN	50 72 21 SW NE	340	4,436	--	--	NO	TTL
P41989W	City of Gillette	MUN	50 72 21 SW NE	75	230	--	--	NO	WAS
P42004W	City of Gillette	MUN	50 72 21 SW NE	110	1,208	--	--	NO	TTL
P10990W	Sinclair, Jack and Lavera	IRR	50 72 21 SW SE	30	275	195	275	YES	WAS
P42002W	City of Gillette	MUN	50 72 21 SW SE	83	301	--	--	YES	WAS
P3100W	Mobil Oil Co.	MIS	50 72 21 SW SW	20	210	80	210	YES	WAS
P25111W	City of Gillette	IND MUN	50 72 22 NE NW	200	8,509	3,220	4,310	YES	TTL
P42000W	City of Gillette	MUN	50 72 22 NE NW	110	243	--	--	YES	WAS
P42010W	City of Gillette	MUN	50 72 22 NE SE	220	2,297	1,337	1,293	YES	TTL
P89C	Chicago Burlington and Quincy Railroad	RAI	50 72 22 NE SW	45	847	802	844	YES	TTL
P60723W	City of Gillette	MUN	50 72 22 NW NE	550	4,350	2,620	4,126	NO	TTL
P27239W	Sherard, Jack	MIS	50 72 22 NW NW	25	275	165	265	YES	WAS
P2736W	Sherard, Orval E. and Nell	DOM	50 72 22 NW NW	8	760	--	--	NO	TTL
P54559W	Inexco Oil Company	MIS	50 72 22 NW NW	15	1,200	1,020	1,050	YES	TTL
P55990W	Razor City Skateland, Inc.	MIS	50 72 22 NW NW	25	1,490	1,220	1,480	YES	TTL
P41993W	City of Gillette	MUN	50 72 22 NW SW	56	283	--	--	YES	WAS
P41994W	City of Gillette	MUN	50 72 22 NW SW	75	222	--	--	YES	WAS
P41995W	City of Gillette	MUN	50 72 22 NW SW	49	283	--	--	YES	WAS
P42001W	City of Gillette	MUN	50 72 22 SE NW	100	283	--	--	YES	WAS
P48651W	Campbell County Park and Recreation	MIS	50 72 22 SE NW	100	300	60	280	YES	WAS
P88C	Chicago Burlington and Quincy Railroad	RAI	50 72 22 SE NW	35	852	786	850	YES	TTL
P3213P	Sherard, Orval	DOM STO	50 72 22 SE SE	4	160	--	--	NO	WAS
P37961W	Campbell County Department of Parks	MIS	50 72 22 SW NW	80	300	90	270	NO	UNK
P41997W	City of Gillette	MUN	50 72 22 SW NW	62	282	--	--	YES	WAS
P61087W	Sherard, Orval and Nell	DOM	50 72 22 SW NW	25	303	--	--	YES	WAS

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydrogeologic unit
P20855W	Anderson's Homeowner's Association	MIS	50 72 23 NE NW	20	1,050	910	955	YES	TTL
P39337W	Bossard, Mark A.	DOM IRR	50 72 23 NE NW	10	252	198	238	YES	WAS
P41941W	Lang, Tom J. and R. Deann	DOM	50 72 23 NE NW	25	380	270	360	YES	COL
P60759W	Record, James R. and Marvis C.	DOM	50 72 23 NE NW	16	384	290	340	YES	COL
P29334W	Mosley, Bob L.	DOM	50 72 23 NE SE	8	322	--	--	YES	COL
P27033W	Anderson Subdivision Homeowners	MIS	50 72 23 NW NE	45	1,270	420	540	YES	TTL
P58354W	Hopkins, William R. and Ella J.	DOM	50 72 23 NW NE	3	120	40	46	YES	WAS
P45223W	Hicks, Alva L. and Virginia L.	DOM	50 72 23 NW NW	25	491	359	450	YES	COL
P29411W	Tri-County Electric Association	MIS	50 72 24 SE SE	10	770	--	--	YES	UNK
P33465W	Interstate Industrial Park	MIS	50 72 24 SE SE	50	1,140	--	--	YES	TTL
P8731P	Shippy, Mary E.	DOM STO	50 72 25 NE SW	20	205	175	198	YES	WAS
P18029P	Landers, Leland R. and Gladys P.	DOM STO	50 72 25 NW NE	25	140	100	140	YES	WAS
P19785P	Gillette Ag. Substation	DOM STO	50 72 25 NW NE	12	260	240	260	YES	TTL
P40405W	Boatright - Smith	IND MIS	50 72 25 NW NW	125	1,230	400	1,230	YES	TTL
P27919W	Johnson, Gary W.	DOM	50 72 26 NW NW	7	118	85	115	YES	WAS
P12484W	Campbell County School District	IRR	50 72 26 NW SW	100	275	80	175	YES	WAS
P16606P	Boden, Glen H. and Janette May	DOM	50 72 26 NW SW	12	155	--	--	NO	WAS
P912W	Wenckus, Stanley and Dorothie	DOM	50 72 26 SE NW	100	1,242	542	--	YES	TTL
P895W	Ostlund, Axel R.	DOM STO	50 72 26 SW NE	10	280	240	--	YES	COL
P40510W	Campbell County School District	MIS	50 72 26 SW SW	200	397	150	397	YES	WAS
P477W	Tanner, Joseph	DOM	50 72 27 NE NE	15	105	80	--	YES	WAS
P4967W	Butler, Eileen	DOM	50 72 27 NE NW	10	200	130	195	YES	WAS
P1220W	City of Gillette	MUN	50 72 27 NE SW	90	500	300	--	NO	WAS
P1221W	City of Gillette	MUN	50 72 27 NE SW	80	500	300	--	NO	WAS
P2237W	Campbell County Cemetery District	IRR	50 72 27 NE SW	60	390	220	320	YES	WAS
P2239W	Campbell County Cemetery District	IRR	50 72 27 NE SW	60	300	170	290	YES	WAS
P52032W	Campbell County Cemetery District	MIS	50 72 27 NE SW	80	1,439	--	--	YES	TTL
P2721W	Williams, James L. and Helen M.	DOM	50 72 27 SE NE	20	190	85	160	YES	WAS
P3330P	Winland, William E.	DOM	50 72 27 SE NE	25	130	--	--	NO	WAS
P64269W	Bennett, William	DOM	50 72 27 SE NE	6	39	10	39	YES	WAS
P4072W	Campbell County Cemetery District	IRR	50 72 27 SW NE	130	252	130	245	YES	WAS
P2259W	Harwood Lumber Mart, Inc.	DOM IND	50 72 27 SW SW	100	171	90	65	YES	WAS
P36926W	Edelman, Anthony W. and Patricia	DOM	50 72 27 SW SW	25	450	425	445	NO	UNK
P8411W	Wagensen and Hayden	STO	50 72 28 NE SE	17	485	460	470	YES	TTL
P3350W	North Central Nursing	IRR	50 72 28 NW NE	55	232	120	232	YES	WAS
P34640W	Pioneer Manor	MIS	50 72 28 NW NE	60	334	90	325	YES	WAS
P42003W	City of Gillette	MUN	50 72 28 NW NE	80	382	--	--	YES	WAS
P26959W	Johnson, Warren	DOM STO	50 72 28 NW NW	1	190	150	190	YES	WAS
P53964W	Baker, Edwin W., Jr.	MIS	50 72 28 NW SW	10	337	197	337	YES	WAS
P51353W	Rocky Mountain Machinery Co.	MIS	50 72 28 SE NW	20	1,070	--	--	YES	TTL
P18671W	Newton, Lee	DOM STO	50 72 29 NE NE	20	1,196	1,075	1,165	YES	TTL
P49801W	Wyorco	MIS	50 72 29 NW SW	200	1,765	1,200	1,630	YES	TTL
P32660W	Sullivan, Jesse E. and Gwendolyn	MIS	50 72 30 NW NW	50	1,040	940	960	YES	TTL
P49802W	Wyorco	MIS	50 72 30 NW SW	160	1,785	890	1,660	YES	TTL
P65803W	Jeffress, Ronald	DOM	50 72 32 NE SE	8	110	93	110	YES	WAS
P67812W	Reardon, Michael J. and Joleen	DOM	50 72 32 NE SE	25	120	110	120	YES	WAS
P37169W	Westridge Sub. Landowner's Association	MIS	50 72 32 NW SE	100	1,250	838	1,231	YES	TTL
P65036W	Tarno, Melvin E.	DOM	50 72 32 NW SE	15	220	140	220	YES	WAS
P7115P	Doud, Russell	STO	50 72 32 SW NE	25	200	--	--	NO	WAS

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydrogeologic unit
P10606W	Rist, Severt R.	DOM	50 72 33 NE SW	0	342	300	342	YES	WAS
P24603W	Westridge Water Users Association	MIS	50 72 33 NE SW	109	1,360	1,130	1,274	YES	TTL
P46017W	Westridge Water Users Association	MIS	50 72 33 NE SW	45	1,186	1,120	1,180	YES	WAS
P68021W	Ferrill, Gerald R. and Barbara	DOM	50 72 33 NE SW	10	240	208	233	YES	WAS
P68141W	Campbell, Jim	DOM	50 72 33 NE SW	5	140	110	123	YES	WAS
P9251W	Ellison, Claude L.	DOM	50 72 33 NW SE	10	327	260	320	YES	WAS
P53414W	Spomer, C. James or Carlene	DOM	50 72 33 NW SW	20	290	90	290	YES	WAS
P65042W	Orr, Stephen S. and Donna Gail	DOM	50 72 33 NW SW	12	200	165	198	YES	WAS
P65109W	Visser, Douglss L. and Lee R.	DOM	50 72 33 NW SW	15	200	170	198	YES	WAS
P14224W	Westridge Water Users Association	DOM	50 72 33 SE SW	30	1,186	1,120	1,180	YES	TTL
P71149W	Vomhof, Dean and Cheryl	DOM	50 72 33 SE SW		306	200	300	NO	WAS
P41831W	City of Gillette	MIS	50 72 33 SW NE	130	1,720	1,062	1,706	YES	TTL
P41830W	City of Gillette	MUN	50 72 33 SW SE	140	1,732	--	--	YES	TTL
P11026W	Cook, Glen E.	DOM	50 72 33 SW SW	15	322	280	320	YES	WAS
P53039W	Ochs, Archie and Dorothy	DOM	50 72 33 SW SW	10	220	180	215	YES	WAS
P2402W	Carson, Robert T. and Frances J.	MIS	50 72 34 NE NE	32	1,112	1,005	1,070	YES	TTL
P2403W	Carson, Robert T. and Frances J.	MIS	50 72 34 NE NE	32	1,106	1,005	1,070	YES	TTL
P24601W	Rucker Acme Tool	COM	50 72 34 NE NE	10	1,130	1,006	1,016	NO	TTL
P2827W	Morfeld, James J.	DOM	50 72 34 NE NE	3	85	--	--	NO	WAS
P371W	Wyoming Game and Fish Commission	MIS	50 72 34 NE SE	250	398	26	--	YES	COL
P2905W	Western Paving Construction Co.	IND MIS	50 72 34 NE SW	330	285	110	270	YES	WAS
P2906W	Western Paving Construction Co.	IND MIS	50 72 34 NE SW	330	280	110	280	YES	WAS
P35419P	MJB Investments	DOM STO	50 72 34 NW NE	3	96	--	--	NO	WAS
P42006W	City of Gillette	MUN	50 72 34 NW NW	125	2,323	1,055	1,690	NO	TTL
P42007W	City of Gillette	MUN	50 72 34 NW NW	125	2,295	1,031	2,295	NO	TTL
P3105W	Ruby Drilling Co., Inc.	DOM MIS	50 72 34 NW SW	75	1,231	1,080	1,125	YES	TTL
P6020W	Black Hills Oil Marketers, Inc.	MIS	50 72 34 NW SW	30	1,218	1,080	1,130	YES	TTL
P2812W	Coltrane, Charles L. and Patricia	DOM	50 72 34 SE NE	25	1,258	1,052	1,062	NO	TTL
P6862W	Anschutz Corporation, Inc.	MIS	50 72 34 SE NE	20	1,129	1,006	1,022	YES	TTL
P26186W	City of Gillette	MIS	50 72 34 SE SE	250	258	131	258	YES	WAS
P6740W	Lee, William D. and Thelma L.	MIS	50 72 34 SW NE	30	1,100	950	1,080	YES	TTL
P2599W	Bird, Betty	MIS	50 72 34 SW SE	60	1,210	--	--	NO	TTL
P31327W	Four Way Company, Inc.	MIS	50 72 34 SW SE	17	1,091	995	1,091	YES	TTL
P67815W	Mollman, Wayne	DOM	50 72 34 SW SE	8	250	110	250	YES	WAS
P36173W	Wright, Robert E., Mrs.	DOM	50 72 35 NE NW	25	1,160	1,025	1,160	YES	TTL
P18162P	Edwards, Joe	DOM	50 72 35 NE SW	3	460	--	--	NO	UNK
P18163P	Edwards, Joe	DOM	50 72 35 NE SW	10	128	--	--	NO	WAS
P43347W	Bell, Melvin A. and Doris R.	DOM	50 72 35 NW NW	15	322	265	310	YES	WAS
P32249W	Edwards, Harold L.	DOM STO	50 72 35 NW SW	12	512	294	330	YES	WAS
P48497W	Edwards, Arlene M.	DOM STO	50 72 35 NW SW	15	741	540	590	YES	TTL
P4973W	Cosner, Harlie E.	DOM	50 72 35 NW SW	10	415	290	385	YES	COL
P4002W	Gillette Golf and Country Club	MIS	50 72 35 SE NE	25	320	230	300	YES	COL
P34787W	McGuire, John C.	DOM	50 72 35 SE NW	20	1,170	975	1,122	YES	TTL
P2123W	Gillette Golf and Country Club	DOM IRR	50 72 35 SE SE	250	305	50	150	YES	WAS
P28936P	Pickrel Land and Cattle Co.	STO	50 72 36 NW SE	5	150	40	60	YES	COL
P68017W	Younkin	DOM STO	50 73 05 SE SW	15	460	415	450	YES	WAS
P5087P	Barlow, Fred L. and Helen M.	STO	50 73 13 NE NE	4	358	--	--	YES	WAS
P38502W	McKenzie, James B.	STO	50 73 13 NE SE	5	348	280	335	YES	WAS
P66239W	Mayer, Ed snd Nancy	DOM	50 73 13 NW SE	20	1,060	1,005	1,025	YES	TTL

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P55899W	Edwards, Allan R.	DOM	50 73 14 NE NW	23	990	960	990	YES	UNK
P51861W	Horton, Margaret	DOM STO	50 73 14 NE SW	15	635	520	635	YES	WAS
P61175W	Gormly, James P. and Laurel J.	DOM	50 73 14 NW SW	12	660	620	640	YES	WAS
P37369W	Adams, James L. and Janet L.	DOM	50 73 14 SW SW	10	629	--	--	YES	WAS
P64176W	Angerhofer, Rick	DOM STO	50 73 15 NE NE	12	355	230	335	YES	WAS
P64354W	Savocchio, Joe and Sandra	MIS	50 73 15 NE NE	22	1,117	--	--	YES	TTL
P52383W	Cooper, Bob Gene	DOM STO	50 73 15 NE SE	20	600	--	--	NO	UNK
P55649W	Yoctorowic, Clarence	DOM STO	50 73 15 NE SW	25	400	--	--	YES	WAS
P60452W	Anderson, Mark W.	DOM STO	50 73 15 SE SE	25	720	685	710	NO	WAS
P65209W	Kramer, Elisabeth	DOM	50 73 15 SE SW	25	1,070	980	1,070	YES	TTL
P3590W	Hines, Annie M.	STO	50 73 15 SW NW	25	335	95	300	YES	WAS
P59041W	Brose, Bradley O. and Patricia D.	DOM	50 73 22 NW NE	12	720	--	--	YES	WAS
P57921W	Clough, Marlene Sue	DOM	50 73 23 NE NW	10	397	345	377	YES	WAS
P64853W	Kramer, Elisabeth	DOM	50 73 23 NE NW	20	1,070	915	1,032	YES	TTL
P59174W	Chase, Clinton Odell	DOM	50 73 23 NE SE	20	615	570	610	YES	WAS
P64807W	Kalious, Janice Colleen	DOM	50 73 23 NE SE	11	240	240	300	YES	WAS
P35052W	Casady, Roy Carlos, Jr.	DOM	50 73 23 NW SE	12	160	152	158	NO	WAS
P71443W	Fitzner, Howard and Pamela	DOM	50 73 23 NW SE	10	400	330	400	YES	WAS
P56132W	Hettinger, Betty and Dale	DOM STO	50 73 23 SE NW	25	424	--	--	YES	WAS
P63837W	Harrold, Michael D.	DOM	50 73 23 SE SW	8	300	260	300	YES	WAS
P67276W	Scott, Douglas C. and Susan C.	DOM	50 73 23 SE SW	6	455	340	450	YES	WAS
P61079W	Waggener, Lloyd Nelson and Yvonne	DOM STO	50 73 24 SW NE	25	590	510	590	YES	WAS
P64843W	Uttenhove, Walter R.	DOM	50 73 26 NE NW	25	340	303	340	YES	WAS
P65103W	Neeman, Robert B.	DOM	50 73 26 NE NW	7	445	380	425	YES	WAS
P3824W	Hines, John J.	STO	50 73 27 NE NE	6	295	250	290	YES	WAS
P55095W	Hines, John J.	STO	50 73 27 NE NE	25	501	385	501	YES	TTL
P55160W	Hines, John J.	MIS	50 73 27 NE NE	25	501	385	501	YES	TTL
P23841P	Greer, William E.	STO	49 70 31 SE NW	25	24	--	--	NO	UNK
P987W	Baumfalk, Minnie L.	IND	49 71 01 NE SW	27	860	770	--	YES	TTL
P61443W	Thar, Rochelle K.	DOM STO	49 71 02 NE SE	25	595	525	575	YES	TTL
P10019W	Chamberlain, Daniel R.	STO	49 71 02 NW NW	3	160	88	145	YES	COL
P37780W	Chamberlain, Daniel R.	DOM STO	49 71 02 NW NW	25	711	--	--	NO	TTL
P20562W	Chamberlain, Daniel R.	STO	49 71 02 NW SE	7	92	50	70	YES	COL
P14631P	Dewing, Earl	DOM STO	49 71 07 SE SW	17	90	--	--	NO	WAS
P28933P	Pickrel Land and Cattle Co.	STO	49 71 08 NE NE	5	279	--	--	YES	TTL
P53469W	Sleepy Hollow Homeowners Association	MIS	49 71 08 SW SW	69	1,164	--	--	NO	TTL
P28935P	Pickrel Land and Cattle Co.	STO	49 71 10 NW NE	5	195	160	190	YES	COL
P30593W	Olsen, Bobby Chris and Mary E.	DOM STO	49 71 11 NW NE	1	370	265	--	YES	UNK
P32142W	Olsen, Bob and Mary	STO	49 71 11 NW NE	25	643	543	630	YES	TTL
P60349W	Prenalta Corporation	IND	49 71 12 NW NW	23	2,958	2,660	2,900	YES	TTL
P25831W	Wolff, William Edward	IRR STO	49 71 14 NE SW	100	500	380	500	YES	TTL
P42984W	Sleepy Hollow Homeowners Association	MIS	49 71 17 NW NW	100	1,180	762	805	YES	TTL
P69562W	Sleepy Hollow Homeowners Association	MIS	49 71 17 NW NW	140	1,473	910	1,445	YES	TTL
P11675W	Japp, Elsie	STO	49 71 17 SE NE	5	228	145	209	YES	WAS
P11674P	Japp, Elsie	STO	49 71 17 SE SE	7	105	52	105	YES	WAS
P35465W	Japp, Elsie	STO	49 71 17 SE SE	5	424	360	409	YES	TTL
P31456W	Wolff, Harry L.	DOM STO	49 71 18 SE SW	12	530	495	530	YES	TTL
P47059W	Wolff, Harry L.	STO	49 71 19 NW NE	10	224	195	224	YES	WAS
P11673P	Wolff, Harry L.	STO	49 71 20 NE SW	2	161	--	--	NO	WAS

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P31475W	Wolff, Ed	DOM STO	49 71 22 SE SE	25	930	844	905	YES	TTL
P35880W	Johnson, Jerry	DOM	49 71 23 NE NE	10	824	--	--	YES	TTL
P50825W	Johnson, Jerry	DOM	49 71 23 NE NE	15	824	--	--	YES	TTL
P53049W	Todd, Warren K.	DOM	49 71 23 NE SW	5	87	15	40	YES	WAS
P40476W	Harris, Charles G.	DOM MIS	49 71 23 NW SE	15	450	40	160	YES	UNK
P40822W	Olson, Lawrence G. and Ethel	DOM MIS	49 71 23 NW SE	15	683	650	670	YES	TTL
P49091W	Olson, Lawrence G. and Ethel	STO	49 71 23 NW SE	0	683	650	670	YES	TTL
P53047W	Harris, Charles Gilbert	DOM	49 71 23 NW SE	14	75	48	27	YES	WAS
P43209W	Bolton, Claire, Mr. and Mrs.	DOM STO	49 71 23 NW SW	10	106	--	--	YES	WAS
P58382W	Todd, Gregory W.	DOM	49 71 23 SE SW	6	86	40	60	YES	WAS
P36652W	Carter, Edna L.	DOM STO	49 71 24 NW SW	25	500	500	625	YES	TTL
P60754W	Greer, Olen C.	STO	49 71 25 NW SW	15	130	100	130	YES	COL
P65750W	Fortner, Berton David	DOM STO	49 71 25 NW SW	10	160	79	160	YES	WAS
P13075P	Wolff, Donald L. and Dorothy A.	STO	49 71 25 SW SE	5	120	40	120	YES	WAS
P53291W	Pierce, Paul and Marsha	DOM	49 71 26 NE NE	9	100	--	--	YES	WAS
P41889W	Foyen, James R.	DOM	49 71 26 NE NW	10	160	--	--	YES	WAS
P37957W	Mickelsons Little Farms Water	MIS	49 71 26 NE SW	100	1,300	1,190	1,281	YES	TTL
P52304W	Webb, Robert A. and Jamie L.	MIS	49 71 26 NE SW	225	1,500	1,200	1,470	YES	TTL
P13077P	Wolff, Donald L. and Dorothy A.	DOM	49 71 26 SW SE	3	307	280	307	YES	WAS
P15390W	Wolff, Donald L. and Dorothy A.	DOM STO	49 71 26 SW SE	20	692	650	680	YES	TTL
P18197P	Rourke, James F.	STO	49 71 28 SE NW	2	130	--	--	NO	WAS
P36417W	Rourke, James F.	IND	49 71 29 SW NE	75	1,210	975	1,063	YES	TTL
P18195P	Rourke, James F.	STO	49 71 29 SW SE	3	120	--	--	NO	WAS
P18196P	Rourke, James F.	DOM	49 71 29 SW SE	4	280	--	--	NO	UNK
P25836W	Campbell County School District	MIS	49 71 30 NE SW	35	212	212	--	YES	WAS
P10599P	Robbins, Placide	STO	49 71 30 NW SE	7	--	--	--	NO	UNK
P18199P	Rourke, James F.	DOM STO	49 71 30 SE SE	2	150	--	--	NO	WAS
P27119W	Greer, William E.	STO	49 71 30 SW NW	150	288	255	270	YES	WAS
P58231W	Rourke, James F.	STO	49 71 31 SE NE	20	256	160	250	YES	WAS
P19817P	Chaney, Thelma M.	DOM	49 71 31 SE NW	3	65	--	--	NO	WAS
P19818P	Chaney, Thelma M.	STO	49 71 31 SE NW	1	85	--	--	NO	WAS
P19816P	Chaney, Thelma M.	STO	49 71 31 SW NW	10	135	--	--	NO	WAS
P13080P	Wolff, Donald L. and Dorothy A.	STO	49 71 34 NW NE	5	165	140	165	YES	WAS
P13079P	Wolff, Donald L. and Dorothy A.	STO	49 71 35 NE SE	4	300	100	255	YES	COL
P23839P	Greer, Olen C.	STO	49 71 36 SW NE	10	50	--	--	NO	UNK
P21909W	Edwards, Carl M.	DOM STO	49 72 02 NE SW	25	505	380	505	YES	COL
P32526W	Henle, Dennis	DOM	49 72 02 NW SE	16	100	--	--	NO	WAS
P14233W	Heimann, John M.	DOM	49 72 02 SE SW	25	382	190	225	YES	WAS
P26009W	Rourke, James F.	DOM	49 72 02 SE SW	20	410	360	410	YES	WAS
P26795W	Frank, Marvin and Billie	MIS	49 72 02 SE SW	25	1,120	970	1,050	YES	TTL
P48535W	Knights of Columbus, 3477 Club	MIS	49 72 02 SE SW	15	400	300	380	YES	WAS
P4975W	King, Kent and Barbara	DOM	49 72 02 SE SW	25	211	140	211	YES	WAS
P5614W	Joslyn, Dean	DOM	49 72 02 SE SW	20	250	140	250	YES	WAS
P5724P	Frank, Billie and Marvin R.	STO	49 72 02 SE SW	15	120	--	--	NO	WAS
P27056W	Norman, William D.	MIS	49 72 02 SW SE	20	470	356	450	YES	COL
P14530P	Hitt, Harold L. and Mary Ruth	DOM STO	49 72 02 SW SW	10	207	--	--	NO	WAS
P1015W	Hoadley, J.E.	MUN	49 72 03 NE SE	15	200	165	--	NO	WAS
P1174W	Sunburst Water and Sewer District	DOM MIS	49 72 03 NE SE	25	540	470	540	YES	COL
P2559W	Sunburst Utility Corporation	MIS	49 72 03 NE SE	17	675	480	585	YES	TTL

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P29612W	Sunburst Water and Sewer District	MIS	49 72 03 NE SE	75	1,220	1,095	1,210	YES	WAS
P33037W	Kemerling, William R.	DOM STO	49 72 03 NW NE	25	1,220	1,090	1,120	YES	TTL
P44340W	O.N.O. Investments	MIS	49 72 03 NW NE	5	1,088	965	994	YES	TTL
P14694W	Nepstad, Marlan	MIS	49 72 03 SW NE	100	1,211	--	--	YES	WAS
P4589W	Reding, Burr, Jr.	DOM	49 72 03 SW NE	18	200	150	200	YES	WAS
P49254W	Knigge, Wayne and Alice	DOM	49 72 03 SW NE	20	220	90	210	YES	WAS
P59490W	Reding, Burr, Jr.	DOM STO	49 72 03 SW NE	18	560	486	540	YES	WAS
P23822P	Saunders, R.D.	STO	49 72 04 NE NE	20	300	--	--	NO	UNK
P23819P	Saunders, R.D.	DOM	49 72 04 NE NW	20	1,250	--	--	NO	TTL
P23821P	Saunders, R.D.	DOM	49 72 04 NW NE	20	250	--	--	NO	UNK
P27647W	Decker, Gary and Lynda	DOM	49 72 04 NW NW	25	1,060	--	--	YES	TTL
P33042W	Porter, William	DOM	49 72 04 NW NW	7	1,020	940	1,000	YES	TTL
P20523W	Edwards, Robert E.	DOM	49 72 05 NE NE	20	403	340	395	YES	WAS
P30949W	Marsh, Greg and Bev	DOM STO	49 72 05 NE NE	17	373	320	360	YES	WAS
P35989W	Edwards, Gerald	DOM STO	49 72 05 NE NE	20	245	190	240	NO	WAS
P39105W	Taylor, Jack and Susan	DOM	49 72 05 NE NE	10	385	295	345	YES	WAS
P39670W	Shane, Jerry Lloyd	DOM	49 72 05 NE NE	25	370	305	360	YES	WAS
P50701W	Edwards, Robert E. and Theo	DOM	49 72 05 NE NE	25	380	300	368	YES	WAS
P6106W	Bertoncel, J. Peter	DOM	49 72 05 NE NE	20	252	135	250	YES	WAS
P30471W	Coulter, Darrell R.	DOM	49 72 05 NE NW	15	1,180	1,060	1,160	YES	TTL
P30481W	Jones, Gerald W.	DOM	49 72 05 NE NW	25	399	310	370	YES	WAS
P53364W	Glover, Dewey	DOM	49 72 05 NE NW	10	1,180	950	1,148	YES	TTL
P31215W	Palmer, Melvin D.	DOM	49 72 05 NE SE	16	415	386	408	NO	UNK
P30799W	Exley, Byron L. and Catherine M.	DOM	49 72 05 NE SW	10	200	65	200	YES	WAS
P23820P	Saunders, R.D.	STO	49 72 05 NW NE	20	250	--	--	NO	UNK
P26519W	Suedkamp, William	DOM	49 72 05 NW NE	7	392	200	255	YES	WAS
P34329W	Dague, Kenneth C.	DOM STO	49 72 05 NW NE	20	100	60	80	YES	WAS
P21835W	Johnson, Arthur R. and Myrtle A.	DOM STO	49 72 05 NW SE	25	175	140	175	YES	WAS
P24762W	Burgess, Dean	DOM	49 72 05 NW SE	3	255	205	255	YES	WAS
P29440W	Baity, Robert E.	DOM	49 72 05 NW SE	20	150	130	150	YES	WAS
P34459W	Matheson, Trusty	DOM	49 72 05 NW SE	18	470	330	470	YES	WAS
P61229W	Harr, Robert and Deborah	DOM	49 72 05 NW SE	18	340	220	260	YES	WAS
P26442W	Williams, E. Dean and Earlene	DOM	49 72 05 NW SW	20	357	265	315	YES	WAS
P23225W	Manion, Roland and Mary	DOM	49 72 05 SE NE	3	150	100	143	YES	WAS
P28033W	Meyers, Joseph L., Mr. and Mrs.	DOM	49 72 05 SE NE	25	370	--	--	YES	WAS
P29569W	Cosner, Ted R.	DOM	49 72 05 SE NE	10	287	--	--	YES	WAS
P33985W	Ward, James A.	DOM	49 72 05 SE NE	25	383	318	365	YES	WAS
P35049W	Craft, Howard E.	DOM	49 72 05 SE NE	10	386	315	370	YES	WAS
P65281W	Carson, Dennis	DOM	49 72 05 SE NE	10	395	325	395	YES	WAS
P16749W	Lynn, Marquis L. and Freda J.	DOM STO	49 72 05 SE NW	18	380	320	370	YES	WAS
P4832P	Lynn, Marquis L. and Freda J.	DOM STO	49 72 05 SE NW	3	75	--	--	NO	WAS
P22721W	Cook, Glen E. and Dorothy	DOM	49 72 05 SE SE	10	180	100	170	YES	WAS
P26291W	McCurley, Doyle and Karan	DOM	49 72 05 SE SE	5	400	320	360	NO	WAS
P33966W	Billingsley, Jay C. and Debrah L.	DOM STO	49 72 05 SE SE	20	520	370	400	YES	UNK
P61141W	Fuchs, Gary and Linda	DOM	49 72 05 SE SE	4	415	350	400	YES	WAS
P23204W	Spangler, William J.	DOM	49 72 05 SE SW	20	140	60	130	YES	WAS
P31786W	Bayles, Ralph W., Jr. and Judith	DOM	49 72 05 SW NE	15	400	330	375	YES	WAS
P32336W	Evans, James A.	DOM	49 72 05 SW NE	15	430	350	430	YES	WAS
P45914W	D.H. and S. Water Users	DOM	49 72 05 SW NE	25	1,002	--	--	NO	TTL

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P65035W	Ashkannejhad, Ahmad and Donna	DOM	49 72 05 SW NE	25	225	165	220	YES	WAS
P22756W	Nord, Finn E.	DOM	49 72 05 SW SE	5	220	140	175	YES	WAS
P35172W	Swetich, Dan or Carolyn	DOM	49 72 05 SW SE	15	390	316	390	YES	WAS
P30209W	Hedlund, Ron R.	MIS	49 72 06 NW SE	100	1,420	--	--	NO	WAS
P1245W	Gregersen, Oluf, Jr.	STO	49 72 06 SE NE	40	130	75	--	YES	WAS
P49067W	Hidden Valley Homeowners	MIS	49 72 06 SE NE	80	1,320	1,209	1,260	YES	TTL
P15864W	Gregersen, Oluf, Mrs.	STO	49 72 06 SW SW	20	215	20	150	YES	WAS
P56602W	Sundog Homeowners Association	MIS	49 72 06 SW SW	90	1,520	1,000	1,420	YES	TTL
P29916W	Sundog Homeowners Association	MIS	49 72 07 NW NW	3	1,150	998	1,030	YES	WAS
P20309W	Doud, Russell	STO	49 72 07 NW SE	10	215	140	190	YES	WAS
P64224W	Matheson, Trusty	MIS	49 72 08 NE NE	20	460	390	460	YES	WAS
P34319W	Gentry, Harry C.	DOM	49 72 08 NW SE	25	1,420	--	--	YES	TTL
P37885W	Sneathen, Charles and Virginia	DOM	49 72 09 NE SE	12	335	270	335	YES	WAS
P37999W	Lodahl, Einar	DOM STO	49 72 09 NW SW	15	455	355	450	YES	WAS
P18756P	Meserve, James	STO	49 72 10 NW SW	8	340	--	--	NO	UNK
P43664W	Wyoming Machinery, Inc.	MIS	49 72 11 NE NE	25	1,215	1,070	1,180	YES	TTL
P45204W	Creative Construction, Inc.	MIS STO	49 72 11 NE SE	25	240	--	--	NO	UNK
P58276W	Hanson, Marvin	DOM	49 72 11 NE SE	10	396	353	396	YES	WAS
P37109W	Winland, William E.	MIS	49 72 11 NW NE	25	206	150	180	YES	WAS
P61523W	Winland Enterprises, Inc.	MIS	49 72 11 NW NE	50	1,190	881	1,052	YES	TTL
P45636W	Custer, Charles D. and Nora J.	DOM	49 72 11 NW SE	25	288	--	--	YES	WAS
P63033W	Kuntz, Lawrence A.	MIS STO	49 72 11 NW SE	25	300	230	290	YES	WAS
P65900W	Ness, Charles R.	DOM STO	49 72 11 NW SE	25	1,160	1,020	1,080	YES	TTL
P42770W	Knutson, Roy E.	DOM MIS	49 72 11 NW SW	6	288	240	268	YES	WAS
P2977P	Mohan, Edith M.	DOM STO	49 72 11 SW NE	9	130	--	--	NO	WAS
P38536W	Crude Company	MIS	49 72 11 SW NE	2	1,210	1,005	1,210	YES	TTL
P6349P	Edwards, James A.	DOM	49 72 12 SE SW	26	1,108	--	--	YES	TTL
P47709W	Japp, John E.	DOM STO	49 72 12 SW NW	8	129	95	125	YES	WAS
P56901W	Anderson, Jimmy L. and Carol A.	MIS	49 72 13 NE NW	200	1,550	1,077	1,508	YES	TTL
P52639W	Steinhoefel Ranch	STO	49 72 13 NW NE	7	140	--	--	YES	WAS
P64375W	Antelope Valley Homeowners'	MIS	49 72 13 NW SW	250	2,130	1,330	2,020	YES	TTL
P64374W	Antelope Valley Homeowners'	MIS	49 72 13 SE SW	190	1,672	980	1,660	YES	TTL
P37361W	Antelope Valley Homeowners'	MIS	49 72 13 SW SW	100	1,305	1,012	1,270	NO	TTL
P69609W	Heimer, Scott A.	DOM	49 72 13 SW SW	18	350	251	333	YES	WAS
P20020P	Swanson, Leonard C.	DOM STO	49 72 14 NW NW	12	234	201	234	YES	WAS
P10601P	Robbins, Placide	STO	49 72 14 SE NW	17	200	138	188	YES	WAS
P20021P	Swanson, Leonard C. and Merna	STO	49 72 14 SW SW	4	234	201	234	YES	WAS
P23823P	Saunders, R.D.	STO	49 72 16 NW NE	20	300	--	--	NO	UNK
P21540P	Milne, Raymond	STO	49 72 17 SE NW	10	227	170	227	YES	WAS
P21541P	Milne, Raymond	STO	49 72 19 NE NE	15	480	425	480	YES	WAS
P21539P	Milne, Raymond	DOM STO	49 72 20 SW NW	25	400	--	--	NO	WAS
P18755P	Meserve, James	STO	49 72 21 NE NE	10	150	--	--	NO	WAS
P65726W	Meserve, James B.	DOM MIS STO	49 72 21 NE NE	100	1,475	960	1,475	YES	TTL
P18757P	Meserve, James	STO	49 72 21 NE SW	3	250	210	250	YES	WAS
P20019W	Swanson, Leonard C.	STO	49 72 23 SW SW	12	194	151	194	YES	WAS
P61346W	Wolff, Harry L.	MIS	49 72 24 NE NE	25	920	656	835	YES	TTL
P52226W	Gould, Robert C.	DOM	49 72 24 NE NW	20	388	312	386	YES	WAS
P67659W	Wolff, James A.	DOM MIS STO	49 72 24 NE SE	25	300	80	222	YES	WAS
P69041W	Wolff, James A.	MIS	49 72 24 NE SE	21	232	75	224	YES	WAS

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P57941W	Lindgren, Theodore W. and Rita M.	DOM	49 72 24 NW NE	10	400	340	400	YES	WAS
P64804W	Mosley, Bob L.	DOM MIS	49 72 24 SE SE	25	1,550	1,230	1,260	YES	TTL
P10598P	Robbins, Placide	STO	49 72 25 NW SE	17	180	--	--	NO	WAS
P66877W	Wolff Land Company Trust	MIS STO	49 72 26 SE SE	16	760	170	320	YES	COL
P16049P	McCreery, Robert P.	STO	49 72 27 NE SE	5	303	270	300	YES	WAS
P21542P	Milne, Raymond	STO	49 72 30 SE SE	15	250	196	250	YES	WAS
P18754P	Meserve, James	STO	49 72 33 NW NW	9	190	160	190	YES	WAS
P16050P	McCreery, Robert P.	STO	49 72 33 SE SW	5	203	160	190	YES	WAS
P16052P	McCreery, Robert P.	STO	49 72 34 SW NE	1	40	--	--	NO	WAS
P16051P	McCreery, Robert P.	STO	49 72 35 NW SW	5	170	--	--	NO	WAS
P16047P	McCreery, Robert P.	STO	49 72 35 SE SW	5	110	--	--	NO	WAS
P16048P	McCreery, Robert P.	DOM	49 72 35 SE SW	4	165	--	--	NO	WAS
P31474W	Gregerson, Oluf	STO	49 73 01 SW SW	25	320	235	295	YES	WAS
P3014P	Barlow, Henry L.	STO	49 73 02 SE NW	15	80	--	--	NO	WAS
P57603W	Sun Agency, Inc.	MIS	49 73 12 NE NE	80	1,530	1,050	1,500	YES	TTL
P2590W	Gregersen, Janice C.	STO	49 73 12 NW SW	10	176	165	176	YES	WAS
P65329W	Ratcliff, Sam R.	DOM STO	49 73 13 SE SW	25	1,194	670	1,175	YES	TTL
P23197W	Mankin, John A.	STO	49 73 23 NE SE	5	335	280	330	YES	WAS
P65279W	Smith, Conley P.	IND	48 70 07 SW SW	22	3,876	3,736	3,830	YES	TTL
P15605W	McGee, John E.	DOM STO	48 70 08 NE SW	2	410	353	365	YES	TTL
P57727W	Exxon Coal USA, Inc.	DOM STO	48 70 08 NW SE	25	475	438	455	NO	TTL
P18144P	Clark, Melvin D. and Ethel L.	STO	48 70 17 SW NW	5	300	275	300	YES	WAS
P23837P	Greer, Olen C.	STO	48 71 01 NE NW	15	343	240	260	NO	UNK
P773G	J. Mill Iron Land Co.	IRR STO	48 71 01 NE SE	350	215	--	--	NO	UNK
P23838P	Greer, Olen C.	STO	48 71 01 SE NE	10	300	--	--	NO	UNK
P20299W	Wolff, Donald L. and Dorothy M.	STO	48 71 01 SW NW	4	68	45	56	YES	WAS
P23840P	Greer, Olen C.	STO	48 71 01 SW SW	10	50	--	--	NO	UNK
P18774P	Clark, Morris A.	DOM STO	48 71 02 NE SE	10	110	--	--	NO	UNK
P32695W	Greer, Olen C.	DOM STO	48 71 02 NE SW	17	304	285	304	YES	UNK
P50992W	Cundy, Arthur	IND STO	48 71 02 SE NW	18	1,100	1,045	1,100	YES	TTL
P18143P	Clark, Melvin D. and Ethel L.	STO	48 71 02 SW SE	4	225	200	225	YES	COL
P57959W	Elmore Livestock Company	STO	48 71 03 NE SW	--	260	160	240	YES	COL
P57957W	Elmore Livestock Company	STO	48 71 03 NW NW	25	20	5	10	YES	WAS
P16959P	Cassidy, James H.	STO	48 71 03 SE NW	7	300	--	--	NO	UNK
P52571W	Exxon Coal USA, Inc.	DOM STO	48 71 03 SE SE	10	295	203	222	YES	TTL
P69169W	Elmore Livestock Company	STO	48 71 04 NE SW	--	160	80	140	YES	WAS
P16961P	Cassidy, James H.	STO	48 71 05 NE SW	10	300	--	--	NO	UNK
P28296W	Moncrief, W.A.	IND	48 71 06 NW SE	100	4,480	9	--	YES	TTL
P10600P	Robbins, Placide	STO	48 71 06 NW SW	17	180	--	--	NO	WAS
P65807W	Blackford, Kirk and Teresa	STO	48 71 06 SW NW	5	780	720	760	YES	TTL
P67809W	Bertalot, Kenneth K. and Angela M.	DOM	48 71 07 NW SW	10	200	160	200	YES	WAS
P66663W	Johnson, Steven E. and Debora R.	DOM	48 71 07 SW NW	15	310	263	290	YES	WAS
P16960P	Cassidy, James H.	STO	48 71 09 NW SW	10	300	--	--	NO	UNK
P18142P	Clark, Melvin D. and Ethel L.	STO	48 71 09 SW SW	10	80	4	80	YES	WAS
P18139P	Clark, Melvin D. and Ethel L.	STO	48 71 11 NW SW	5	170	100	170	YES	COL
P18140P	Clark, Melvin D. and Ethel L.	DOM	48 71 11 NW SW	10	170	100	170	YES	COL
P18141P	Clark, Melvin D. and Ethel L.	STO	48 71 11 SW SW	5	30	20	30	YES	UNK
P1815W	Czapla, T.W. and Herma L.	DOM	48 71 12 SW NW	2	255	245	255	YES	COL

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P1816W	Czapla, T.W. and Herma L.	DOM STO	48 71 12 SW NW	4	270	260	267	YES	COL
P18773P	Clark, Morris A.	STO	48 71 15 NE NE	10	165	--	--	NO	UNK
P3582W	Robb, Howard Ray	DOM STO	48 71 17 NE NE	10	276	188	260	YES	COL
P23436P	Dunlap, Richard O.	STO	48 71 19 SE NE	25	250	--	--	NO	UNK
P39054W	Campbell County Concrete, Inc.	MIS	48 71 21 NE NE	60	108	65	105	YES	TTL
P18096P	Mitchum, Eileen	STO	48 71 21 NW NE	2	60	--	--	NO	UNK
P18097P	Foley, Joe	STO	48 71 21 SW NE	2	130	--	--	NO	WAS
P5509P	Clabaugh, Leslie	STO	48 71 26 SW SW	10	10	--	--	YES	WAS
P5511P	Clabaugh, Leslie	STO	48 71 28 NW SE	5	130	--	--	YES	WAS
P5510P	Clsbaugh, Leslie	STO	48 71 29 NE NE	4	65	--	--	NO	WAS
P23439P	Dunlap, Richard O.	STO	48 71 29 SW SW	25	120	--	--	NO	UNK
P23437P	Dunlap, Richard O.	DOM STO	48 71 31 NW NE	10	250	--	--	NO	UNK
P23438P	Dunlap, Richard O.	DOM STO	48 71 31 NW NE	25	120	--	--	NO	WAS
P5512P	Clabaugh, Leslie	DOM STO	48 71 33 SE SE	18	150	--	--	YES	COL
P5515P	Clabaugh, Leslie	STO	48 71 34 NW SW	10	114	--	--	YES	COL
P44519W	Mesdowlark Farms, Inc.	STO	48 72 00 NE NW	5	320	161	208	YES	WAS
P10602P	Robbins, Placide	DOM	48 72 01 NE NE	10	60	--	--	NO	WAS
P16046P	McCreery, Robert P.	DOM STO	48 72 01 SE NW	5	240	--	--	NO	UNK
P17457W	McCreery, Robert P.	STO	48 72 03 NW NE	3	194	120	194	YES	WAS
P19219P	Appel, Leonard	STO	48 72 05 NE SW	4	140	--	--	NO	WAS
P13429W	Appel, Leonard T.	MIS RES STO	48 72 07 NW NE	100	147	70	140	YES	WAS
P19220P	Appel, Leonard	STO	48 72 09 SE NW	8	365	--	--	NO	WAS
P31074W	Appel, Leonard T.	STO	48 72 09 SE SW	15	145	110	135	YES	WAS
P60104W	Appel, Leonard T.	STO	48 72 09 SW SW	15	179	118	138	YES	WAS
P18198P	Rourke, James F.	STO	48 72 12 SE SE	2	130	--	--	NO	WAS
P23435P	Dunlap, Richard O.	STO	48 72 13 SE SE	25	206	160	206	YES	WAS
P54526W	Appel, Leonard T.	STO	48 72 14 SW NW	15	196	106	186	YES	WAS
P19222P	Appel, Leonard	STO	48 72 16 NW NW	5	15	--	--	NO	WAS
P19223P	Appel, Leonard	STO	48 72 16 SE SE	5	113	--	--	NO	WAS
P13429W	Appel, Leonard T.	MIS RES STO	48 72 17 SW NE	30	160	40	95	YES	WAS
P19221P	Appel, Leonard	STO	48 72 18 NW SE	4	135	--	--	NO	WAS
P70169W	I.W. and Lynde Trust	MIS STO	48 72 21 NW NE	200	245	50	230	YES	WAS
P64992W	Wyoming State Highway Department	MIS	48 72 25 NW SW	50	300	14	44	YES	WAS
P26012W	Morgan, Marshall Jerome	DOM	48 72 25 SE NW	15	190	165	180	YES	WAS
P29727W	Lawson, Robert W. and Beverly B.	DOM	48 72 25 SE NW	10	222	--	--	YES	WAS
P61463W	Morgan, Marshall Jerome	MIS STO	48 72 25 SE NW	15	180	155	180	YES	WAS
P68719W	Morgan, Marshall J.	STO	48 72 25 SE NW	0	190	165	180	YES	WAS
P23712W	Morgan, Norvin D., Jr.	DOM STO	48 72 26 NE SE	20	355	320	355	YES	COL
P61G	Morgan, Alfreda	DOM IRR STO	48 72 27 NE SE	50	47	30	47	YES	WAS
P22722W	Morgan, Cecil T.	STO	48 72 32 SE NE	7	100	20	85	YES	WAS
P23442P	Dunlap, Richard O.	STO	48 72 35 NE NW	25	120	--	--	NO	WAS
P64991W	Wyoming State Highway Department	MIS	48 72 36 NW NW	55	290	160	205	YES	WAS
P13720W	Raitt, Flora	STO	47 70 35 NW SE	5	8	7	8	YES	WAS
P5514P	Clabaugh, Leslie	STO	47 71 04 SW SW	4	210	--	--	YES	WAS
P23440P	Dunlap, Richard O.	STO	47 71 06 NE SW	25	80	--	--	NO	WAS
P23441P	Dunlap, Richard O.	STO	47 71 07 SW SW	25	120	--	--	NO	WAS
P5516P	Clabaugh, Leslie	STO	47 71 08 SE SE	5	120	--	--	YES	WAS
P22621P	Raitt, Flora M.	STO	47 71 14 NE NE	5	170	--	--	NO	UNK
P7294P	Frank P. Schneider Trust B	STO	47 71 15 SW NE	7	315	--	--	NO	UNK

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P63501W	Hettinger, Betty M.	STO	47 71 15 SW SW	3	183	128	183	YES	WAS
P7290P	Frank P. Schneider Trust B	STO	47 71 16 SE NW	7	300	--	--	NO	UNK
P7291P	Frank P. Schneider Trust B	STO	47 71 16 SW SW	7	130	--	--	NO	WAS
P18701P	Hayden, Glenn	STO	47 71 17 NE SW	5	140	--	--	NO	WAS
P18700P	Hayden, Glenn	STO	47 71 17 SE SE	5	220	--	--	NO	WAS
P22588P	Duvall, Kenneth R.	STO	47 71 19 NW NE	2	30	--	--	NO	WAS
P22589P	Duvall, Kenneth R.	STO	47 71 19 SW NE	4	84	--	--	NO	WAS
P35842W	Glenn Hayden Family Ranch	STO	47 71 20 NE NE	25	906	770	850	YES	TTL
P55070W	Duncan, Raymond T.	IND	47 71 20 NE NW	--	4,650	4,415	4,604	YES	TTL
P22590P	Duvall, Kenneth R.	STO	47 71 20 SW NW	5	208	--	--	NO	WAS
P7288P	Frank P. Schneider Trust B	DOM	47 71 22 NW SW	7	25	--	--	YES	WAS
P68362W	Hettinger, Betty Mae, lessee	MIS	47 71 22 SW SW	25	600	402	560	YES	TTL
P7292P	Frank P. Schneider Trust B	STO	47 71 23 NW SE	7	140	--	--	NO	UNK
P7289P	Frank P. Schneider Trust B	STO	47 71 27 NE SW	5	270	--	--	NO	UNK
P18695P	Hayden, Glenn	DOM STO	47 71 28 NE SE	10	140	--	--	NO	WAS
P18718P	Haight, Macsy	STO	47 71 29 NE NW	25	40	--	--	NO	WAS
P18717P	Haight, Macsy	STO	47 71 29 SE NW	7	135	--	--	NO	WAS
P18727P	Haight, Macsy	STO	47 71 30 SW NE	7	100	--	--	NO	WAS
P27535W	Haight, Macsy	STO	47 71 33 NE NE	10	500	--	--	YES	UNK
P18696P	Hayden, Glenn	DOM STO	47 71 33 SE SE	5	35	--	--	NO	UNK
P18697P	Hayden, Glenn	STO	47 71 34 NE NE	5	130	--	--	NO	UNK
P18699P	Hayden, Glenn	STO	47 71 34 SW NW	5	85	--	--	NO	UNK
P18698P	Hayden, Glenn	STO	47 71 34 SW SE	5	270	--	--	NO	UNK
P18719P	Haight, Macsy	STO	47 71 36 NW NE	7	85	--	--	NO	UNK
P43775W	Maystrick, Robert F.	STO	47 72 07 SE SW	5	181	--	--	YES	WAS
P45813W	Carter, Edna L.	STO	47 72 08 NW SE	2	270	200	270	YES	WAS
P32841W	Carter, Edna L.	STO	47 72 09 NE SW	15	150	95	148	YES	WAS
P68811W	Carter, Edna L.	MIS	47 72 09 NE SW	75	154	106	154	YES	WAS
P32840W	Carter, Edna L.	DOM STO	47 72 09 SE NW	25	400	185	210	YES	WAS
P52263W	Carter, Edna L.	DOM STO	47 72 09 SE NW	15	354	215	350	YES	WAS
P64990W	Wyoming State Highway Department	MIS	47 72 11 NE SE	75	280	103	173	YES	WAS
P24866P	Morgan, Alfreda M.	DOM	47 72 11 NW NE	25	21	15	15	YES	WAS
P22587P	Duvall, Kenneth R.	DOM STO	47 72 13 SE SE	25	209	--	--	NO	WAS
P3436W	Romaker, Ruth M.	STO	47 72 20 SE NW	5	342	250	342	YES	WAS
P18725P	Haight, Lena	STO	47 72 22 NE NW	7	60	--	--	NO	WAS
P18722P	Haight, Lena	STO	47 72 22 SW SE	7	95	--	--	NO	WAS
P18721P	Haight, Milo	STO	47 72 26 NE SW	7	165	--	--	NO	WAS
P18720P	Haight, Lena	STO	47 72 26 SE NW	25	100	--	--	NO	WAS
P21667P	Lindsey, M.P.	STO	47 72 32 SE NW	10	463	415	454	YES	WAS
P28636W	Wagensen and Hayden	STO	47 72 35 SE SE	25	256	170	250	YES	WAS
P19832P	Thrush, R.S.	STO	46 70 17 SE NE	3	118	--	--	NO	UNK
P19834P	Thrush, R.S.	STO	46 70 20 SW SW	10	800	--	--	NO	UNK
P24355W	Broyles, Richard L.	STO	46 70 30 NW SE	5	210	160	185	YES	TTL
P5688P	Broyles, Richard	STO	46 70 31 SW NE	8	218	--	--	YES	UNK
P22726W	Osborn Ranch Corporation, Inc.	STO	46 70 33 NE SE	5	252	180	220	YES	TTL
P134W	Osborn, Glen	DOM STO	46 70 33 SE SE	10	140	60	--	YES	WAS
P15843P	Angela A. Boos Trust	STO	46 71 02 SE SE	2	60	--	--	NO	UNK
P59069W	Haight, Milo	STO	46 71 04 NE NE	25	900	770	860	YES	TTL
P18724P	Haight, Lena M.	STO	46 71 04 NE SW	7	85	--	--	NO	WAS

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P18723P	Thrush, David	STO	46 71 05 NW SE	7	35	--	--	NO	WAS
P70173W	Apache Corporation	IND	46 71 06 NE NE	15	1,075	--	--	YES	TTL
P29025P	Pickrel Land and Cattle Co., Inc.	STO	46 71 07 SE SW	--	75	--	--	NO	WAS
P15841P	Angela A. Boos Trust	DOM	46 71 11 NW NE	4	300	230	255	YES	TTL
P22624P	Raitt, Flora M.	STO	46 71 13 SE SW	5	500	--	--	NO	UNK
P71303W	Hoadley Estate	DOM STO	46 71 14 SW SW	5	120	--	--	NO	WAS
P15839P	Angela A. Boos Trust	STO	46 71 15 NE SE	7	258	100	190	YES	COL
P21662P	Newton, Sylvia	DOM STO	46 71 19 NW SW	22	200	--	--	NO	WAS
P71306W	Hoadley Estate	STO	46 71 21 SE SW	6	55	--	--	NO	UNK
P71304W	Hoadley Estate	STO	46 71 22 SW NE	5	110	--	--	NO	WAS
P19833P	Thrush, R.S.	DOM STO	46 71 24 SE NE	10	155	--	--	NO	UNK
P13439W	Thrush, James	STO	46 71 25 NW NW	10	465	420	465	YES	TTL
P5690P	Broyles, Richard	STO	46 71 26 SE SE	10	180	--	--	NO	WAS
P4311P	Evans, E.M.	STO	46 71 33 NE NE	10	355	--	--	YES	WAS
P4436W	Stoltz and Co.	STO	46 71 33 NW SW	25	1,457	1,262	1,346	YES	TTL
P9258W	Inexco Oil Co.	IND	46 71 34 SE NE	350	4,830	4,560	4,730	YES	TTL
P9259W	Inexco Oil Co.	IND	46 71 34 SE SE	357	4,830	4,610	4,728	NO	TTL
P29022P	Pickrel Land and Cattle Co.	STO	46 72 01 NW SW	5	100	--	--	NO	WAS
P29024P	Pickrel Land and Cattle Co.	STO	46 72 01 SE SE	7	80	--	--	NO	WAS
P29023P	Pickrel Land and Cattle Co.	STO	46 72 02 NE SE	7	100	--	--	NO	WAS
P29021P	Pickrel Land and Cattle Co.	DOM	46 72 02 SE SE	5	--	--	--	NO	WAS
P54996W	Barlow, Robert F.	STO	46 72 03 NE NW	15	650	490	650	YES	WAS
P31453W	Schiermiester, Milton O.	STO	46 72 03 SE SE	5	594	287	471	YES	WAS
P20709P	Carter, Omer	STO	46 72 03 SE SW	7	121	--	--	NO	WAS
P21665P	Lindsey, M.P.	DOM STO	46 72 10 SE SE	10	162	105	160	YES	WAS
P22250P	Osborn, Perry	DOM STO	46 72 11 NE NE	25	90	--	--	NO	WAS
P20315W	Osborn, Perry	STO	46 72 11 NE SE	15	108	65	105	YES	WAS
P29026P	Pickrel Land and Cattle Co.	STO	46 72 11 NW NE	5	--	--	--	NO	WAS
P59475W	Osborne, Perry	STO	46 72 12 NE NW	25	320	--	--	NO	UNK
P21659P	Newton, Sylvia	STO	46 72 12 SE SW	4	100	--	--	NO	WAS
P21660P	Newton, Sylvia	STO	46 72 13 SW NE	4	120	--	--	NO	WAS
P22251P	Osborn, Perry	STO	46 72 14 NE SE	7	165	--	--	NO	WAS
P22253P	Osborn, Perry	STO	46 72 15 NE SE	7	80	--	--	NO	WAS
P22252P	Osborn, Perry	STO	46 72 23 SE NW	7	80	--	--	NO	WAS
P21661P	Newton, Sylvia	STO	46 72 24 NW NE	4	120	--	--	NO	WAS
P4535P	Broyles, Warren	STO	45 70 04 NW NW	0	12	--	--	YES	WAS
P4534P	Broyles, Warren	STO	45 70 04 SW SW	3	110	--	--	NO	UNK
P4533P	Broyles, Warren	STO	45 70 06 NE NE	3	125	--	--	NO	UNK
P4532P	Broyles, Warren	DOM STO	45 70 06 SE SE	10	280	--	--	YES	WAS
P25837W	Campbell County School District	MIS	45 70 07 NW NW	20	410	410	--	YES	TTL
P15083W	Broyles, Warren	DOM	45 70 08 NE NE	25	300	240	290	YES	TTL
P11005W	Inexco Oil Co.	IND	45 70 08 NW NW	400	4,425	4,286	4,344	YES	TTL
P11880P	Edwards, Guy W.	STO	45 70 08 SE SW	5	130	--	--	NO	UNK
P11003W	Inexco Oil Co.	IND	45 70 09 SE SW	374	4,358	4,190	4,250	YES	TTL
P4536P	Broyles, Warren	STO	45 70 10 NE SE	3	110	--	--	YES	TTL
P11877P	Edwards, Guy W.	STO	45 70 15 NE NE	5	85	--	--	NO	UNK
P11889W	Edwards, Guy W.	DOM STO	45 70 15 NE SE	25	793	737	765	YES	TTL
P11002W	Inexco Oil Co.	IND	45 70 16 NE SW	65	4,453	4,295	4,330	YES	TTL
P11879P	Edwards, Guy W.	STO	45 70 16 NW SW	25	10	3	10	YES	WAS

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P11881P	Edwards, Guy W.	STO	45 70 17 SE SW	4	22	19	22	YES	WAS
P10727W	Broyles, Richard	STO	45 70 18 NE SE	10	790	690	750	YES	TTL
P5689P	Broyles, Richard	STO	45 70 18 NW NW	10	80	--	--	NO	UNK
P11004W	Inexco Oil Co.	IND	45 70 18 SE NE	275	4,510	4,370	4,406	YES	TTL
P2958P	Mills Land and Livestock Co.	STO	45 70 19 NE NW	6	85	--	--	YES	WAS
P4130P	Mills Land and Livestock Co.	DOM STO	45 70 19 NW SW	5	385	--	--	YES	UNK
P4131P	Mills Land and Livestock Co.	DOM	45 70 19 NW SW	2	30	--	--	NO	UNK
P4132P	Mills Land and Livestock Co.	STO	45 70 19 SW SW	2	20	--	--	NO	UNK
P4133P	Mills Land and Livestock Co.	STO	45 70 19 SW SW	4	77	--	--	NO	UNK
P11878P	Edwards, Guy W.	STO	45 70 21 NW NE	5	90	--	--	NO	UNK
P11882P	Edwards, Guy W.	STO	45 70 22 SE SW	4	320	--	--	NO	UNK
P2960P	Mills Land and Livestock Co.	STO	45 70 30 NE NE	6	124	85	--	YES	TTL
P65967W	Mills Brothers Partnership	DOM STO	45 70 30 SW NE	10	170	145	160	YES	WAS
P28315W	Franklin Realty	MIS	45 70 31 SE SE	0	120	--	--	YES	WAS
P10722W	Edwards, Guy W.	STO	45 70 32 NW NE	5	189	126	132	YES	WAS
P11884P	Edwards, Guy W.	STO	45 70 33 SE SE	5	12	--	--	NO	UNK
P11883P	Edwards, Guy W.	STO	45 70 33 SW NE	3	60	47	58	YES	WAS
P11886P	Edwards, Guy W.	DOM STO	45 70 33 SW SE	7	120	--	--	NO	UNK
P4308P	Evans, E.M.	STO	45 71 01 NW SE	7	180	--	--	NO	UNK
P4304P	Evans, E.M.	STO	45 71 02 NE NE	10	165	--	--	NO	WAS
P34479W	Evans, Richard M.	DOM STO	45 71 02 NW NE	10	323	250	320	YES	COL
P4377W	Evans, E.M.	STO	45 71 02 SW NW	50	296	120	230	YES	COL
P4309P	Evans, E.M.	STO	45 71 03 SE NE	10	165	--	--	NO	WAS
P13294P	Durham Meat Co.	STO	45 71 07 SW NW	3	49	--	--	NO	WAS
P4307P	Evans, E.M.	STO	45 71 10 NE NE	7	170	--	--	NO	WAS
P6759W	Phillips Petroleum Co.	DOM	45 71 10 SE NE	5	778	380	778	YES	TTL
P34479W	Evans, Richard M.	DOM STO	45 71 11 NW NE	10	323	245	323	YES	COL
P4306P	Evans, E.M.	STO	45 71 11 NW NW	5	160	--	--	NO	WAS
P135W	Osborn, Glen	STO	45 71 12 NE SW	20	120	80	--	YES	WAS
P66010W	Guy W. Edwards Trust	DOM STO	45 71 12 NE SW	0	150	130	150	YES	WAS
P5691P	Broyles, Richard	DOM	45 71 12 NW NE	10	162	--	--	NO	UNK
P15082W	Mills, Clark K.	STO	45 71 13 SE SW	20	190	130	190	YES	WAS
P2957P	Mills Land and Livestock Co.	STO	45 71 13 SW SE	5	90	--	--	NO	UNK
P11007W	Inexco Oil Co.	IND	45 71 14 NE SE	250	4,750	4,598	4,672	YES	TTL
P4305P	Evans, E.M.	STO	45 71 15 SE NW	7	100	--	--	NO	WAS
P13293P	Durham Meat Co.	STO	45 71 18 SW NW	25	200	--	--	NO	WAS
P65505W	Durham Ranches	STO	45 71 21 NE SE	15	236	205	236	YES	WAS
P30155P	McManus, John D. and Edith	DOM STO	45 71 22 NE SE	5	110	--	--	NO	WAS
P30152P	McManus, John D. and Edith	STO	45 71 22 NE SW	7	100	--	--	NO	WAS
P2959P	Mills Land and Livestock Co.	STO	45 71 23 SW NE	6	105	18	--	YES	WAS
P30153P	McManus, John D. and Edith C.	DOM	45 71 23 SW SW	2	120	--	--	NO	WAS
P2733W	Mills, Clark K.	STO	45 71 25 SE NE	5	105	65	105	YES	WAS
P2961P	Mills Land and Livestock Co.	STO	45 71 25 SW SW	3	24	--	--	NO	UNK
P16030W	Mills, Clarke	STO	45 71 26 NW NE	5	60	50	60	YES	WAS
P9680W	Belle Fourche Pipeline Co.	DOM STO	45 71 26 SE SW	25	190	110	170	YES	WAS
P4439W	Caldwell, W.V.	COM DOM STO	45 71 26 SW SW	105	200	100	190	YES	WAS
P5492W	McCulloch Oil Corporation	IND	45 71 26 SW SW	25	831	750	778	YES	TTL
P3051W	Jacobs, John E.	IND STO	45 71 27 NE NE	25	230	80	220	YES	WAS
P4583W	Jacobs, John E.	STO	45 71 27 NE NE	150	570	310	370	YES	COL

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P47620W	Inexco Oil Co.	MIS	45 71 35 NW NE	15	1,333	--	--	YES	TTL
P2871W	Jacobs, John E.	IND	45 71 35 NW NW	100	350	60	170	YES	WAS
P3443W	Jacobs, John E.	IND	45 71 35 NW NW	150	500	60	170	YES	WAS
P62470W	Reynolds, Butch	DOM STO	45 71 35 SE SW	22	203	120	186	YES	WAS
P2962P	Mills Land and Livestock Co.	STO	45 71 35 SW SE	5	150	--	--	NO	WAS
P2601W	Jacobs, John E.	STO	45 71 35 SW SW	7	155	112	155	YES	WAS
P11009W	Inexco Oil Co.	IND	45 71 36 NW NW	200	5,000	4,844	4,914	NO	TTL
P2963P	Mills Land and Livestock Co.	STO	45 71 36 SE SE	5	110	--	--	NO	WAS
P51186W	Morgan, Richard	DOM	45 72 01 NW NE	25	375	320	360	YES	WAS
P13270P	Durham Meat Co.	STO	45 72 02 NW SE	15	265	150	265	YES	WAS
P13292P	Durham Meat Co.	STO	45 72 13 NE SE	25	80	--	--	NO	WAS
P11885P	Edwards, Guy W.	STO	44 70 03 NW SW	5	10	--	--	NO	UNK
P11012W	Inexco Oil Co.	IND	44 70 07 NW NW	350	4,940	4,730	4,834	NO	TTL
P28318W	Franklin Realty	MIS	44 70 07 NW NW	0	275	--	--	YES	COL
P28319W	Franklin Realty	MIS	44 70 07 NW NW	0	270	--	--	YES	COL
P28316W	Franklin Realty	MIS	44 70 07 SW NE	0	160	--	--	YES	WAS
P28317W	Franklin Realty	MIS	44 70 07 SW NE	0	170	--	--	YES	WAS
P5224W	Ostlund Investments	DOM STO	44 70 17 SE NW	25	620	530	575	YES	TTL
P10403W	Mills, Dale	STO	44 70 19 SW NW	7	190	105	170	YES	WAS
P28612P	Jacobs Land and Livestock Co.	STO	44 70 28 NW NE	10	267	--	--	YES	COL
P28613P	Jacobs Land and Livestock Co.	STO	44 70 28 SW SW	10	261	--	--	YES	WAS
P28611P	Jacobs Land and Livestock Co.	DOM STO	44 70 29 SE NE	5	292	--	--	YES	UNK
P59111W	Jacobs Land and Livestock Co.	DOM STO	44 70 29 SE NE	7	620	578	600	YES	TTL
P2974P	Mills Land and Livestock Co.	STO	44 70 30 SW NE	5	60	--	--	NO	WAS
P2975P	Mills Land and Livestock Co.	STO	44 70 31 SW NW	5	60	--	--	NO	WAS
P28617P	Jacobs Land and Livestock Co.	STO	44 70 32 SE SE	10	273	--	--	YES	COL
P28616P	Jacobs Land and Livestock Co.	STO	44 70 33 NE SW	15	110	--	--	NO	UNK
P28615P	Jacobs Land and Livestock Co.	STO	44 70 34 NW NW	5	260	--	--	YES	COL
P28618P	Jacobs Land and Livestock Co.	STO	44 70 35 NW NE	25	300	--	--	NO	UNK
P28619P	Jacobs Land and Livestock Co.	STO	44 70 35 NW NE	20	280	--	--	NO	UNK
P2964P	Mills Land and Livestock Co.	STO	44 71 02 NE NE	5	170	--	--	NO	WAS
P2965P	Mills Land and Livestock Co.	STO	44 71 02 SE NW	2	60	--	--	NO	WAS
P2966P	Mills Land and Livestock Co.	STO	44 71 11 NE NW	4	60	--	--	NO	WAS
P2967P	Mills Land and Livestock Co.	STO	44 71 11 NW NE	5	90	--	--	NO	WAS
P2969P	Mills Land and Livestock Co.	STO	44 71 11 NW SE	6	233	190	--	YES	WAS
P11011W	Inexco Oil Co.	IND	44 71 12 NW NW	300	5,110	4,836	4,926	NO	TTL
P2968P	Mills Land and Livestock Co.	STO	44 71 12 SE NW	5	180	--	--	NO	WAS
P2970P	Mills Land and Livestock Co.	STO	44 71 13 NE SW	5	190	--	--	NO	WAS
P6349W	Springen, Carl J.	STO	44 71 14 SW NW	14	104	52	104	YES	WAS
P3214P	Ferguson, Feriba F.	DOM STO	44 71 22 SE SE	10	50	--	--	YES	WAS
P2971P	Mills Land and Livestock Co.	STO	44 71 23 NW NE	6	90	--	--	NO	WAS
P2972P	Mills Land and Livestock Co.	STO	44 71 23 SW NE	5	42	25	--	YES	WAS
P19252P	Revland, Kenneth and Sylvia	STO	44 71 24 NE SW	7	75	--	--	NO	WAS
P2973P	Mills Land and Livestock Co.	STO	44 71 25 SE NE	4	90	--	--	NO	WAS
P3215P	Ferguson, W.L.	DOM	44 71 27 SE NE	10	24	--	--	YES	WAS
P3216P	Ferguson, W L.	DOM STO	44 71 27 SE NE	10	100	--	--	YES	WAS
P5971W	Stuart Brothers, Inc.	STO	44 71 34 NE SE	25	245	115	166	YES	WAS
P5972W	Stuart Brothers, Inc.	STO	44 71 34 NE SE	25	250	115	160	YES	WAS
P30419W	Revland, Kenneth C.	DOM STO	44 71 35 NE NE	25	303	--	--	YES	WAS

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydrogeologic unit
P19250P	Revland, Kenneth and Sylvia	DOM STO	44 71 35 SE NE	15	125	--	--	NO	WAS
P28607P	Jacobs Land and Livestock Co.	STO	43 70 02 NE NE	8	255	--	--	YES	TTL
P28606P	Jacobs Land and Livestock Co.	STO	43 70 03 NW SW	5	220	--	--	NO	UNK
P8961P	U.S. Forest Service	STO	43 70 05 NW SW	4	268	205	265	YES	COL
P2976P	Mills Land and Livestock Co.	STO	43 70 06 SW NE	5	260	--	--	YES	COL
P19254P	Revland, Kenneth and Sylvia	STO	43 70 07 NW SE	7	36	20	36	YES	WAS
P31780W	Reno Livestock Corporation	STO	43 70 07 SW NW	25	110	73	104	YES	WAS
P67545W	U.S. Forest Service	STO	43 70 08 NE NE	4	354	279	350	YES	UNK
P39104W	Stuart Brothers, Inc.	STO	43 70 08 NE SE	5	290	260	285	YES	TTL
P4393W	U.S. Forest Service	STO	43 70 19 NE SE	5	390	330	350	YES	TTL
P5861P	Reno Livestock Corporation	STO	43 70 32 NW SE	2	233	--	--	YES	COL
P7409W	Reno Livestock Corporation	STO	43 70 32 SW NE	25	130	60	130	YES	WAS
P9681W	Belle Fourche Pipeline Co.	DOM STO	43 71 01 NE NE	30	346	150	330	YES	UNK
P19251P	Revland, Kenneth and Sylvia	STO	43 71 02 NW SE	7	147	80	128	YES	WAS
P3050W	Stuart Brothers, Inc.	STO	43 71 03 SW SE	5	145	120	145	YES	WAS
P3343W	Stuart Brothers, Inc.	STO	43 71 04 SW NE	5	273	230	273	YES	WAS
P45855W	U.S. Forest Service	STO	43 71 10 SW NE	3	383	328	373	YES	WAS
P12762P	U.S. Forest Service	STO	43 71 11 SE NW	4	146	--	--	NO	WAS
P5866W	Reno Livestock Corporation	STO	43 71 12 SW NE	25	212	70	212	YES	WAS
P5862P	Reno Livestock Corporation	STO	43 71 13 NE SW	2	324	--	--	YES	WAS
P19253P	Revland, Kenneth and Sylvia	STO	43 71 14 SE NW	7	80	--	--	NO	WAS
P8912W	U.S. Forest Service	STO	43 71 22 NW NW	4	--	--	--	NO	UNK
P8913W	U.S. Forest Service	STO	43 71 22 SW NW	5	--	--	--	NO	UNK
P44326W	U.S. Forest Service	STO	43 71 23 SW SW	3	375	300	370	YES	WAS
P5860P	Reno Livestock Corporation	STO	43 71 25 SE SE	1	--	--	--	NO	UNK
P44329W	U.S. Forest Service	STO	43 71 34 NW SE	60	353	160	220	YES	WAS
P14237W	U.S. Forest Service	STO	43 71 35 SW NW	5	275	20	275	YES	TTL
P44452W	Industrial Pipelines South	MIS	43 71 35 SW NW	100	360	245	350	YES	WAS
P67820W	U.S. Forest Service	STO	42 69 28 SW NE	0	8	7	8	YES	WAS
P8975P	U.S. Forest Service	STO	42 69 31 NE SE	4	107	70	107	YES	WAS
P29743W	U.S. Forest Service	STO	42 69 31 SW SW	10	440	--	--	YES	UNK
P5858P	Reno Livestock Corporation	STO	42 70 02 SW SW	2	255	--	--	YES	WAS
P5857P	Reno Livestock Corporation	STO	42 70 04 SW SW	2	233	--	--	YES	COL
P5859P	Reno Livestock Corporation	STO	42 70 06 SW SW	2	--	--	--	NO	UNK
P5865P	Henderson, Nan	STO	42 70 07 SE NE	1	75	--	--	YES	WAS
P8894W	Reno Livestock Corporation	STO	42 70 11 SW NE	50	80	30	80	YES	WAS
P8951P	U.S. Forest Service	STO	42 70 15 SW SW	4	435	417	430	YES	TTL
P8981P	U.S. Forest Service	STO	42 70 18 NW SE	4	110	96	108	YES	WAS
P25605P	Wilkinson, Paul and Edith Ruth	DOM STO	42 70 19 NE SW	5	12	7	12	YES	WAS
P67797W	U.S. Forest Service	STO	42 70 23 NE SE	1	8	--	8	YES	UNK
P12746P	U.S. Forest Service	STO	42 70 25 NE SW	4	98	--	--	NO	WAS
P8960P	U.S. Forest Service	STO	42 70 26 SW SW	4	464	420	452	YES	WAS
P25701W	Enercor, Inc.	DOM STO	42 70 28 SW SW	20	570	480	565	YES	WAS
P60275W	Enercor, Inc.	MIS	42 70 32 NE NW	80	485	365	485	YES	TTL
P25702W	Mackey, Robert R. and Dorothy W.	DOM STO	42 70 32 NW SE	7	85	--	--	NO	WAS
P63169W	Phillips Petroleum Co.	MIS	42 70 36 SW SW	4	209	200	209	YES	WAS
P12757P	U.S. Forest Service	STO	42 71 02 NE NW	4	165	--	--	NO	WAS
P44327W	U.S. Forest Service	STO	42 71 02 NW SW	3	373	309	346	YES	WAS
P32145W	U.S. Forest Service	STO	42 71 11 SW NE	10	380	248	348	YES	WAS

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P8987P	U.S. Forest Service	STO	42 71 12 SE SE	4	172	115	164	YES	WAS
P12755P	U.S. Forest Service	STO	42 71 13 SW SW	4	121	--	--	NO	WAS
P12760P	U.S. Forest Service	STO	42 71 19 NE SE	4	175	--	--	NO	WAS
P61754W	U.S. Forest Service	STO	42 71 24 NW SE	5	110	94	107	YES	WAS
P25606P	Wilkinson, Paul and Edith Ruth	DOM STO	42 71 26 NE SE	2	220	191	221	YES	WAS
P25608P	Wilkinson, Paul and Edith Ruth	STO	42 71 26 SW NW	4	110	50	110	YES	WAS
P5849W	Wilkinson, Paul	STO	42 71 26 SW NW	2	140	97	104	YES	WAS
P29746W	U.S. Forest Service	STO	42 71 27 NE NW	10	175	--	--	YES	WAS
P29747W	U.S. Forest Service	STO	42 71 30 NE NW	3	520	--	--	YES	COL
P53195W	Dilts Brothers	STO	42 71 32 NW NW	10	735	628	695	YES	TTL
P12758P	U.S. Forest Service	STO	42 71 33 SE NE	4	--	--	--	NO	UNK
P44329W	U.S. Forest Service	STO	42 71 34 NW SE	3	183	100	175	YES	WAS
P12756P	U.S. Forest Service	STO	42 71 35 SW SE	4	20	--	--	NO	WAS
P37351W	Matheson, Halbert	STO	42 72 12 SE SE	25	150	140	150	NO	WAS
P37352W	Matheson, Halbert	STO	42 72 13 SE NE	25	200	180	200	YES	WAS
P29020W	U.S. Forest Service	STO	42 72 24 NW SE	5	440	--	--	YES	WAS
P67821W	U.S. Forest Service	STO	41 69 06 SW NE	1	8	7	8	YES	WAS
P8998P	U.S. Forest Service	STO	41 70 02 SW SE	4	395	355	395	YES	UNK
P25607P	Wilkinson, Paul and Edith Ruth	STO	41 70 06 NW SE	4	805	795	805	YES	TTL
P2314W	Dilts, John C.	STO	41 70 09 SW NW	4	700	630	685	YES	TTL
P61524W	Phillips Petroleum Co.	MIS	41 70 12 NW NE	100	1,820	--	--	YES	TTL
P33290W	U.S. Forest Service	STO	41 70 18 SE NW	10	644	465	520	YES	TTL
P12754P	U.S. Forest Service	STO	41 71 03 NE SW	4	122	--	--	NO	WAS
P44330W	U.S. Forest Service	STO	41 71 03 NW SE	3	163	80	163	YES	WAS
P5611P	Isenberger, Robert E.	STO	41 71 06 SW NW	5	344	--	--	YES	WAS
P23599W	Isenberger, Patricia L.	STO	41 71 07 NW SE	10	252	205	240	YES	WAS
P23603P	Isenberger, Patricia L.	STO	41 71 07 NW SW	25	8	4	8	YES	WAS
P58121W	Big Horn Fractionation	MIS	41 71 11 NE NE	25	396	317	390	YES	WAS
P67807W	U.S. Forest Service	STO	41 71 13 NW NW	0	8	7	8	YES	WAS
P44331W	U.S. Forest Service	STO	41 71 14 SE SE	3	605	530	595	YES	TTL
P5612P	Isenberger, Robert E.	STO	41 71 19 NW NE	1	175	--	--	YES	WAS
P23604P	Isenberger, Patricia L.	STO	41 71 21 SE SW	25	8	4	8	YES	WAS
P63112W	Bridle Bit Ranch	STO	41 71 24 SW NE	6	442	400	423	YES	TTL
P67899W	U.S. Forest Service	STO	41 71 27 NE SW	0	8	--	8	YES	WAS
P23605P	Isenberger, Patricia L.	STO	41 71 27 SW SW	25	8	4	8	YES	WAS
P23601P	Isenberger, Patricia L.	STO	41 71 29 SW NW	7	250	--	--	NO	UNK
P11719W	Isenberger, Robert E.	STO	41 71 31 SE SE	5	508	420	508	YES	TTL
P23606P	Isenberger, Patricia L.	STO	41 71 31 SW SW	25	8	4	8	YES	WAS
P23602P	Isenberger, Patricia L.	STO	41 71 33 NW NW	10	600	--	--	NO	UNK
P9571W	U.S. Forest Service	STO	41 71 33 SW SE	4	495	453	483	YES	TTL
P23594W	Isenberger, Patricia L.	STO	41 71 34 SW NE	10	640	600	640	YES	TTL
P23596P	Isenberger, Patricia L.	DOM STO	41 71 35 NE NE	5	--	--	--	NO	UNK
P11652W	Isenberger, Robert E.	STO	41 71 35 SE NE	25	30	8	30	YES	COL
P16602W	Matheson, H.R.	IND	41 71 35 SW NW	500	50	--	--	NO	UNK
P3439W	Reno, Floyd C., Jr. and Eda J.	STO	41 72 10 SE NE	20	344	224	338	YES	WAS
P23599P	Isenberger, Patricia L.	DOM STO	41 72 13 NE NW	10	225	--	--	NO	WAS
P52637W	Litton, Patricia L. Isenberger	DOM STO	41 72 13 NE NW	15	179	146	179	YES	WAS
P50639W	Isenberger, Patricie L.	RES STO	41 72 13 NW NE	10	182	147	170	YES	WAS
P23600P	Isenberger, Patricia L.	STO	41 72 13 SW SE	7	300	--	--	NO	UNK

Table 32.--Privately owned water-supply wells in the area of potential cumulative water-level declines--Continued

Permit number	Owner	Use of water	Location	Yield (gal/min)	Depth (feet)	Top and bottom of main water-yielding zone (feet below land surface)		Driller's log available	Hydro-geologic unit
P18843P	Floyd C. Reno and Son's, Inc.	DOM STO	41 72 18 NW SE	5	200	--	--	NO	WAS
P14235W	U.S. Forest Service	STO	41 72 22 NW NW	5	280	220	275	YES	WAS
P50639W	Isenberger, Patricia L.	STO	41 72 23 SW NE	15	210	170	210	YES	WAS
P23595P	Isenberger, Patricia L.	STO	41 72 24 SW SE	10	525	--	--	NO	UNK
P69891W	Litton, Patricia L. Isenberger	MIS	41 72 24 SW SE	25	861	665	825	YES	TTL
P9921W	Moore, W.I., Jr.	STO	41 72 30 SW SW	5	--	--	--	NO	UNK
P4389W	Reno, Floyd C., Jr. and Eda J.	STO	41 72 34 NE NW	4	687	54	664	YES	TTL
P18842P	Floyd C. Reno and Son's, Inc.	STO	41 73 13 SE SE	5	720	--	--	NO	TTL
P37364W	U.S. Forest Service	STO	40 71 03 NE SW	10	585	530	585	YES	TTL
P59883W	Jacobs, Donald B.	DOM	40 71 07 NE NW	25	1,275	757	1,248	YES	TTL
P12753P	U.S. Forest Service	STO	40 71 17 NE SE	4	--	--	--	NO	UNK
P4524P	U.S. Forest Service	STO	40 71 19 NW NE	5	700	--	--	YES	TTL
P18840P	Floyd C. Reno and Son's, Inc.	STO	40 72 04 SE NW	15	550	--	--	NO	UNK
P18850P	Floyd C. Reno and Son's, Inc.	DOM	40 72 09 NW SE	15	656	--	--	NO	UNK
P18839P	Floyd C. Reno and Son's, Inc.	STO	40 72 10 NW NW	10	550	--	--	NO	UNK
P59882W	Jacobs, Donald B.	STO	40 72 12 NW NE	5	640	564	601	YES	TTL
P12477P	Haefele, Duane and Chloe	DOM STO	40 72 13 SE SW	10	880	--	--	YES	UNK
P12478P	Haefele, Duane and Chloe	DOM STO	40 72 14 NE SE	15	640	585	625	YES	UNK
P18849P	Floyd C. Reno and Son's, Inc.	STO	40 72 17 NE NW	10	600	--	--	NO	UNK
P54G	Dilts, John C.	STO	40 72 18 SE NW	45	530	482	530	YES	TTL
P12479P	Haefele, Duane and Chloe	STO	40 72 23 NE SW	20	--	--	--	NO	UNK
P19940W	Dilts, John C.	STO	40 72 34 NW NE	15	1,010	978	1,000	YES	TTL
P2307W	Dilts, John C.	STO	40 72 35 SW NW	6	854	787	854	YES	TTL
P9920W	Moore, W.I., Jr.	STO	40 73 01 NE NW	5	--	--	--	NO	UNK
P2309W	Dilts, John C.	STO	40 73 13 NE NE	6	--	--	--	NO	UNK
P2310W	Dilts, John C.	STO	40 73 13 SE NW	4	--	--	--	NO	UNK

Table 33.--Surface-water data network operated by coal-mining companies

[Station number assigned by coal-mining company; location is by township, range, section, and quarter-quarter; present, 1987; --, no data]

Site number (fig. 14)	Station number (fig. 14)	Station name	Station owner (coal mine)	Location	Drainage area (square miles)	Period of record: Discharge From	Discharge To	Quality From	Quality To
34	SW-2	Antelope Creek	Antelope	41 71 34 SW SW	796	1979	present	1979	present
35	SW-3	Antelope Creek	Antelope	41 70 31 SW SW	836	1979	present	1979	present
36	SW-5	Antelope Creek	Antelope	41 71 35 NW NW	--	1979	present	1979	present
37	SW-9	Horse Creek	Antelope	41 71 26 SE SW	15.2	1979	present	1979	present
38	SW-10	Spring Creek	Antelope	41 71 33 NE SE	66.8	1979	present	1979	present
39	SW-12	Unnamed	Antelope	41 71 36 SW NW	1.3	1979	present	1979	present
40	1	Porcupine Creek	North Antelope	41 70 06 NE NW	--	11/1977	05/1984	11/1977	05/1984
41	GS-1	Porcupine Creek	North Antelope	41 70 05 NE SW	96.0	05/1980	present	02/1980	present
42	3	Porcupine Creek	North Antelope	41 70 22 SW SW	--	03/1978	05/1984	03/1978	05/1984
43	GS-5	Porcupine Creek	North Antelope	41 70 21 NW NW	117	05/1980	present	02/1980	present
44	GS-2	Payne Draw	North Antelope	41 70 05 NE SE	4.8	05/1980	present	02/1980	present
45	GS-3	Rogers Draw	North Antelope	41 70 07 NE SE	1.5	05/1980	present	02/1980	present
46	GS-4	Knapp Draw	North Antelope	41 70 10 NE NW	3.4	05/1980	present	02/1980	present
47	4	Antelope Creek	North Antelope	41 71 36 NW SW	--	05/1977	05/1984	05/1977	05/1984
48	5	Antelope Creek	North Antelope	41 70 35 NE SW	--	05/1977	present	05/1977	present
49	6	Antelope Creek	North Antelope	41 70 36 NW SW	--	05/1977	present	05/1977	present
50	RS-4	Beckwith Creek	Rochelle	41 69 16 SE SW	7.7	07/1981	present	07/1981	present
51	RS-5	Boltz Draw	Rochelle	41 70 22 SE SW	7.1	07/1981	present	07/1981	present
52	CG-8	West School Creek	North Rochelle	42 70 11 SW NE	1.8	03/1980	01/1987	03/1980	01/1987
53	CG-3	West School Creek	North Rochelle	42 70 12 NE NW	3.7	01/1980	01/1987	11/1983	01/1987
54	CG-2	Trussler Creek	North Rochelle	42 70 09 SW SE	1.8	01/1980	01/1987	03/1980	01/1987
55	CG-4	Trussler Creek	North Rochelle	42 70 05 SE SE	3.9	01/1980	01/1987	--	--
56	NP-1	North Prong Little Thunder Creek	Black Thunder	43 71 12 NE SE	--	03/1979	07/1986	03/1979	05/1984
57	MD-1	Mills Creek	Black Thunder	43 70 08 SW SW	5.5	04/1984	07/1986	03/1979	05/1984
58	SMC-1	North Prong Little Thunder Creek	Black Thunder	43 70 17 NW NE	--	03/1979	06/1982	03/1979	06/1982
59	NP-2	North Prong Little Thunder Creek	Black Thunder	43 70 16 SE SE	--	03/1979	07/1986	03/1979	06/1982
60	NP-3	North Prong Little Thunder Creek	Black Thunder	43 70 22 NW NE	--	06/1982	--	06/1982	03/1985
61	NP-5	North Prong Little Thunder Creek	Black Thunder	43 70 23 SE NW	--	10/1983	07/1986	02/1984	03/1985
62	NP-4	North Prong Little Thunder Creek	Black Thunder	43 70 23 NE SW	--	03/1979	--	03/1979	03/1985
63	NP-4	Little Thunder Creek	Black Thunder	43 70 19 SE SW	--	--	--	--	--
64	LT-5	Little Thunder Creek	Black Thunder	43 70 19 SW SW	--	05/1976	07/1986	05/1976	05/1984
65	TC-1	Trussler Creek	Black Thunder	43 70 32 SW SE	11.0	10/1983	07/1986	--	--
66	LT-8	Unnamed	Black Thunder	43 70 29 SE NE	--	06/1982	--	06/1982	05/1984
67	LT-4	Little Thunder Creek	Black Thunder	43 70 28 NE SW	--	05/1982	07/1982	05/1982	05/1986
68	LT-7	Unnamed	Black Thunder	43 70 27 SW SW	--	06/1982	06/1982	06/1982	05/1984
69	LT-3	Little Thunder Creek	Black Thunder	43 70 27 NE SE	--	05/1974	06/1982	05/1974	06/1986
70	LT-2	Little Thunder Creek	Black Thunder	43 70 26 NW NE	--	03/1972	07/1986	03/1979	05/1984
71	LT-2	Unnamed	Black Thunder	43 70 26 SW NE	--	--	--	--	--
72	LT-2	Little Thunder Creek diversion	Black Thunder	43 70 17 SW SW	--	--	--	--	--
73	SD-1	Shipley Draw	Black Thunder	43 70 08 SW SE	3.0	10/1984	07/1986	03/1979	05/1984
74	BCD-1	Burning Coal Draw	Jacobs Ranch	43 70 10 NE NE	.6	05/1980	05/1981	--	--
75	BCD-2	Burning Coal Draw tributary	Jacobs Ranch	43 70 10 NE NE	.3	10/1979	05/1981	--	--
76	EBC-3	Unnamed	Jacobs Ranch	43 70 12 SW NW	.6	10/1979	05/1981	03/1979	05/1981
77	EBC-2	Unnamed	Jacobs Ranch	43 70 12 SE NW	.1	06/1980	05/1981	03/1979	--
78	EBC-1	Unnamed	Jacobs Ranch	43 70 12 NE SE	--	10/1979	05/1981	--	--
79	HAC-1	Unnamed	Jacobs Ranch	43 70 01 SE NE	.3	10/1979	05/1981	--	--
80	NPT-1	Unnamed	Jacobs Ranch	43 70 15 SW NW	.3	04/1980	06/1980	03/1979	--
81	BCD-3	Burning Coal Draw	Jacobs Ranch	43 70 14 NW NW	2.0	04/1980	--	--	--
82	1	East tributary of Burning Coal Draw	Jacobs Ranch	43 70 12 NE SW	--	--	--	07/1975	10/1984

Table 33.--Surface-water data network operated by coal-mining companies--Continued

Site number (fig. 14)	Station number (fig. 14)	Station name	Station owner (coal mine)	Location	Drainage area (square miles)	Period of record: Discharge From	Discharge To	Quality From	Quality To
83	2	Stockpond, Burning Coal Draw	Jacobs Ranch	43 70 11 NW SW	--	--	--	02/1976	02/1976
84	3	Stockpond, Burning Coal Draw	Jacobs Ranch	43 70 14 NE SW	--	--	--	10/1975	02/1976
85	4	Stockpond, North Prong of Little Thunder Creek	Jacobs Ranch	43 70 22 SE NE	--	--	--	07/1975	07/1975
86	4B	Stockpond, North Prong of Little Thunder Creek	Jacobs Ranch	43 70 22 SE SE	--	--	--	08/1975	08/1975
87	5	Stockpond, North Prong of Little Thunder Creek	Jacobs Ranch	43 70 23 SW NW	--	--	--	07/1975	07/1975
88	6	Stockpond, North Prong of Little Thunder Creek	Jacobs Ranch	43 70 15 SW SW	--	--	--	07/1975	08/1975
89	7	Stockpond, North Prong of Little Thunder Creek	Jacobs Ranch	43 70 22 NW NE	--	--	--	--	--
90	8	Stockpond, North Prong of Little Thunder Creek	Jacobs Ranch	43 70 22 NE NE	--	--	--	04/1975	04/1975
91	9	Playa	Jacobs Ranch	43 70 10 NW	--	--	--	02/1976	02/1976
92	10	Unnamed	Jacobs Ranch	43 70 15 SE SW	--	--	--	02/1976	02/1976
93	KLSP-28	Stockpond	Keeline	45 70 28 SE SW	--	--	--	05/1984	10/1984
94	XC-4	Black Thunder Creek	Keeline	45 70 33 SE SE	1.0	--	--	03/1979	10/1984
95	CG-1	Black Thunder Creek	Keeline	44 70 04 NE NE	--	05/1981	05/1981	--	--
96	XC-3	Black Thunder Creek	Keeline	44 70 04 NE NE	1.6	--	--	10/1984	10/1984
97	XC-2	Black Thunder Creek	Keeline	44 70 03 NW SW	2.4	--	--	03/1979	03/1979
98	CG-2	Black Thunder Creek	Keeline	44 70 03 NW SW	--	05/1981	05/1981	--	--
99	S-2	Black Thunder Creek	Keeline	44 70 10 SW SE	--	--	--	03/1978	03/1978
100	CG-5	Unnamed	Keeline	45 70 32 NE SE	--	--	--	--	--
101	KLPL-33	Playa Lake	Keeline	45 70 33 SE SW	--	--	--	05/1984	05/1984
102	XC-8	Unnamed	Keeline	44 70 09 SE NE	.9	--	--	02/1984	02/1984
103	KLPL-5	Playa Lake	Keeline	44 70 05 SE NE	--	--	--	05/1984	05/1984
104	KLSP-9	Stockpond	Keeline	44 70 09 NW NW	--	--	--	05/1984	05/1984
105	XC-7	Unnamed	Keeline	44 70 10 SW SW	4.8	--	--	03/1978	10/1984
106	1	Middle Fork Coal Creek	Wymo	45 70 16 SW NW	1.3	04/1981	06/1985	07/1981	10/1981
107	CSG-2	Middle Fork Coal Creek	Wymo	45 70 16 SW SW	--	06/1978	08/1985	02/1981	07/1981
108	CSG-3	Guy Draw	Wymo	45 70 16 SE NE	1.3	--	--	02/1981	07/1981
109	CSG-4	Kintz Creek	Wymo	45 70 20 SW NE	--	--	--	05/1981	07/1981
110	CSG-5	Kintz Creek	Wymo	45 70 20 SE SE	.8	06/1978	08/1985	02/1981	05/1981
111	CC-9	Coal Creek	Coal Creek	46 71 12 NW SE	64.0	01/1975	present	03/1979	05/1983
112	TCC-2	Coal Creek Tributary	Coal Creek	46 70 18 SE SW	2.9	12/1975	08/1981	03/1979	03/1979
113	EF-3	East Fork Coal Creek	Coal Creek	46 70 19 NW SE	17.6	10/1974	09/1981	03/1979	05/1982
114	EF-5	East Fork Coal Creek	Coal Creek	46 70 34 SW SE	7.6	01/1975	present	05/1979	05/1983
115	MF-1	Middle Fork Coal Creek	Coal Creek	46 70 32 SW SE	1.9	01/1975	10/1980	05/1977	03/1979
116	TDF-7	Section 16 tributary to Dry Creek	Coal Creek	46 70 16 NE NE	1.5	12/1974	present	03/1979	03/1979
117	TEF-8	Section 27 tributary to East Fork Coal Creek	Coal Creek	46 70 27 NW SE	3.0	07/1981	present	03/1979	06/1983
118	MF-19	Coal Creek	Coal Creek	46 70 19 SE SW	37.7	07/1981	present	03/1979	07/1981
119	S-8	Five Card Draw	Coal Creek	46 70 08 NE SW	1.1	07/1981	present	--	--
120	EF-6	East Fork Coal Creek	Coal Creek	46 70 28 SW SE	--	--	--	05/1977	03/1979
121	EF-11	East Fork Coal Creek	Coal Creek	46 70 29 SE NW	--	--	--	05/1977	05/1977
122	EF-11	Upper Dry Fork Little Powder River	Rawhide	51 72 13 SW NE	--	--	--	1973	1986
123	EF-11	Lower Dry Fork Little Powder River	Rawhide	51 72 12 NW NE	13.8	--	--	1972	1986
124	EF-11	Little Rawhide Creek	Rawhide	51 72 04 SE NE	38.3	--	--	1973	1986
125	EF-11	Upper Rawhide Creek	Rawhide	51 72 06 NW SE	--	--	--	1973	1986
126	EF-11	Lower Rawhide Creek	Rawhide	51 72 03 NE NW	61.8	--	--	1973	1986
127	EF-11	Small watershed	Rawhide	52 73 36 NW SE	--	--	--	--	1986

Table 33.--Surface-water data network operated by coal-mining companies--Continued

Site number (fig. 14)	Station number (fig. 14)	Station name	Station owner (coal mine)	Location	Drainage area (square miles)	Period of record: Discharge From	Discharge To	Quality From	Quality To
128	BA-1	Caballo Creek	Belle Ayr	48 71 31 NE SW	--	10/1975	present	10/1975	present
129	BA-2	Caballo Creek	Belle Ayr	48 71 33 SE NE	--	10/1975	present	10/1975	present
130	BA-4	Caballo Creek	Belle Ayr	48 71 36 NW SW	--	03/1975	12/1985	03/1975	09/1986
131	BA-6	Caballo Creek	Belle Ayr	47 72 01 SW NW	--	10/1980	12/1986	03/1981	05/1986
132	BA-7	Demott Draw	Belle Ayr	48 71 33 SE SE	--	10/1981	present	10/1981	present
133	BA-8	Les Draw	Belle Ayr	48 71 35 SW SE	--	10/1981	present	10/1981	present
134	BA-8	Upper Tisdale Creek	Caballo	48 71 16 NW NW	13.3	04/1977	02/1986	04/1977	02/1986
135	BA-8	Lower Tisdale Creek	Caballo	48 71 26 NE NE	26.5	04/1977	02/1986	04/1977	02/1986
136	BA-8	Upper North Tisdale Creek	Caballo	48 71 11 SW SW	4.7	03/1978	02/1986	03/1978	03/1985
137	BA-8	Upper Gold Mine Creek	Caballo	48 71 12 SW NE	5.0	03/1977	02/1986	03/1977	02/1986
138	BA-8	Lower Gold Mine Creek	Caballo	48 71 25 NW NE	10.5	03/1977	02/1986	03/1977	02/1986
139	0104004	Donkey Creek above Wyodak Mine	Wyodak	50 71 32 NW SE	77.0	10/1975	10/1986	periodic	periodic
140	0104005	Donkey Creek below Wyodak Mine	Wyodak	50 71 27 SE NW	93.0	10/1975	10/1986	periodic	periodic
141	1	Dry Draw above East Gillette	East Gillette	50 71 15 SW SW	--	1981	present	1981	present
142	2	Dry Draw below mouth of Brad Creek	East Gillette	50 71 21 NE NE	--	1981	present	1981	present
143	3	Little Creek below permit boundary	East Gillette	50 71 21 NW NW	--	1981	present	1981	present
144	4	'B' Draw above East Gillette	East Gillette	50 71 09 NE SW	--	1981	present	1981	present
145	5	'B' Draw below East Gillette	East Gillette	50 71 09 SW NW	--	1981	present	1981	present
146	6	'A' Draw above permit boundary	East Gillette	50 71 09 SW SW	--	1981	present	1981	present
147	EB-1	Little Rawhide Creek	Eagle Butte	51 72 21 SW SW	--	03/1974	03/1985	12/1975	04/1985
148	EB-2	Little Rawhide Creek	Eagle Butte	51 72 09 SE SE	--	03/1974	12/1985	12/1975	04/1986
149	EB-11	Little Powder River	Eagle Butte	51 72 35 SE NE	--	01/1983	12/1985	01/1983	06/1984
150	EB-12	Little Rawhide Creek	Eagle Butte	51 72 32 NE NE	--	04/1985	12/1985	05/1985	09/1986
151	CSG-1	Unnamed	Cordero	47 71 24 NW SE	.1	--	--	--	--
152	CSG-2	South Fork Kicken Draw	Cordero	47 71 14 NE SE	.1	--	--	--	--
153	CSG-3	South Fork Kicken Draw	Cordero	47 71 14 NE SE	.3	--	--	--	--
154	CSG-4	South Fork Kicken Draw	Cordero	47 71 13 SW SE	.4	--	--	--	--
155	CSG-5	South Fork Kicken Draw	Cordero	47 71 13 SE SE	.7	--	--	--	--
156	CSG-6	South Fork Kicken Draw	Cordero	47 71 13 SW SE	.2	--	--	--	--
157	CSG-7	North Fork Kicken Draw	Cordero	47 71 13 SW NE	.9	--	--	--	--
158	CSG-8	North Fork Kicken Draw	Cordero	47 71 13 SW NE	.3	--	--	--	--
159	CSG-9	North Fork Kicken Draw	Cordero	47 71 13 NW NW	.2	--	--	--	--
160	CSG-10	Diversion ditch	Cordero	47 71 25 NE NW	--	--	--	--	--
161	CSG-11	Unnamed	Cordero	47 71 35 NE SE	.4	--	--	--	--
162	CSG-12	Diversion ditch	Cordero	47 71 25 NW NW	--	--	--	--	--
163	CSG-13	Diversion ditch	Cordero	47 71 22 SE NE	--	--	--	--	--
164	CSG-14	North Fork Bengal Draw	Cordero	47 71 23 SE NW	.2	--	--	--	--
165	CSG-15	East Prong North Fork Bengal Draw	Cordero	47 71 14 SE SE	.1	--	--	--	--
166	CSG-16	North Fork Bengal Draw	Cordero	47 71 14 NE SE	.2	--	--	--	--
167	CSG-17	East Prong Middle Fork Bengal Draw	Cordero	47 71 15 NE SE	.3	--	--	--	--
168	CSG-18	Middle Fork Bengal Draw	Cordero	47 71 15 NW SE	.6	--	--	--	--
169	CSG-19	South Fork Bengal Draw	Cordero	47 71 22 SE NE	1.6	--	--	--	--
170	CSG-20	South Fork Bengal Draw	Cordero	47 71 22 SW NE	.4	--	--	--	--
171	CSG-21	South Fork Bengal Draw	Cordero	47 71 22 NW NE	.1	--	--	--	--
172	CSG-22	South Fork Bengal Draw	Cordero	47 71 22 SE NW	.4	--	--	--	--
173	CSG-23	South Fork Bengal Draw	Cordero	47 71 22 NW NW	.2	--	--	--	--
174	CSG-24	South Fork Bengal Draw	Cordero	47 71 22 NW NW	.1	--	--	--	--
175	CSG-25	Bakken Draw	Cordero	47 71 27 SW NW	2.0	--	--	--	--
176	CSG-26	Bakken Draw	Cordero	47 71 27 NE SW	2.3	--	--	--	--
177	CSG-27	Bakken Draw	Cordero	47 71 34 NE NE	3.1	--	--	--	--
178	CSG-28	Bakken Draw	Cordero	47 71 34 NE NE	3.3	--	--	--	--
179	CSG-29	Butte Draw	Cordero	47 71 34 SW NW	.7	--	--	--	--

Table 33.--Surface-water data network operated by coal-mining companies--Continued

Site number (fig. 14)	Station number (fig. 14)	Station name	Station owner (coal mine)	Location	Drainage area (square miles)	Period of record: Discharge From	Period of record: Discharge To	Period of record: Quality From	Period of record: Quality To
180	CSG-30	Butte Draw	Cordero	47 71 34 NE SW	1.0	--	--	--	--
181	CSG-31	Belle Fourche River	Cordero	46 71 02 NW NW	501	--	--	--	--
182	CSG-32	Unnamed	Cordero	46 71 03 NW NE	.3	--	--	--	--
183	CSG-33	Unnamed	Cordero	46 71 03 NW NW	.2	--	--	--	--
184	CSG-34	Unnamed	Cordero	46 71 10 NE NW	4.0	--	--	--	--
185	CSG-35	Kicken Draw	Cordero	47 71 13 SE SE	1.9	--	--	--	--
186	IW-1	Kicken Draw	Cordero	47 70 19 NW NW	1.9	1982	present	--	--
187	IW-2	West diversion ditch	Cordero	47 71 26 SE NE	3.8	1982	present	--	--
188	IW-3	Coal Creek	Cordero	46 71 02 NE NE	--	1982	1983	--	--
189	IW-4	Unnamed draw	Cordero	47 71 35 SW SW	1.2	1982	present	--	--
190	IW-5	Bakken Draw	Cordero	47 71 35 SE NW	--	1982	present	--	--
191	R-14-1	Knowland Reservoir	Cordero	47 71 14 SE SW	--	--	--	1982	present
192	R-22-1	Unnamed reservoir	Cordero	47 71 22 SW NE	--	--	--	1982	present
193	R-34-1	Unnamed reservoir	Cordero	47 71 34 NE NE	--	--	--	1982	present
194	R-13-1	Unnamed reservoir	Cordero	47 71 13 SE SE	--	--	--	--	--
195	R-15-1	Unnamed reservoir	Cordero	47 71 15 SW SW	--	--	--	1982	present
196	001	National Pollutant Discharge Elimination System outflow	Cordero	47 71 26 SE NE	--	--	--	--	--
197	002	National Pollutant Discharge Elimination System outflow	Cordero	47 71 25 SW NE	--	--	--	--	--
198	0642572	Belle Fourche River	Cordero	46 71 09 NE NE	--	--	--	--	--
199	0642578	Belle Fourche River	Cordero	47 71 25 SE NE	--	--	--	--	--
200	SW-1	Prairie Creek above railroad crossing	Fort Union	51 71 33 NW SW	--	1979	present	1979	present
201	SW-2	Prairie Creek Tributary Garner Lake road	Fort Union	51 71 21 NW SW	--	1979	present	1979	present
202	SW-3	Prairie Creek at Garner Lake road	Fort Union	51 71 20 SE SE	2.1	1979	present	1979	present
203	SW-4	East Fork Prairie Creek at upper station	Fort Union	51 71 28 NW NE	3.2	1979	present	1979	present
204	SW-5	Little Prairie Creek	Fort Union	51 71 28 SE SE	1.3	1979	present	1979	present
205	WS-1	Dry Fork near weir-flume	Fort Union	50 72 01 NW NW	3.0	1979	present	1979	present
206	WF-2	Dry Fork permit boundary	Fort Union	51 72 36 SW SW	3.0	1979	present	1979	present
207	CS-2	Dry fork above weir-flume site	Fort Union	50 72 02 NE SE	--	1979	present	1979	present
208	CS-3	West Draw at north permit boundary	Fort Union	50 72 01 NW NE	.4	1979	present	1979	present
209	CS-4	Dry Fork at upper station	Fort Union	50 72 12 SW NW	--	1979	present	1979	present
210	CS-5	East Draw at upper station	Fort Union	50 71 07 NE NW	--	1979	present	1979	present
211	CS-6	Tributary to Ditto Lake	Fort Union	50 71 18 NE SE	--	1979	present	1979	present
212	WS-1	Dry Fork Little Powder River	Dry Fork	51 72 36 SW SW	--	03/1979	05/1979	01/1982	08/1982
213	WS-3	West Draw near south permit boundary	Dry Fork	51 72 36 SE SE	--	03/1979	03/1980	--	--
214	KM-1	East Draw near south Permit boundary	Dry Fork	51 71 31 SE SW	1.7	10/1976	12/1982	01/1982	08/1982
215	CR-3	Dry Fork above mouth of Moyer Spring	Dry Fork	51 72 24 SE SE	9.0	10/1981	12/1982	06/1974	08/1982
216	SG-3	Railroad Loop Draw	Dry Fork	51 71 31 SE NE	--	--	--	04/1979	12/1979
217	SG-2	Railroad Loop Draw	Dry Fork	51 71 30 NE SE	--	--	--	04/1979	08/1979
218	CR-1	Moyer Springs Creek at v-notch weir	Dry Fork	51 71 30 NW NW	--	10/1980	12/1982	04/1979	12/1982
219	CR-2	Moyer Springs Creek at mouth	Dry Fork	51 72 24 NE SE	2.2	10/1981	12/1982	05/1981	12/1982
220	CSG-1	North Draw	Dry Fork	51 72 24 NW SE	--	--	--	01/1982	10/1982
221	CSG-2	North Draw	Dry Fork	51 72 24 NE SE	--	--	--	12/1981	12/1982
222	CM3-D	Unnamed	Dry Fork	51 72 13 SE SE	--	--	--	04/1979	10/1982
223	MC-3	Dry Fork north of permit boundary	Dry Fork	51 72 13 SW NE	--	03/1979	09/1980	--	--