HYDROGEOLOGY OF AND POTENTIAL MINING IMPACTS ON STRIPPABLE LIGNITE AREAS IN THE DENVER AQUIFER, EAST-CENTRAL COLORADO

By Nancy E. Driver and Robert S. Williams, Jr.

U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS REPORT 84-4366

Prepared in cooperation with the
U.S. BUREAU OF LAND MANAGEMENT

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

Lakewood, Colorado
1986

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

Colorado District Chief
U.S. Geological Survey, WRD
Box 25046, Mail Stop 415
Denver Federal Center
Denver, Colorado 80225

Copies of this report
can be purchased from:

Open-File Services Section
Western Distribution Branch
U.S. Geological Survey
Denver Federal Center
Box 25425, Mail Stop 306
Denver, CO 80225
Telephone: (303) 236-7476

CONTENTS

FIGURES

TABLES

METRIC CONVERSION FACTORS

The inch-pound units used in this report may be converted to metric SI (International System of Units) units by using the following conversion factors:

Multiply inch-pound unit	*By*	*To obtain metric unit*
foot	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
gallon per minute (gal/min)	0.06309	cubic meter per second
inch	25.40	millimeter
mile	1.609	kilometer
square mile	2.590	square kilometer

To convert degrees Celsius (°C) to degrees Fahrenheit (°F) use the following formula: (°Cx9/5)+32=°F.

The following terms and abbreviations also are used in this report: micrograms per liter (μg/L); milligrams per liter (mg/L); and microsiemens per centimeter at 25° Celsius (μS/cm).

HYDROGEOLOGY OF AND POTENTIAL MINING IMPACTS ON STRIPPABLE LIGNITE AREAS IN THE DENVER AQUIFER, EAST-CENTRAL COLORADO

By Nancy E. Driver and Robert S. Williams, Jr.

ABSTRACT

This study describes the hydrogeology of and potential mining impacts on areas of strippable lignite in the Denver aquifer in the east-central Colorado plains. Strippable lignitic coal seams, 20 to 60 feet thick, are present in the Denver Formation. The Denver aquifer, the saturated part of the Denver Formation, is likely to be affected locally by surface mining of lignite. Transmissivity of the aquifer in the study area ranges from 15 to 160 feet squared per day. Dissolved-solids concentrations increase from 145 to 1,000 milligrams per liter to the northeast in the study area as hydraulic head decreases from 6,600 to 5,400 feet. Distance-drawdown curves show the extent of water-level drawdown near a dewatered surface mine. After reclamation of the lignite mine pit, flow through the lignite spoil pile may increase the dissolved-solids concentrations in the Denver aquifer. This increase could occur because, as water from rain and overland flow percolates through the newly-exposed rock surfaces in the spoil material, minerals from the overburden can be dissolved in the water, which then joins with water from the aquifer. This increase could locally change streams, springs, and alluvial aquifers and affect users of domestic water.

INTRODUCTION

The Denver aquifer is the principal source of domestic and stock water in the study area, which is located in the east-central Colorado plains. It is also the only bedrock aquifer that would be directly affected by strip mining of the lignite zones. The U.S. Bureau of Land Management is required to determine suitability of land for leasing federally-owned coal under its jurisdiction. The hydrologic system is one component of the natural regime that needs to be evaluated in the suitability assessment. Lands in this category overlie the Denver Formation in the study area and are called Preference Right Lease Application areas, hereafter referred to as PRLA areas, by the U.S. Bureau of Land Management. A PRLA area is a site where the Federal Government owns the mineral rights, and the minable coal is within 200 feet of the land surface.

Purpose and Scope

The purposes of this report are to: (1) Provide interpretive information on the geologic setting and hydraulic and chemical characteristics of the ground water in the Denver Formation in and adjacent to the area of possible lignite mining; and (2) hypothesize potential changes in the hydrology and water quality of the area caused by lignite mining.

Results of this study will help U.S. Bureau of Land Management personnel make reasonable estimates of the potential hydrologic impacts of the surface mining of federally-owned coal within the Denver Formation. New data collected for this study consist of 15 water-quality samples and several water-level measurements taken from the 1,650 square-mile study area in east-central Colorado.

Previous Work

The Denver Formation, its lignitic coal seams, and its ground water have been investigated in many studies; however, only one study has addressed the potential impacts of coal mining on the Denver aquifer, the saturated part of the Denver Formation (Robson and Romero, 1981).

Several reports have been written on the coal resources of the Denver Formation. Soister (1972) prepared a detailed map of the Strasburg Northwest quadrangle and graphic sections of 22 coal prospects and 10 water-well logs. Soister (1974) produced a preliminary report on the mining history and geology of the lignite in the Denver Formation. Soister (1981) discussed the suitability of Colorado lignite for underground coal gasification. Kirkham (1978) compiled a listing of coal mines and coal analysis from drill holes in the Denver basin. Kirkham and Ladwig (1979) prepared a report on the general geology, coal-mining history, and coal resources of the Denver Formation. Kirkham and Ladwig (1980) discussed resource characteristics, developmental potential, and environmental problems associated with mining lignite in the Denver Formation.

McLaughlin (1946) described the geology and ground-water resources of parts of Lincoln, Elbert, and El Paso Counties. Romero (1976) provided detailed information on the geology, ground-water resources, and chemical quality of the ground water of the Denver basin aquifers. Robson and Romero (1981) presented the geologic structure, hydrology, and water quality of the Denver aquifer. Robson (1983) described the hydraulic characteristics of the Denver basin bedrock aquifers.

Acknowledgments

Appreciation is extended to the landowners who permitted water samples to be collected on their property. Richard Watson of the U.S. Bureau of Land Management contributed significantly to the study with detailed information and maps within and surrounding the study area. Field data were collected and preliminary data manipulations were performed by Stephen E. Hammond of the U.S. Geological Survey.

DESCRIPTION OF STUDY AREA

The study area, approximately 1,650 square miles, extends from 5.5 miles north of Watkins to 7.6 miles south of Calhan and lies in sections of Arapahoe, Elbert, and El Paso Counties, east-central Colorado (fig. 1). The study area lies in the Colorado Piedmont physiographic division which characteristically has late mature to old elevated plains. Boundaries of the study area encompass the region that may be affected by surface mining in the PRLA areas.

The study area consists of gently rolling plains averaging 300 to 500 feet of local relief. Altitudes range from 5,500 feet in the north to 6,700 feet in the south. Grasses and small cacti are the primary vegetation. Groves of pine trees are on some of the hilltops. Hay and wheat are grown on dryland farms on the lowlands. Primary use of the land is cattle grazing. Four intermittent creeks flow through the study area: Kiowa, Wolf, Comanche, and West Bijou. Primary uses of water in the area are for residents and livestock as little water is used for irrigation of croplands. There presently (1984) is no coal mining in the area.

The average annual rainfall in the study area ranges from 13 to 17 inches (U.S. National Oceanic and Atmospheric Administration, 1982). Most of the precipitation falls as rain, primarily in the spring, but 2 to 6 feet of snowfall in the winter is common. Low humidity and high winds are characteristic of the area. The average monthly temperature ranges from 15° to 75°F, with an annual average of 59°F. The extremes in temperature range from -38°F to more than 100°F (Hansen and others, 1978).

The study area is populated by a widely dispersed rural community; only three towns, Bennett, Calhan, and Kiowa, were listed in the 1980 Census (U.S. Department of Commerce, 1980). Populations of these towns range from about 200 to 900 people.

GEOLOGIC SETTING

Denver Basin

The Denver basin (fig. 2) extends over a 6,700 square-mile area from Greeley in the north to Colorado Springs in the south, and from the Front Range in the west to near Limon in the east. The Denver basin is the southern basin of two basins that were formed by an assymetrical, plunging syncline with its long axis extending in a north-south direction. A series of anticlinal arches form topographic boundaries around much of the basin. The beds on the southern, eastern, and northern margins of the Denver basin dip gently toward the basin center. However, the western boundary is unlike the rest of the basin's boundaries in that it is marked by abrupt topographic relief and a major structural zone, the Front Range structural zone. The Precambrian rocks here generally dip 40° to 45° to the east (Kirkham and Ladwig, 1979).

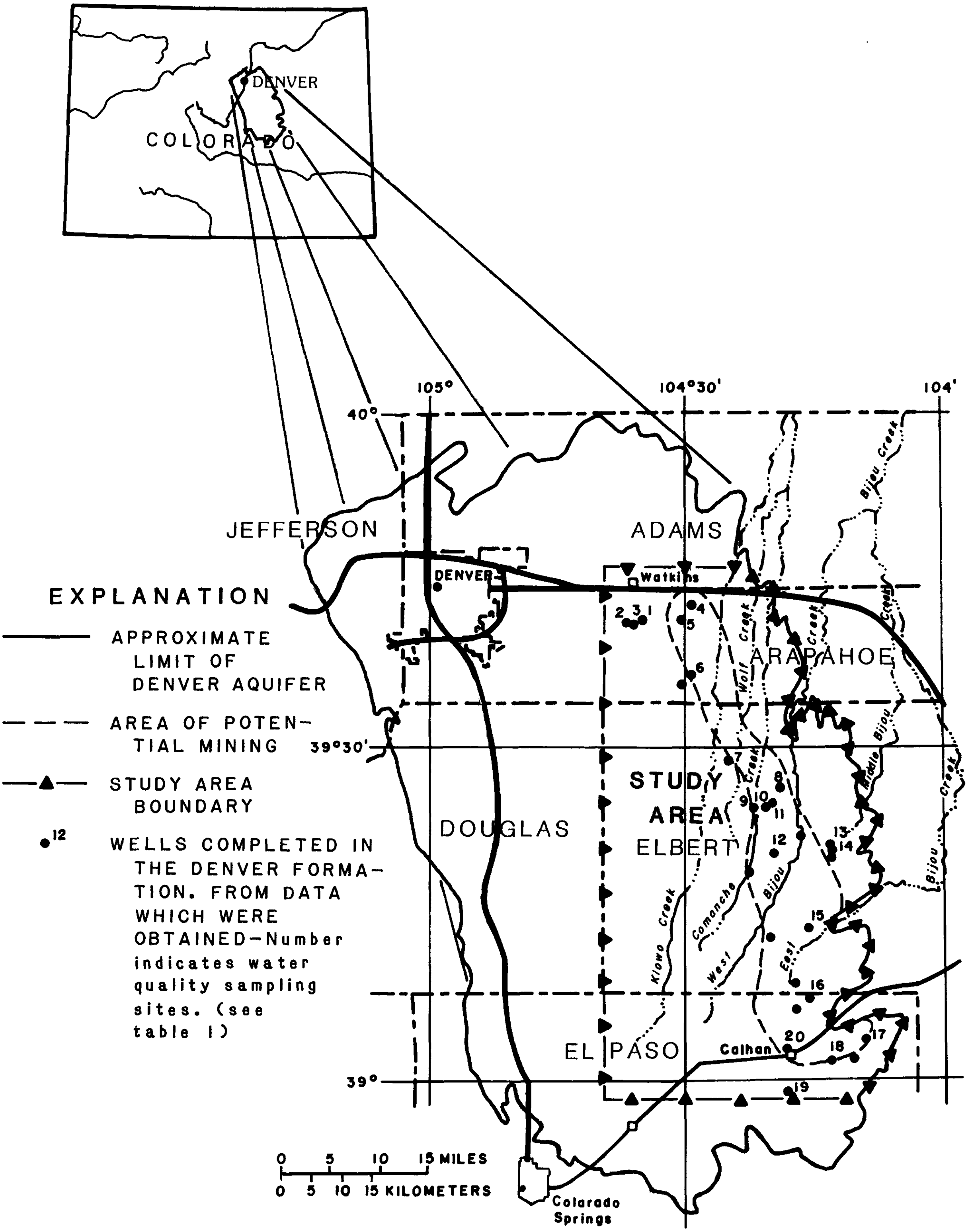
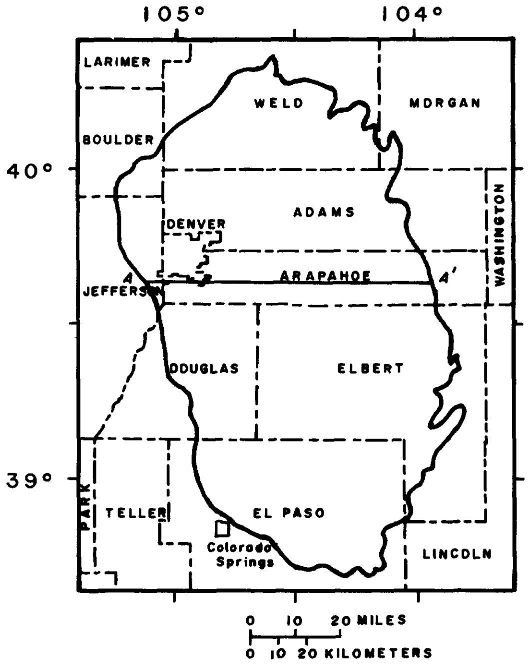
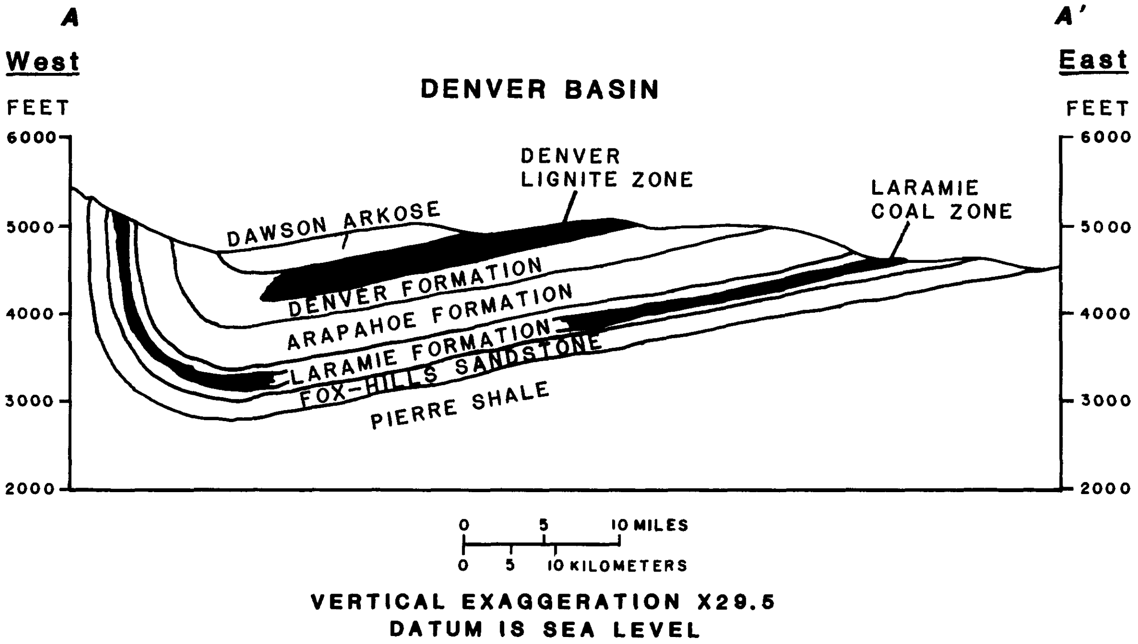


Figure 1.--Location of study area and wells from which data were obtained.



A. Boundary of Denver basin



B. Generalized geologic section of Denver basin showing coal resources (modified from Kirkham and Ladwig, 1979).

Figure 2.--Boundary and generalized geologic section of Denver basin: A, Boundary of Denver basin, and B, Generalized geologic section of Denver basin showing coal resources (modified from Kirkham and Ladwig, 1979).

Four major aquifers occur in the uppermost formations of the Denver basin; they are, in ascending order: (1) Fox Hills Sandstone and the Laramie Formation of Late Cretaceous age, (2) Arapahoe Formation of Late Cretaceous age, (3) Denver Formation of Late Cretaceous and early Tertiary age, and (4) Dawson Arkose of Tertiary age (fig. 2). The nearly impermeable Pierre Shale of Late Cretaceous age underlies the Fox Hills Sandstone and is considered to be the base of the major bedrock-aquifer system. Drilling through as much as 8,000 feet of the Pierre Shale would be required to obtain water, which would be briny, from formations below the Fox Hills Sandstone.

Denver Formation

Description

The Denver Formation consists of 600 to 1,600 feet of medium-yellow to light-gray claystone, shale, siltstone, very fine to fine-grained sandstone, and andesitic conglomerate. The Denver Formation crops out throughout the study area, where it ranges in thickness from 100 to 800 feet. Throughout most of the outcrop area, the formation is generally exposed or covered by a thin layer of soil. Along the small stream valleys, the formation is buried by 20 to 100 feet of Quaternary deposits. The presence of andesite clasts in the conglomerate beds is a distinguishing characteristic of the Denver Formation. Thick lignite beds, fossilized plant remains, and carbonaceous shales are present in the upper 500 feet of the formation. The lignite beds are thickest and most prevalent in the eastern part of the basin.

The formation was deposited in a continental environment. Sandstone and conglomerate beds east of the uplifted Rocky Mountains were deposited in a braided-stream complex. East of this depositional complex, silts, clays, and lignites were deposited on an alluvial plain in low-gradient streams, overbank areas, and marshes (Kirkham and Ladwig, 1979).

Lignite Resources

The Denver Formation is of primary interest in this study because all the strippable lignite in the study area lies within this formation (fig. 2). Thick lignite beds are present in the upper 300 to 500 feet of the Denver Formation; they are thickest and most prevalent in its eastern part. The most visible outcrops of the lignite are in streams and roadcuts in the West Bijou Valley and the Kiowa Creek area. Because the lignite weathers rapidly and disintegrates completely, the lignite zone is well-exposed only in recent road cuts.

The lignite zone consists of three to eight lignite beds interbedded with carbonaceous shale. Total thickness of the interbedded lignite zone within the 200-foot strippable depth ranges from 20 to 60 feet. Individual lignite beds range from 0.5 to 30 feet thick in the study area and average 10 to 15 feet thick. Most lignite beds contain numerous noncoal partings consisting of claystone, siltstone, and sandstone. Parting thickness ranges from less than 0.1 inch to more than 2 feet. Generally, net lignite thickness is 70 to

95 percent of gross lignite thickness, which also includes the partings (Kirkham and Ladwig, 1979).

The areal extent of the lignite zone within the study area is depicted in figure 3. The zone is divided into a northern and southern lignite area, each with its unique stratigraphy. Individual beds are continuous throughout most of the northern area. Along the southern edge of the northern lignite area, the lignite beds thin and completely pinch out. In the southern lignite area, the beds are in a stratigraphic sequence completely dissimilar lithologically to that of the northern lignite area.

The deepest lignite bed in the northern area is within 200 feet of the surface and is strippable throughout the study area. In the southern lignite area, the base of the Dawson Arkose, which is 25 to 75 feet above the top of the uppermost lignite bed, marks the top of the lignite zone.

The lignite in the Denver Formation is brownish-black to black and weathers and disintegrates quickly. Quality of the lignite is inconsistent and varies with the number and thickness of noncoal partings and the rank and physical character of lignite. Analyses indicate that most of the lignite ranks as lignite A, which is a high grade of lignite.

Kaolin, a group of high-alumina clay minerals having the approximate composition, $Al_2Si_2O_5(OH)_4$, is the primary parting in the lignite. In some areas, kaolinite beds 2 to 5 feet thick overlie individual lignite seams. The kaolinite contains alumina (Al_2O_3), which is a potential source of aluminum (Kirkham and Ladwig, 1979). If an extraction process becomes economically feasible, the Denver Formation may have a dual-resource potential. Therefore, the mining of the lignite also may be economically benefited by the mining of kaolinite.

HYDROGEOLOGIC SETTING

The water-bearing layers of the Denver Formation are sandstone and siltstone that are present in irregular beds scattered among thick sequences of claystones and shales. The sandstone and siltstone layers generally are lens-shaped and range in thickness from a few inches to 50 feet (Robson and Romero, 1981). Because the sandstones and siltstones are moderately consolidated and more coarse-grained than the claystones and shales, ground water flows easily through the sandstones and siltstones, but flow is inhibited in the claystones and shales. Therefore, the aquifer consists of a complex pattern of permeable and impermeable beds that differ in their ability to store and transmit water.

The ground-water level near the margin of the Denver aquifer is below the top of the Denver Formation, and the formation is only partly saturated. The Denver aquifer in this area extends approximately from the base of the Denver Formation to the potentiometric surface. Where the Dawson Arkose overlies the Denver Formation, the entire thickness of the Denver Formation is assumed to be saturated. The size, shape, and thickness of the Denver aquifer, as described in Robson and Romero (1981), generally correspond with the size, shape, and thickness of the Denver Formation.

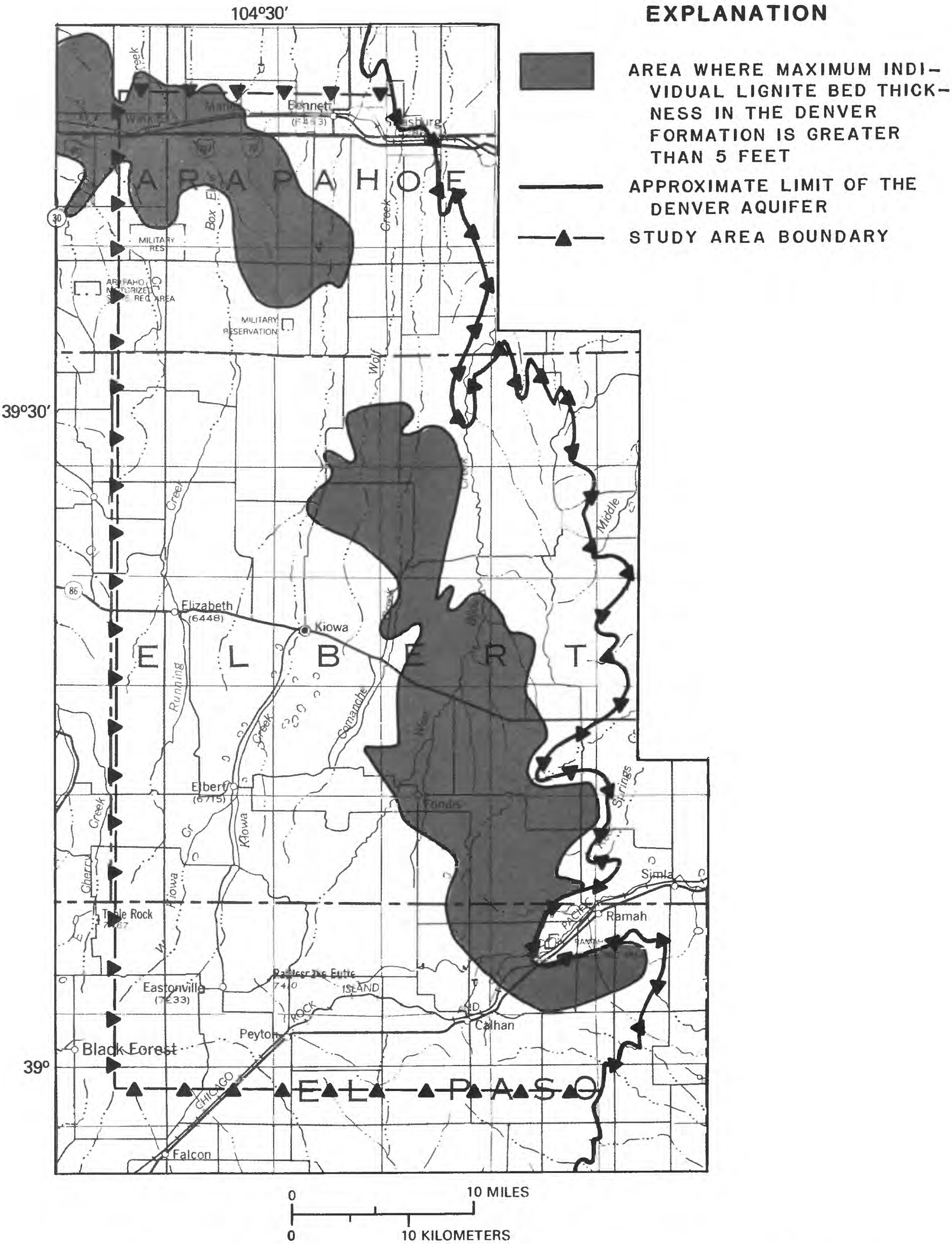


Figure 3.--Map showing areal extent of the lignite beds in the Denver Formation, where maximum individual lignite-bed thickness is greater than 5 feet.

The Denver aquifer is one of the major bedrock aquifers in the Denver basin. The aquifers are, from deepest to shallowest: (1) Laramie-Fox Hills aquifer; (2) Arapahoe aquifer; (3) Denver aquifer; and (4) Dawson aquifer (fig. 4). The Denver aquifer is the subject of this report because it is the only bedrock aquifer that would be directly affected by strip mining of the lignite zones in the study area.

The Denver aquifer is the principal source of domestic and stock water for rural residents in the western half of Arapahoe County, central Elbert County, and north-central El Paso County. Although hay and other crops are cultivated throughout these counties, little or no water is withdrawn from this aquifer to irrigate commercial crops (Robson and Romero, 1981).

In the study area, the Denver aquifer consists of water-bearing sandstone and siltstone lenses above and below the lignite beds. Because drill holes in the study area are sparse and located at irregular intervals, the areal extent and thickness of the sandstone and siltstone units in the study area are difficult to determine. However, available data indicate that the water-bearing sandstone and siltstone units are lens-shaped and discontinuous. In the strippable interval, the top 200 feet of the Denver Formation in the study area, sandstone and siltstone lenses probably range in thickness from a few inches to 20 feet; local, isolated lenses are as much as 30 to 40 feet thick.

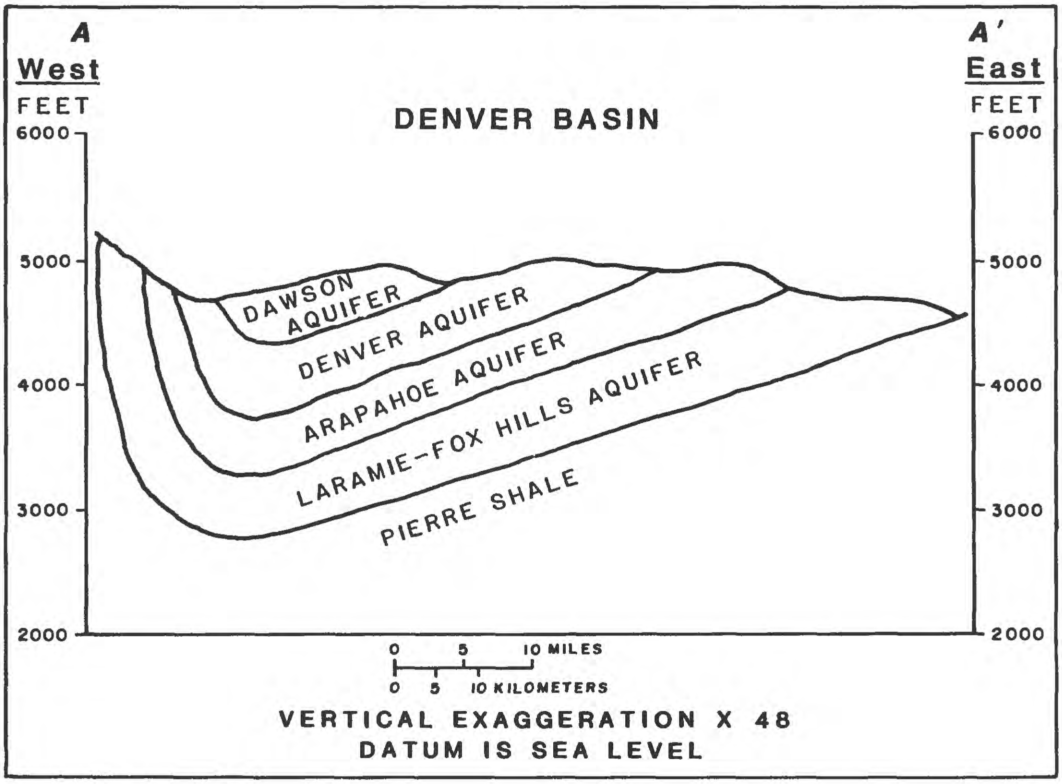


Figure 4.--Generalized west-east section of the Denver basin aquifers.

The Denver aquifer is a series of confined and unconfined sandstone and siltstone units surrounded by claystone and shale. Most of the lower part of the Denver aquifer is confined; whereas, the upper part of the aquifer generally is unconfined (Robson, 1983). The unconfined part of the aquifer would be affected most by mining. Lignite zones are present in the upper part of the aquifer in the study area. Logs of wells drilled in the study area indicate that the lignite zones are surrounded by clay and that confined or unconfined conditions may exist there. Existing data indicate that lignite beds are not major water-bearing units but may transmit some water (Kirkham and Ladwig, 1980).

The direction of ground-water movement in the Denver aquifer is variable. Generally, ground water flows from the south-central area, where the Denver aquifer underlies the Dawson aquifer, toward the aquifer outcrop in the northern, eastern, and southern margins of the Denver Formation (Robson and Romero, 1981). After reaching these margins, the ground water then moves toward the north-trending stream valleys. In the western part of the aquifer, the movement is approximately parallel to the aquifer limit toward the north and south, or east from the aquifer limit toward the South Platte River (Robson and Romero, 1981).

Recharge to the Denver aquifer is from direct precipitation, overland flow, and infiltration or leakage from the overlying Dawson aquifer. In the outcrop of the Denver aquifer, where the study area is located, the Dawson aquifer is not present. The Denver aquifer gains and loses water to alluvial aquifers and streams. Small amounts of water from the aquifer also percolate downward to the Arapahoe aquifer (fig. 5). Ground water discharged from the Denver aquifer into stream valleys is either lost to evapotranspiration, or it is stored in alluvial deposits and does not result in measurable increases in streamflow.

HYDRAULIC CHARACTERISTICS OF AQUIFERS

Transmissivity

Transmissivity values used in this report are derived from the equation:

$$T=Kb,$$

where

T is transmissivity, in feet squared per day;
K is hydraulic conductivity, in feet per day; and
b is saturated thickness of the aquifer, in feet.

Transmissivity represents the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient. Hydraulic conductivity is a measure of the relative ease with which a porous media can transmit a liquid under a potential gradient.

Transmissivity values of the Denver aquifer were based on specific-capacity tests on wells near and within the study area. Also, laboratory analyses of hydraulic conductivity, porosity, specific retention, specific yield, and grain-size distribution from undisturbed samples of permeable

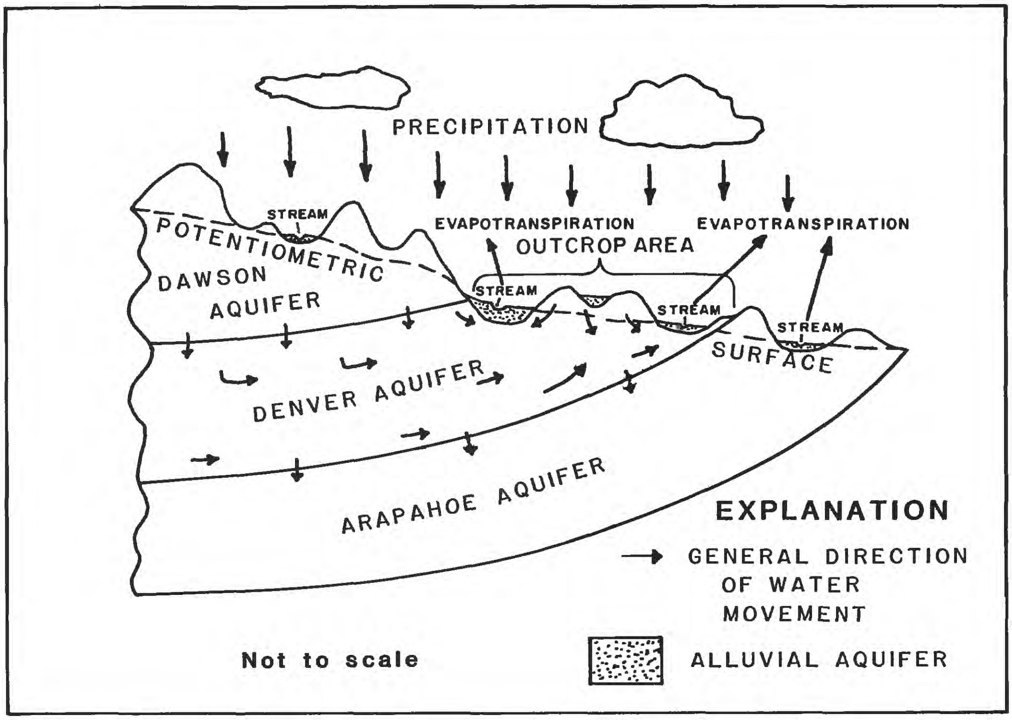


Figure 5.--Diagrammatic section of the Denver aquifer flow system (modified from Robson and Romero, 1981).

bedrock were performed to supplement the specific-capacity tests (Robson, 1983). Saturated-thickness values were taken from a sandstone- and siltstone-thickness map that depicts the water-yielding beds in the Denver Formation (Robson and Romero, 1981). A transmissivity map (fig. 6), modified from Robson (1983), depicts the transmissivity values within the study area. Transmissivity values in the study area range from 15 to 160 feet squared per day, with an average transmissivity of 50 feet squared per day. If hydraulic conductivity data were not available, hydraulic conductivity was estimated as depicted in figure 6 (Robson, 1983).

Specific Storage and Storage Coefficient

Specific storage and storage coefficients of confined and unconfined systems vary substantially; representative average values for each parameter were used for hydraulic analyses. Specific storage in a confined aquifer is related to porosity, compressibility of the rock, and compressibility of water by the equation:

$$S_s = Y(\Phi C_w + C_r),$$

where

S_s is specific storage, in foot^{-1};

Y is specific weight of water, in pounds per cubic inch;

ϕ is porosity (dimensionless);

C_w is compressibility of water, in inches squared per pound; and

C_r is compressibility of the rock, in inches squared per pound.

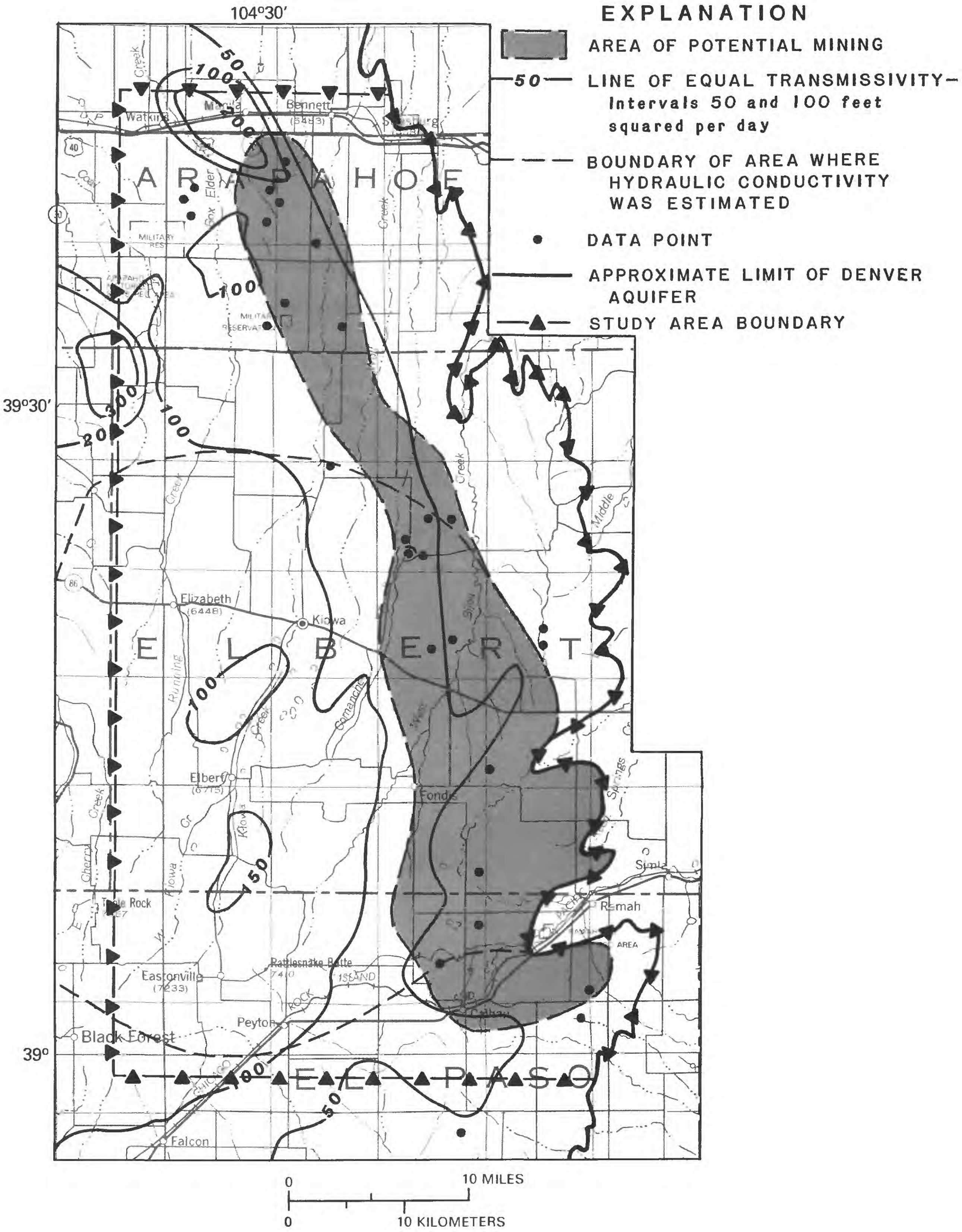


Figure 6.--Transmissivity of the Denver aquifer in the study area (modified from Robson, 1983).

The average storage coefficient for the confined water-bearing material is computed as the product of the average specific storage, 2×10^{-6}, (Robson, 1983) and the thickness of the saturated material in the Denver aquifer as shown in Robson and Romero (1981). The computed average storage coefficient, S, is 2×10^{-4} (range 1×10^{-4} to 3×10^{-4}). The drawdown values calculated at storage coefficients of 1×10^{-4} or 3×10^{-4} differ by less than 8 percent from the drawdown values calculated at the average storage coefficient, 2×10^{-4}. Saturated thickness in the study area ranges from 30 to 165 feet.

The average storage coefficient of the unconfined water-bearing material is derived from the average specific yield, 19 percent, of sandstones and siltstones in the aquifer multiplied by the percent composition, 30 percent, of these units within the aquifer. The computed average storage coefficient is 0.06 (range 0.04 to 0.08). The drawdown calculated at storage coefficients of 0.04 or 0.08 differs by less than 10 percent from the drawdown values calculated at the average storage coefficient of 0.06. The percent differences of the drawdown values calculated at the average storage coefficients for confined and unconfined water-bearing material are insignificant in regard to predicted effects.

Curves Relating Drawdown, Distance from the Pumped Well, Pumping Rate, and Duration of Pumping

Five diagrams showing water-level drawdown with distance for the Denver aquifer (figs. 7-11) depict the drawdown that could be expected to occur in an idealized confined or unconfined aquifer as a result of pumping water from wells. These diagrams are a tool for estimating the long- and short-term effects of dewatering a mine within the study area. These curves serve only as a general guide to the possible range of drawdowns since they assume idealized conditions. In practice, the rate at which water is pumped from the mines will vary with time as the saturated thickness of the aquifer changes. If several coal mines start up and pumping expands in the study area, the water pumped from a single mine and hydraulic gradient will be altered. Site-specific information will be needed to predict the effects of dewatering.

These head-loss curves were calculated using the Theis nonequilibrium formula (Theis, 1935):

$$s = \frac{Q}{4\pi T} W(u),$$

where

s is drawdown, in feet;
Q is pumping rate, in cubic feet per day;
T is transmissivity, in feet squared per day; and
W(u) is well function (dimensionless).

The value of the well function, W(u), is given by the series

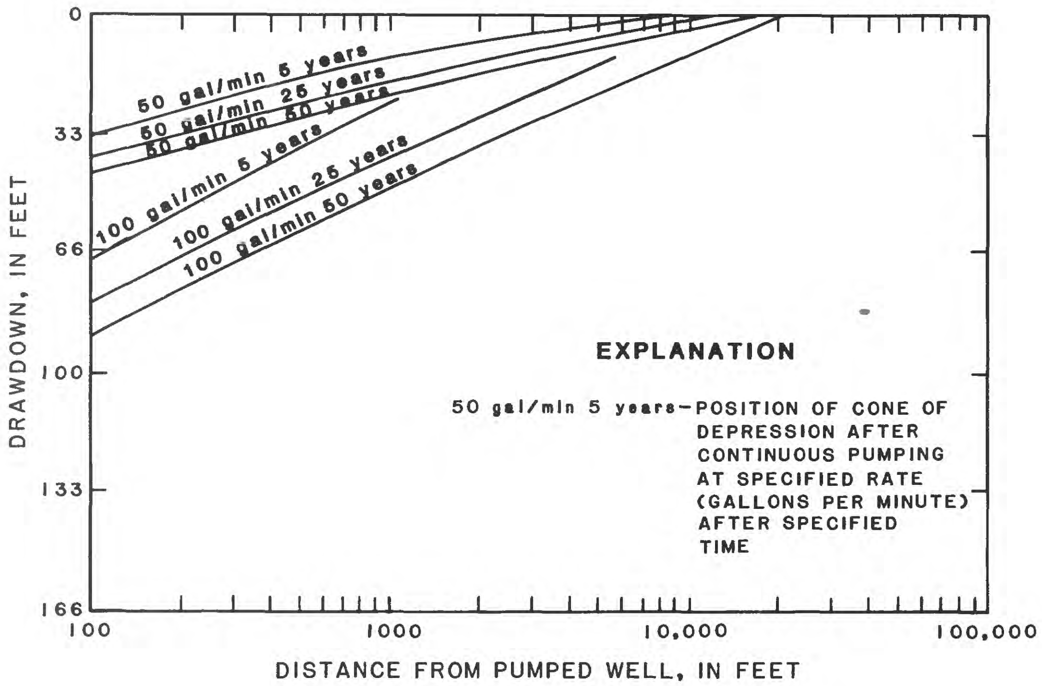


Figure 7.--Distance-drawdown curves for an unconfined aquifer (storage coefficient=0.06) having a transmissivity of 160 feet squared per day.

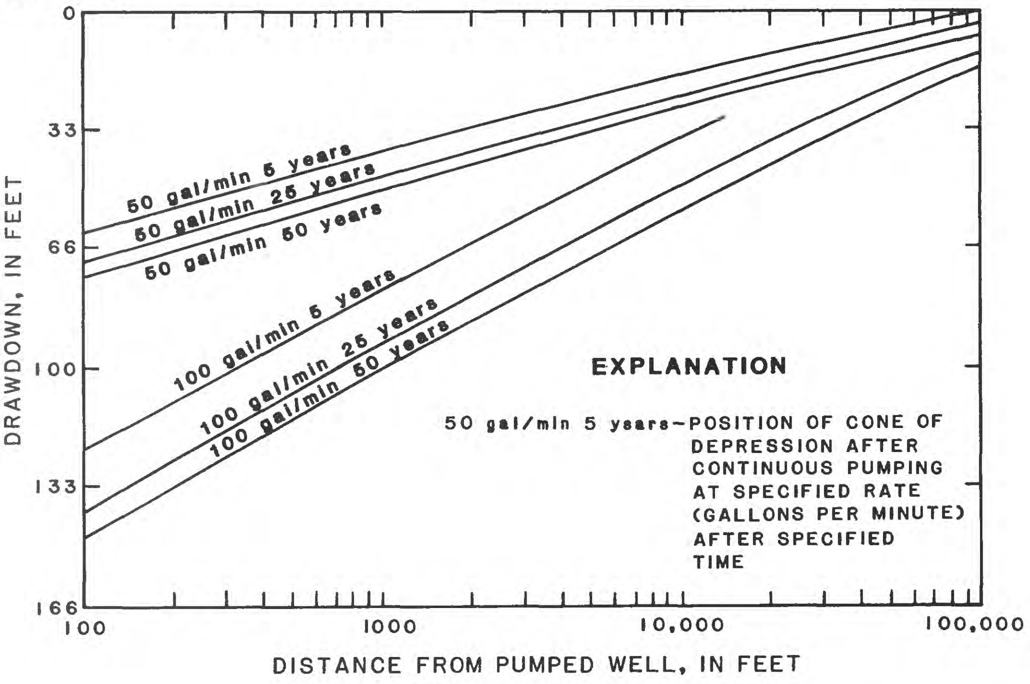


Figure 8.--Distance-drawdown curves for a confined aquifer (storage coefficient=0.0002) having a transmissivity of 160 feet squared per day.

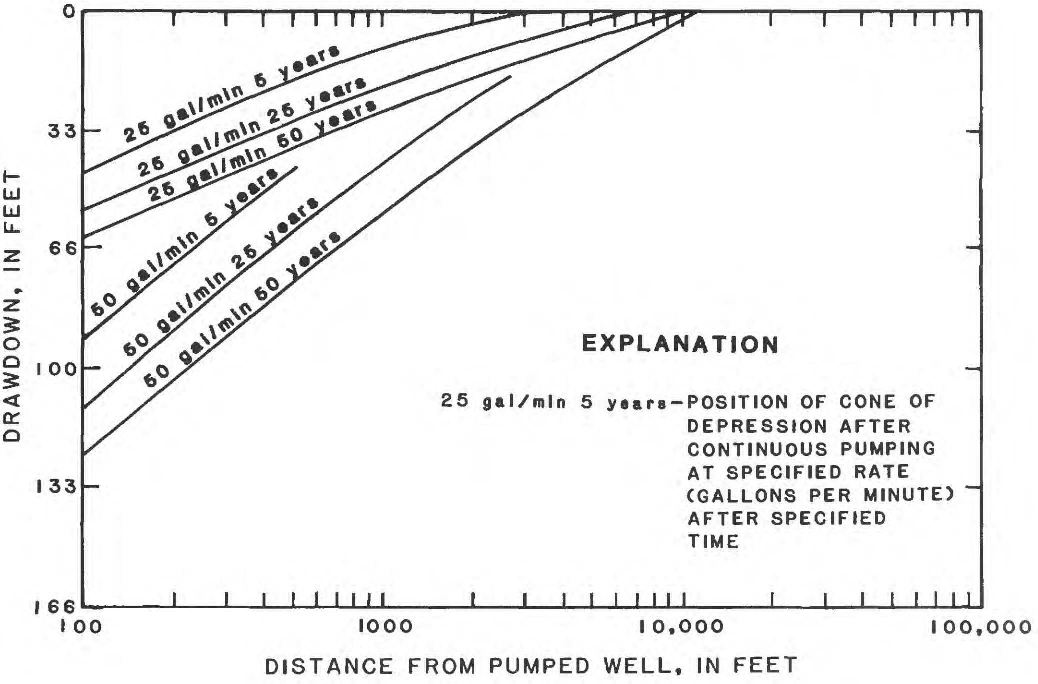


Figure 9.--Distance-drawdown curves for an unconfined aquifer (storage coefficient=0.06) having a transmissivity of 50 feet squared per day.

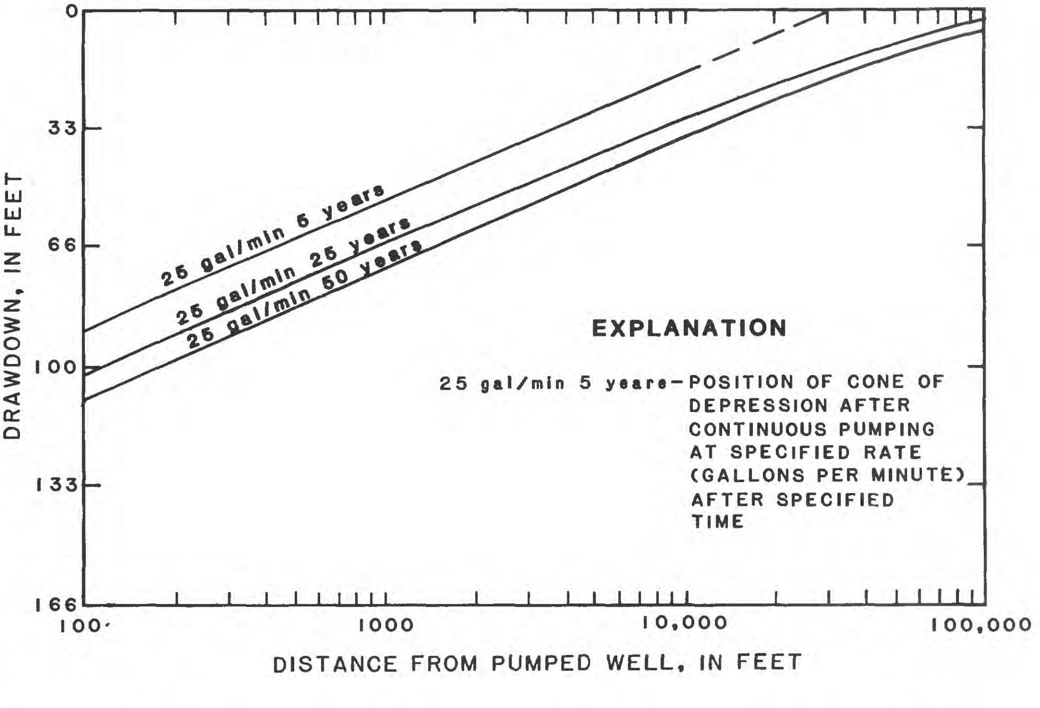


Figure 10.--Distance-drawdown curves for a confined aquifer (storage coefficient=0.0002) having a transmissivity of 50 feet squared per day.

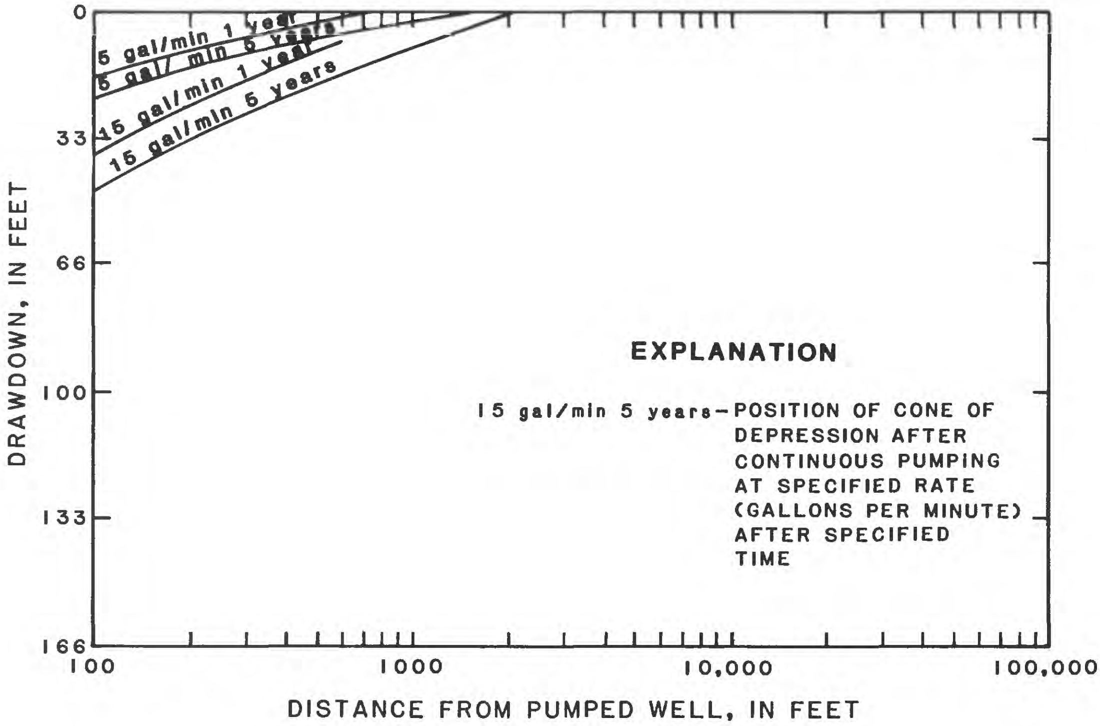


Figure 11.--Distance-drawdown curves for an unconfined aquifer (storage coefficient=0.06) having a transmissivity of 15 feet squared per day.

$$W(u)=-0.5772-\log_e u + u - \frac{u^2}{2x2!} + \frac{u^3}{3x3!} - \cdot \cdot \cdot$$

where

$$u=\frac{r^2 S}{4Tt}$$

r is distance from pumped well, in feet;
S is storage coefficient (dimensionless);
T is transmissivity, in feet squared per day; and
t is time since pumping started, in days.

W(u) is normally obtained from well-function tables, which can be found in Theis (1935).

The smallest (15 feet squared per day), average (50 feet squared per day), and greatest (160 feet squared per day) transmissivity values of the Denver aquifer in the study area were used to construct the curves. Because the Denver aquifer contains confined and unconfined units, two values of storage were used with two of the three transmissivity values to define the curves. As previously stated, an average storage coefficient of 0.0002 was used to represent confined aquifers; whereas, an average storage coefficient value of 0.06 was used to represent unconfined aquifers.

Distance-drawdown curves are useful and relatively simple tools for the resource manager who needs to estimate the effects of dewatering a particular site. The distance-drawdown curves in figures 7-11 show sample calculations of instantaneous drawdowns that could occur during mine floor dewatering. These rough estimates provide qualitative information. Three hydraulic characteristics must be determined at each site to apply the curves: (1) Aquifer transmissivity; (2) whether the aquifer is unconfined or confined; and (3) rate of pumping. Application of these curves is discussed in the section, Potential Impacts of Mining.

Distance-drawdown curves are theoretical tools. Assumptions in applying the Theis nonequilibrium equation are: (1) That the aquifer is homogenous, isotropic, of uniform thickness, and of infinite areal extent; (2) that the pumped well penetrates the entire aquifer, and flow is everywhere horizontal within the aquifer to the well; and (3) that transmissivity is constant at all times. Other assumptions are described in Theis (1935). When large drawdown occurs in a water-table aquifer, the dewatering causes a reduction in transmissivity that violates the assumptions. To avoid incorrect application of the distance-drawdown curves, the resource manager must limit the use of the curves to large radial distances from the well or mine. At large distances from the center of the cone of depression, transmissivity does not change significantly. Therefore, distance-drawdown curves may be used to estimate drawdowns with time at a distance, but not to estimate drawdown near the well or mine. At the time of mining, site-specific information must be collected to determine effects of dewatering.

The maximum saturated thickness of the Denver aquifer near and within the study area is approximately 200 feet (Robson and Romero, 1981). The maximum depth of a strip mine in the study area would be approximately 200 feet. In order to dewater a large area of the mine, some wells may need to be drilled deeper than 200 feet; however, a more typical dewatering practice would be direct pumping from the mine floor. The curves, therefore, are presented with a maximum drawdown of approximately 200 feet.

In an unconfined aquifer having a transmissivity of 160 feet squared per day, drawdown after 50 years of pumping is negligible at about 4 miles from the pumped well (fig. 7). Where the aquifer is confined and has an equally large transmissivity, smaller pumping rates must be assumed to prevent rapid lowering of the head in the well (fig. 8). However, the effects of pumping after 50 years will be negligible beyond a radius of 70 miles.

The distance-drawdown relation for unconfined aquifers having a transmissivity of 50 feet squared per day is illustrated in figure 9. The greatest distance measurably affected by pumping at a mine under these conditions would be approximately 2 miles. Drawdowns in a confined aquifer having a transmissivity of 50 feet squared per day are shown in figure 10. The effects of pumping 50 gallons per minute for 50 years will be negligible beyond a radius of 40 miles.

Distance-drawdown curves for an unconfined aquifer having a transmissivity of 15 feet squared per day are depicted in figure 11. The maximum radius of the area that would be significantly affected by pumping is less than one-half mile. The families of curves relating drawdown, distance from the pumped well, and duration of pumping are chosen to represent a range of possible values, because the hydrogeologic properties of the aquifers vary tremendously throughout the study area.

Potentiometric Surface

Water levels were measured in April 1982 in wells near and in the study area. Depths to water in 1982 closely correlated with measurements taken in 1978. The potentiometric-surface map of the study area (fig. 12), modified from the potentiometric-surface map by Robson and Romero (1981), is based on both 1978 and 1982 water-level measurements.

The potentiometric-surface map depicts the altitudes of standing-water levels in part of the Denver aquifer. The altitude of the potentiometric surface is highest in the south and lowest in the north. Water in the aquifer moves from points of higher water-level altitude to areas of lower water-level altitude along lines that are at right angles to the potentiometric contours shown on the map. Therefore, the water in the study area generally flows in a northeasterly direction.

GROUND-WATER QUALITY

Analyses of 15 ground-water samples were used as a basis for interpretation. The samples were taken from wells located in or near the eastern outcrop of the Denver aquifer within the 1,650-square-mile study area. The limited number of analyses does not allow intensive evaluations of downgradient flow paths or chemical evolution. This section describes the water quality of the wells sampled. The sampled wells are open to the Denver aquifer which could be affected by lignite mining. This section also discusses possible reasons for the chemical characteristics of the ground water. However, additional information and analysis are needed to properly identify the geochemical controls acting on the ground-water system.

To determine the impacts that surface mining could have on ground-water quality, the premining ground-water flow path, the chemical quality of the water, and the chemical-equilibrium conditions of the ground water need to be defined before mining. The flow path shows the direction in which potential solutes from mining probably would travel. Under normal conditions, ionic concentrations would form certain patterns along the flow path. Therefore, the following chemical patterns would be expected along the flow path in the study area before mining: dissolved-solids, sulfate, and bicarbonate concentrations and pH values should increase downgradient from the area of recharge toward the area of discharge. Chemical-equilibria data help determine the direction of the flow path and which dissolved constituents are likely to enter the aquifer system as a result of mining. The following data (tables 1, 2, and 3) were used to determine these changes.

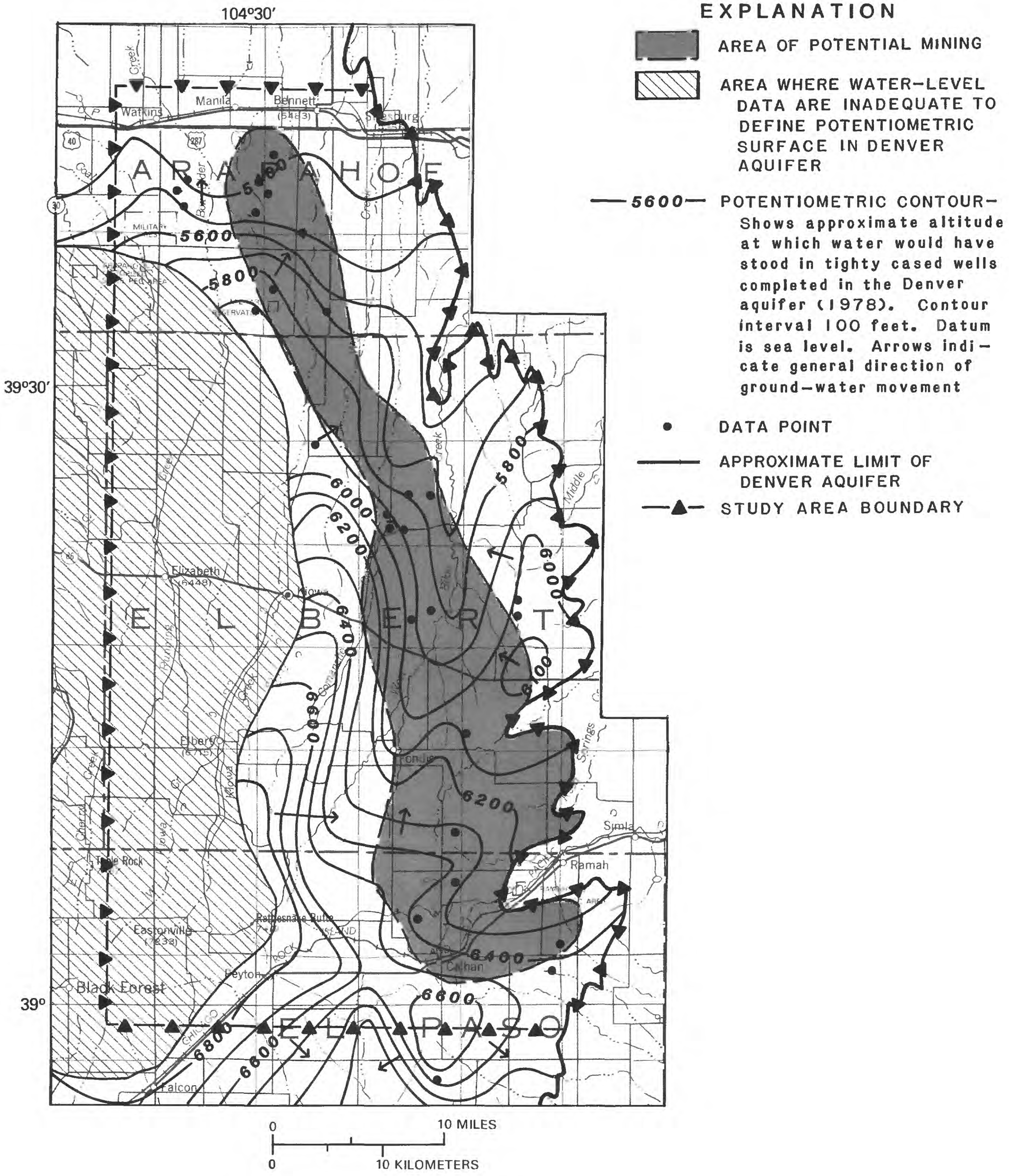


Figure 12.--Potentiometric surface of the Denver aquifer (modified from Robson and Romero, 1981).

Table 1.--*General information on the wells sampled in the Denver aquifer for water-quality analysis in the study area*

Sample number	Well identifier	Lithology within the Denver aquifer	Elevation (in feet)	Depth drilled (in feet)	Depth of screened intervals (in feet)	Water level (feet below land surface)
1	SC00406416CDD1	sandy clay	5,735	731	468-475, 559-585, 610-710	330
2,3	SC00406420CDB1	sandstone	5,752	575	340-575	240
4	SC00406307CCB1	sandstone	5,717	515	415-515	191
5	SC00406413CCA1	sandstone	5,754	755	555-755	414
6	SC00506424BDA1	sandy shale	6,000	156	114-142	112
7	SC00606334CAB1	sandy shale	6,067	155	111-155	120
8	SC00706214BDB1	sandstone	5,770	189	75-120, 130-157, 160-180	64
9	SC00706227BCB1	sandy shale	5,910	307	79-105, 210-235, 283-303	137
10,11	SC00706229ADA1	sandstone	6,150	479	299-383, 404-479	399
12	SC00806222AAB1	sandstone and shale	5,960	275	200-275	156
13	SC00806222ACB1	sandstone	6,110	174	111-165	125
14	SC00806127BDB1	sandstone	6,224	200	160-190	178
15	SC01006130ABC1	sandstone and shale	6,325	227	165-220	12
16	SC01106106DBD1	sandstone	6,360	231	91-101, 161-171, 211-231	145
17	SC01106031AAA1	sandstone	6,535	190	70-96, 136-190	178
18	SC01206104CCB1	sandstone	6,660	290	200-290	144
19	SC01306201CCB1	sandstone	6,673	225	165-225	171
20	SC01106234DCA1	sandy clay	6,512	195	58-195	41

Table 2.--*Specific conductance, pH, dissolved solids, and major dissolved constituents of ground-water samples in the Denver aquifer*

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; FET-FLD, fixed endpoint titration, onsite value]

Sample number	Well identifier	Date of sample	Specific conductance (µS/cm)	pH onsite	Solids, sum of constituents, dissolved (mg/L)	Bicarbonate FET-FLD (mg/L as HCO3)	Calcium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Sulfate, dissolved (mg/L)
1	SC00406416CDD1	82-05-12	340	8.3	224	195	11	77	17
2	SC00406420CDB1	78-09-19	450	7.7	309	290	24	98	15
3	SC00406420CDB1	82-05-12	460	7.9	286	293	21	90	5.0
4	SC00406307CCB1	82-05-12	350	8.0	274	256	22	91	5.0
5	SC00406413CCA1	82-05-12	410	8.2	269	268	15	89	5.0
6	SC00506424BDA1	82-05-12	1,000	7.5	817	195	130	97	430
7	SC00606334CAB1	78-09-19	845	7.4	600	170	110	70	280
8	SC00706214BDB1	82-05-18	1,400	7.8	964	256	89	200	510
9	SC00706227BCB1	82-05-18	780	7.6	544	317	46	140	170
10	SC00706229ADA1	78-10-09	470	8.0	316	320	12	110	12
11	SC00706229ADA1	82-05-18	500	8.0	369	317	35	140	10
12	SC00806222AAB1	82-05-18	930	8.2	602	293	22	160	250
13	SC00806122ACB1	82-05-18	350	7.1	301	96	63	49	100
14	SC00806127BDB1	82-05-18	890	7.2	659	183	100	100	330
15	SC01006130ABC1	82-05-17	1,100	8.5	676	268	18	210	290
16	SC01106106DBD1	78-09-21	1,480	7.4	972	460	28	320	370
17	SC01106031AAA1	78-10-04	561	7.3	337	210	45	54	59
18	SC01206104CCB1	82-05-17	370	6.8	242	43	68	28	68
19	SC01306201CCB1	78-10-02	232	8.2	145	110	3.3	49	24
20	SC01106234DCA1	82-05-17	600	7.4	446	134	59	70	210

Table 3.--*Temperature, alkalinity, hardness, and minor constituents of ground-water samples in the Denver aquifer*

[mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than]

Sample number	Well identifier	Date of sample	Temperature (degrees Celsius)	Alkalinity field (mg/L as $CaCO_3$)	Hardness (mg/L as $CaCO_3$)	Magnesium dissolved (mg/L)	Nitrogen, NO2+NO3 dissolved (mg/L as N)	Phosphorus, dissolved (mg/L)	Potas-, sium, dissolved (mg/L)	Chloride, dissolved (mg/L)
1	SC00406416CDD1	82-05-12	15.5	160	31	0.9	.02	.050	2.5	6.0
2	SC00406420CDB1	78-09-19	21.0	240	67	1.8	.04	--	3.4	11
3	SC00406420CDB1	82-05-12	15.0	240	59	1.5	.03	.060	3.4	9.7
4	SC00406413CCA1	82-05-12	13.0	210	64	2.3	.03	.070	3.4	8.5
5	SC00406413CCA1	82-05-12	12.0	220	42	1.2	.18	.060	2.7	9.3
6	SC00506424BDA1	82-05-12	11.5	160	380	13	.13	.080	10	24
7	SC00606334CAB1	78-09-19	13.0	140	300	6.3	.32	--	9.5	15
8	SC00706214BDB1	82-05-18	21.0	210	260	8.7	.89	<.010	5.1	9.6
9	SC00706227BCB1	82-05-18	21.5	260	140	7.2	.18	.020	3.2	8.7
10	SC00706229ADA1	78-10-09	17.0	260	35	1.3	.02	.010	3.1	7.7
11	SC00706229ADA1	82-05-18	18.5	260	100	3.2	.09	.020	3.8	7.6
12	SC00806222AAB1	82-05-18	25.0	240	63	2.0	.02	.040	3.2	6.8
13	SC00806122ACB1	82-05-18	25.0	79	180	5.9	.17	<.010	6.0	1.8
14	SC00806127BDB1	82-05-18	25.0	150	280	8.1	.17	.030	7.4	6.1
15	SC01006130ABC1	82-05-17	18.0	220	53	1.9	.17	.030	2.5	10
16	SC01106106DBD1	78-09-21	14.0	380	81	2.8	.71	.030	2.8	8.5
17	SC01106031AAA1	78-10-04	11.5	170	150	10	5.2	.010	4.2	22
18	SC01206104CCB1	82-05-17	18.0	35	210	10	<.50	.030	6.5	17
19	SC01306201CCB1	78-10-02	16.0	90	9	.20	.10	.030	.7	2.3
20	SC01106234DCA1	82-05-17	19.5	110	170	5.0	.23	<.010	3.1	5.3

Table 3.--*Temperature, alkalinity, hardness, and minor constituents of ground-water samples in the Denver aquifer*--Continued

Sample number	Well identifier	Date of sample	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Lead, dissolved (µg/L)	Manganese, dissolved (µg/L)	Zinc, dissolved (µg/L)	Selenium, dissolved (µg/L)
1	SC00406416CDD1	82-05-12	2.3	11	60	34	<1	8	13	<1
2	SC00406420CDB1	78-09-19	1.1	11	--	30	--	20	--	--
3	SC00406420CDB1	82-05-12	1.3	10	50	39	<1	15	15	<1
4	SC00406307CCB1	82-05-12	2.6	13	60	95	<1	27	35	<1
5	SC00406413CCA1	82-05-12	1.7	13	60	73	<1	21	13	<1
6	SC00506424BDA1	82-05-12	1.1	14	50	440	<1	180	220	1
7	SC00606334CAB1	78-09-19	.8	23	--	40	--	20	--	--
8	SC00706214BDB1	82-05-18	.8	10	60	37	<1	110	120	1
9	SC00706227BCB1	82-05-18	1.5	10	60	49	<2	67	110	<1
10	SC00706229ADA1	78-10-09	1.9	9.9	--	140	--	20	--	--
11	SC00706229ADA1	82-05-18	1.9	11	60	75	<5	44	25	<1
12	SC00806222AAB1	82-05-18	.9	13	50	27	<2	57	31	<1
13	SC00806122ACB1	82-05-18	1.0	26	40	88	<2	160	280	<1
14	SC00806127BDB1	82-05-18	.5	15	70	21	<2	110	530	<1
15	SC01006130ABC1	82-05-17	1.9	9.4	40	21	5	26	13	1
16	SC01106106DBD1	78-09-21	1.1	9.1	--	20	--	60	--	--
17	SC01106031AAA1	78-10-04	.6	15	--	130	--	20	--	--
18	SC01206104CCB1	82-05-17	.1	23	20	100	<5	240	180	10
19	SC01306201CCB1	78-10-02	.6	10	--	20	--	<10	--	--
20	SC01106234DCA1	82-05-17	.4	26	30	13	<5	5	42	<1

Fifteen domestic and stock wells were sampled in April 1982; water samples had been collected from five wells in September 1978, near and within the study area. The 15 wells were selected for sampling because they were in or near the coal-lease areas, were completed solely in the Denver aquifer, and drilling and completion information were available (table 1). Specific conductance, pH, and temperature were measured at the time of sample collection. Samples were analyzed for major and minor dissolved constituents at the U.S. Geological Survey National Water-Quality Laboratory in Arvada, Colo. Data on specific conductance, pH, dissolved solids, and major dissolved constituents are reported in table 2; data on temperature, alkalinity, hardness, and minor constituents are presented in table 3.

The diagram in figure 13 depicts the types of water represented by the samples from the Denver aquifer. The points on the diagram are numbered to correspond with the tabulated water-quality information in tables 2 and 3. This diagram, based on the dominant ions in water, uses a percentage of equivalents per million of the anions and cations (Davis and DeWiest, 1966).

Dissolved-Solids Concentration

In general, dissolved-solids concentration of ground water increases as the water moves downgradient. In the Denver aquifer, dissolved-solids concentrations gradually increase as the water travels from areas of recharge to areas of discharge because of the dissolution of minerals by the water. The direction in which the dissolved-solids concentrations increase helps delineate the flow path of the water. According to Robson and Romero (1981), the dissolved-solids concentration is less in the central part of the aquifer where the Dawson aquifer overlies the Denver aquifer. The Dawson aquifer, primarily a sandstone formation, contains better quality water than generally exists in the Denver aquifer. Thus, any mixing of water from the Dawson aquifer with water of the Denver aquifer would improve the water quality in the Denver aquifer.

Where not overlain by the Dawson aquifer, water in the Denver aquifer generally contains larger concentrations of dissolved solids. The aquifer generally contains poor quality water near the margins where the aquifer is thinner and discharge occurs.

The dissolved-solids concentration of ground water in the study area increases in a direction generally perpendicular to the potentiometric contours of the Denver aquifer (fig. 14). Thus, dissolved-solids concentrations increase in the same general direction that ground water flows. The concentration of dissolved solids ranges from a minimum of 145 mg/L (milligrams per liter) to nearly 1,000 mg/L.

Dissolved-solids concentrations at two locations in the study area are not consistent with the increase in dissolved-solids concentrations along the flow path. In the area south of Watkins, water samples from four deep wells (samples 1-5) had substantially lower concentrations of dissolved solids than samples from other nearby wells. One possible explanation for this anomaly is that these deep wells are closer to, or are in the direct flow path of, recharge from the better quality water of the Dawson aquifer. Another

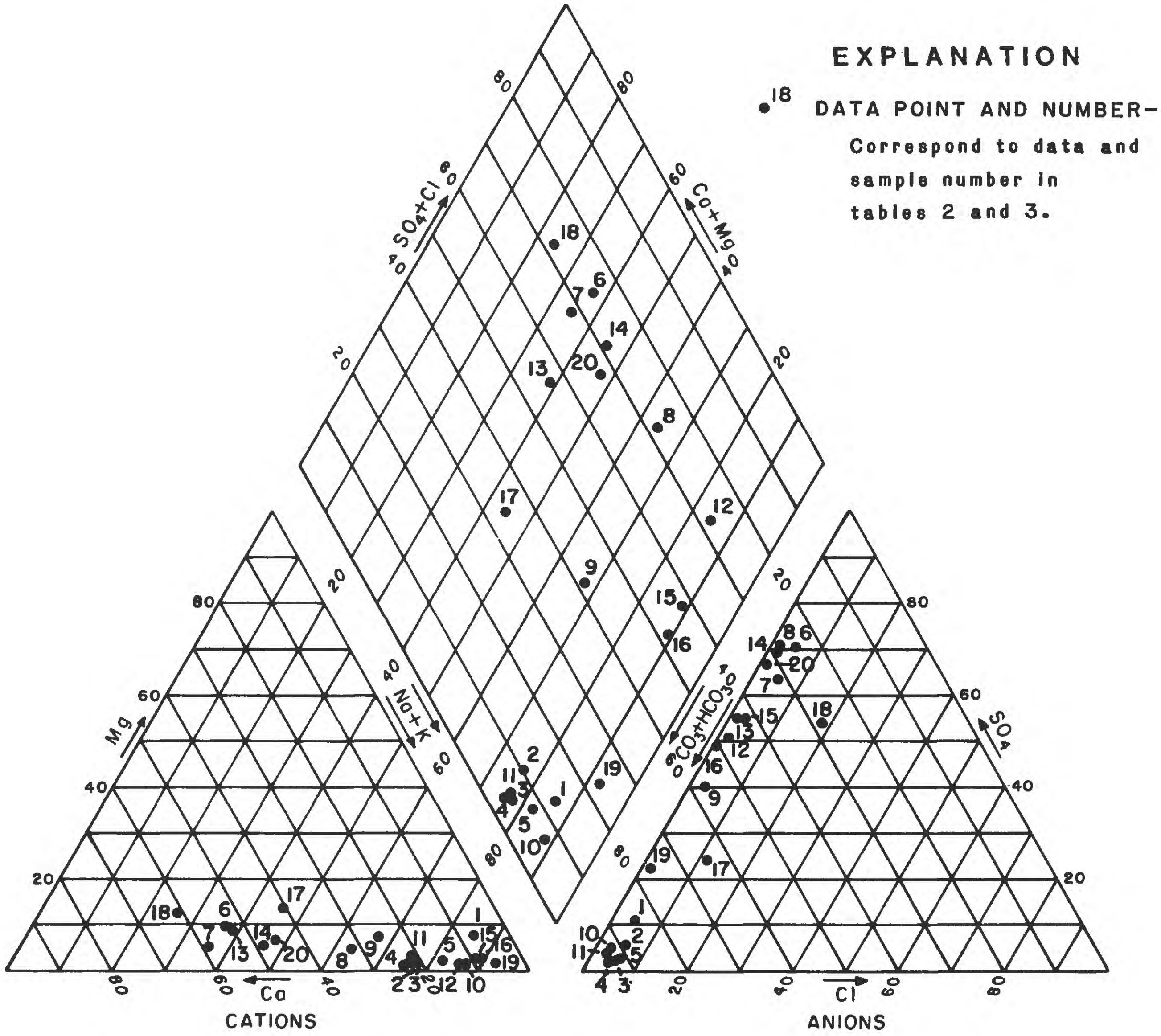


Figure 13.--Percentage-reacting values of cations and anions in water samples from the Denver aquifer.

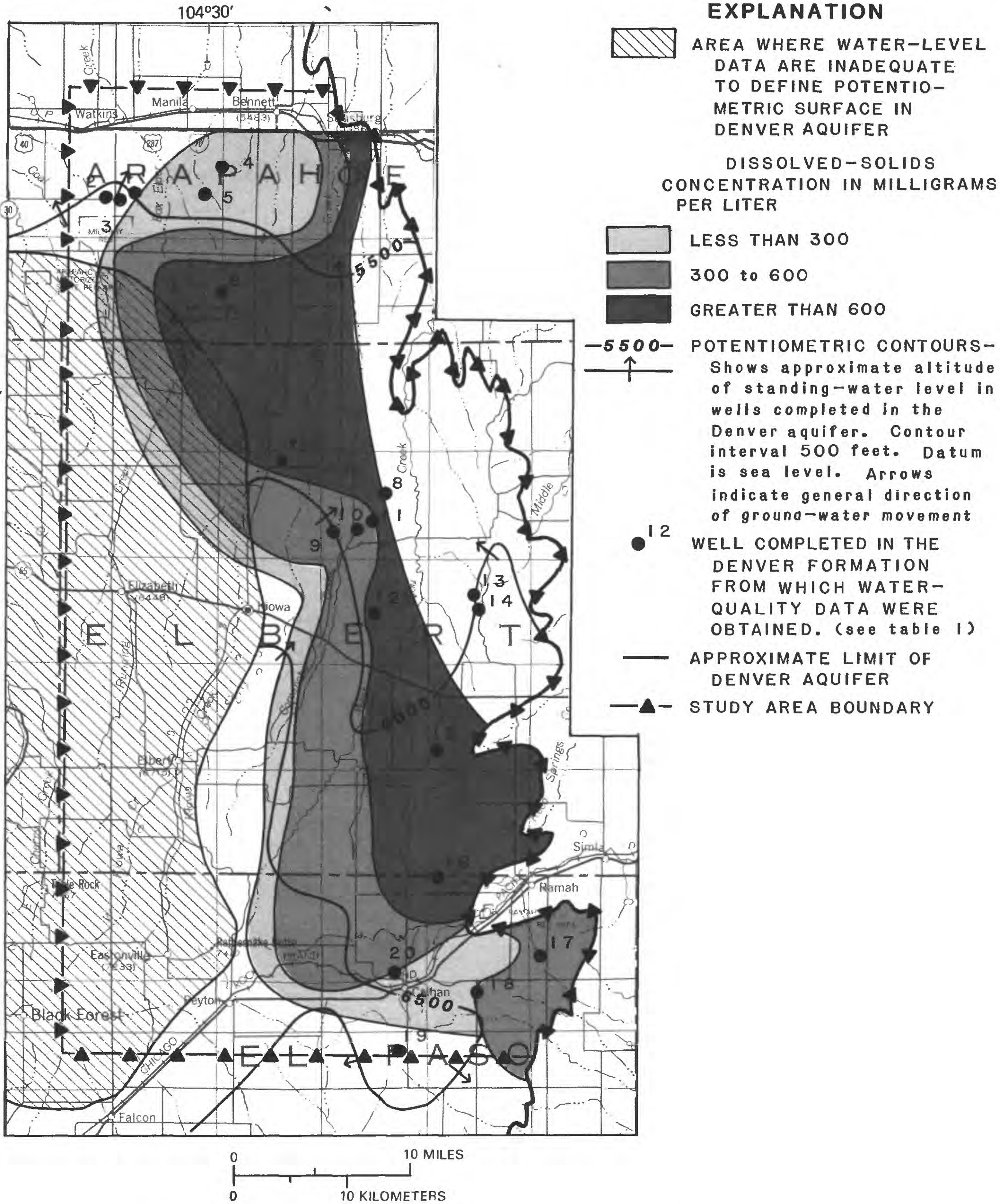


Figure 14.--Dissolved-solids concentration and potentiometric contours in the Denver aquifer.

possibility is that the drillers' logs are incorrect, and the wells are actually completed in both the Denver and Arapahoe aquifers. The second area, just south of Calhan, is a zone of recharge. Therefore, the water has not been in contact with the formation long enough to accumulate a large concentration of dissolved solids. Additional information is needed to explain these anomalies.

Dissolved-Sulfate Concentration

Sulfate ions can be introduced into the ground-water system from gypsum and pyrite. As the distance from the area of recharge increases, more sulfates will dissolve into the system until it becomes saturated. Because the Denver aquifer consists primarily of tight claystones and shales, as well as siltstone, very fine to fine-grained sandstone, and andesitic conglomerate, the ground-water flow tends to be very slow, thereby allowing available sulfates to easily dissolve into the system.

The concentration of sulfate ions in the water of the Denver aquifer follows a pattern similar to that of the dissolved solids. Generally, the dissolved-sulfate concentration increases downgradient from the southwest to the northeast (fig. 15). The central part of the Denver aquifer underlying the Dawson aquifer is low in sulfates (Robson and Romero, 1981). The concentration of dissolved sulfate is greater in the eastern part of the Denver aquifer where the aquifer thins and is closer to the surface. Three factors could cause the increase in sulfate: (1) The major source of sulfate is from the water dissolving sulfate-producing minerals as it flows downgradient; (2) because the aquifer in the study area is fairly close to the surface, a minor source of sulfate may come from sulfate-producing minerals near the surface that may have been transported to the aquifer by percolation; (3) oxidation of pyrite can input sulfate into the ground water.

The concentration of dissolved sulfate does not increase northeastward at two locations in the study area. In the area just south of Watkins, only trace amounts of sulfate ions were present in the water from sampled wells. This anomaly probably is because of the proximity of these wells to the Dawson aquifer. These wells are in the direct flow path of recharge from the better quality water of the Dawson aquifer. They also are closer than any other wells in the study area to the Dawson aquifer's recharge area. Another possibility is that the drillers' logs are inaccurate, and the wells are actually completed in both the Denver and Arapahoe aquifers. The sulfate concentration in the Denver aquifer just south of Calhan is less than that north of Calhan because the source of ground water in that area is infiltration directly from the surface. Ground water must have the opportunity to be in contact with sulfate-producing minerals before the sulfate concentration can increase. The shallow ground-water system in the Calhan area has not had sufficient contact with sulfate-producing minerals; as a result, the sulfate concentration is less in the Calhan area than in other areas.

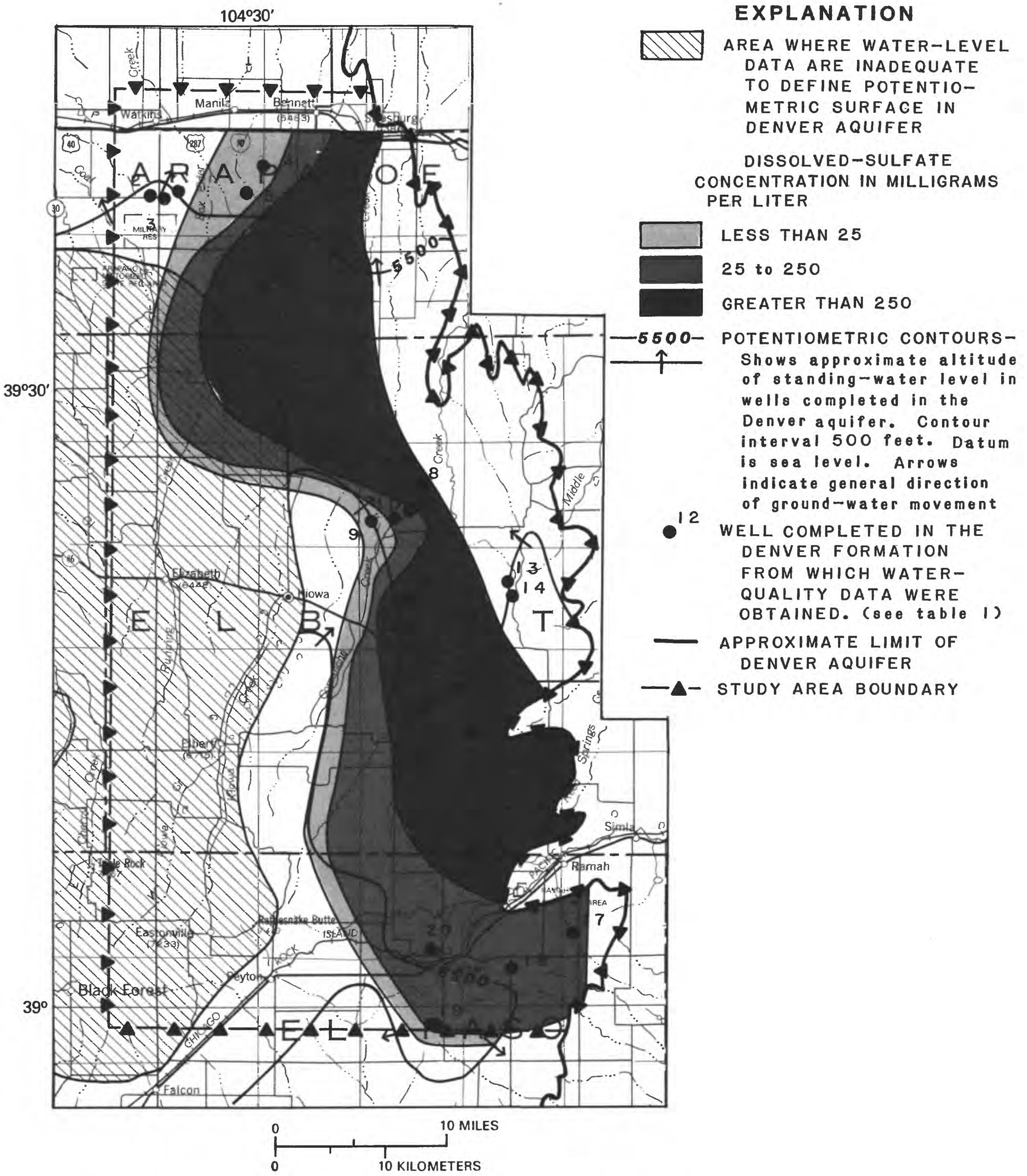


Figure 15--Dissolved-sulfate concentration and potentiometric contours in the Denver aquifer.

Dissolved-Bicarbonate Concentration and pH Values

Bicarbonate forms in the water in areas of soil-water recharge when carbon dioxide is introduced into the system through plant respiration, aerobic decay, carbonate dissolution, or the atmosphere. The partial pressure of CO_2 in the water samples shows that water in the aquifer contains CO_2 in greater concentration than exists in the atmosphere, thus indicating that CO_2 enters the system through the soil matrix. The bicarbonate concentration (fig. 16) and pH values (fig. 17) decrease very slightly from the south to the north.

Chemical Equilibrium Conditions

Chemical-equilibrium conditions of the Denver aquifer in the study area need to be defined to determine the impacts that coal mining may have on the ground-water system. Knowledge of these conditions provides a means for testing the direction of the flow path. Equilibrium conditions were determined by using the solution mineral-equilibrium model SOLMNEQ (Kharaka and Barnes, 1973).

Calcium is dissolved from calcite and gypsum. When calcium ions come in contact with sodium-rich shales and claystones, calcium in the water is replaced by sodium from the rocks resulting in sodium-type water. This exchange results in the water having a greater sodium activity (fig. 18) and smaller calcium activity. The ratio of calcium activity to sodium activity is high when the sodium activity is low. Generally, the areas having low-sodium activity and high activity ratios are in the southwestern part of the study area. This implies little cation exchange has occurred in this area. In the northeast, sodium activity values are higher and activity ratios are lower, implying additional cation exchange has occurred. This change in activities and activity ratios supports the conclusion that ground-water movement in the study area is from the southwest to the northeast. The conclusion is made in conjunction with the assumption that no additional geochemical reactions are occurring that alter the activities of calcium and sodium.

In the study area, the water is saturated or supersaturated with calcite in 13 of 20 samples. In these areas, additional dissolution of calcite minerals would be minimal unless equilibrium conditions change. However, ground water in the system is substantially undersaturated with sulfate. Therefore, as the mining process exposes new rock surfaces to physical and chemical weathering, exposed sulfate-producing minerals could be dissolved into the ground-water system.

POTENTIAL IMPACTS OF MINING

Mining can affect both the quantity and quality of an aquifer system. The following sections discuss potential premining, during mining, and after mining hydrologic conditions in the study area.

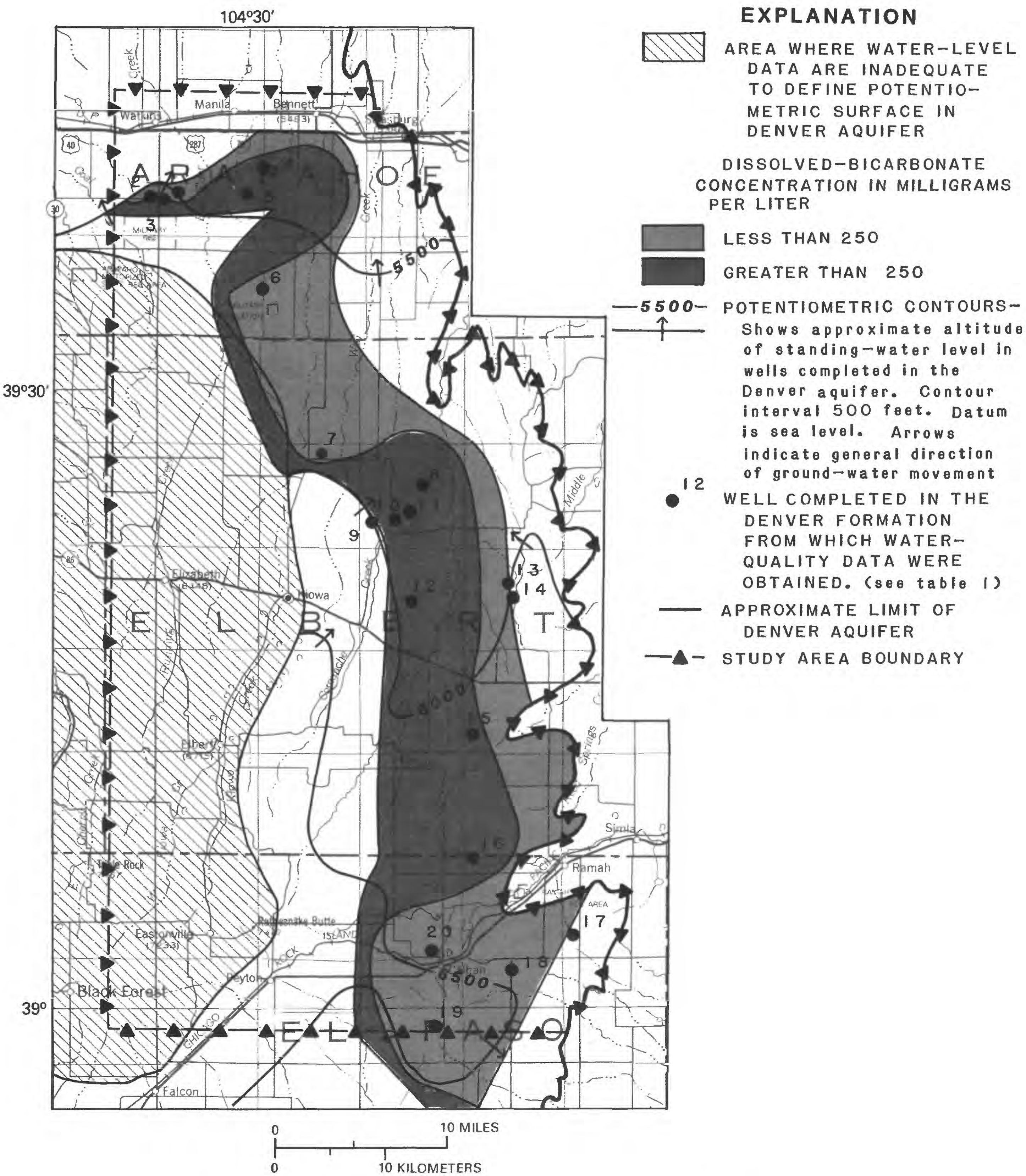


Figure 16.--Dissolved-bicarbonate concentration and potentiometric contours in the Denver aquifer.

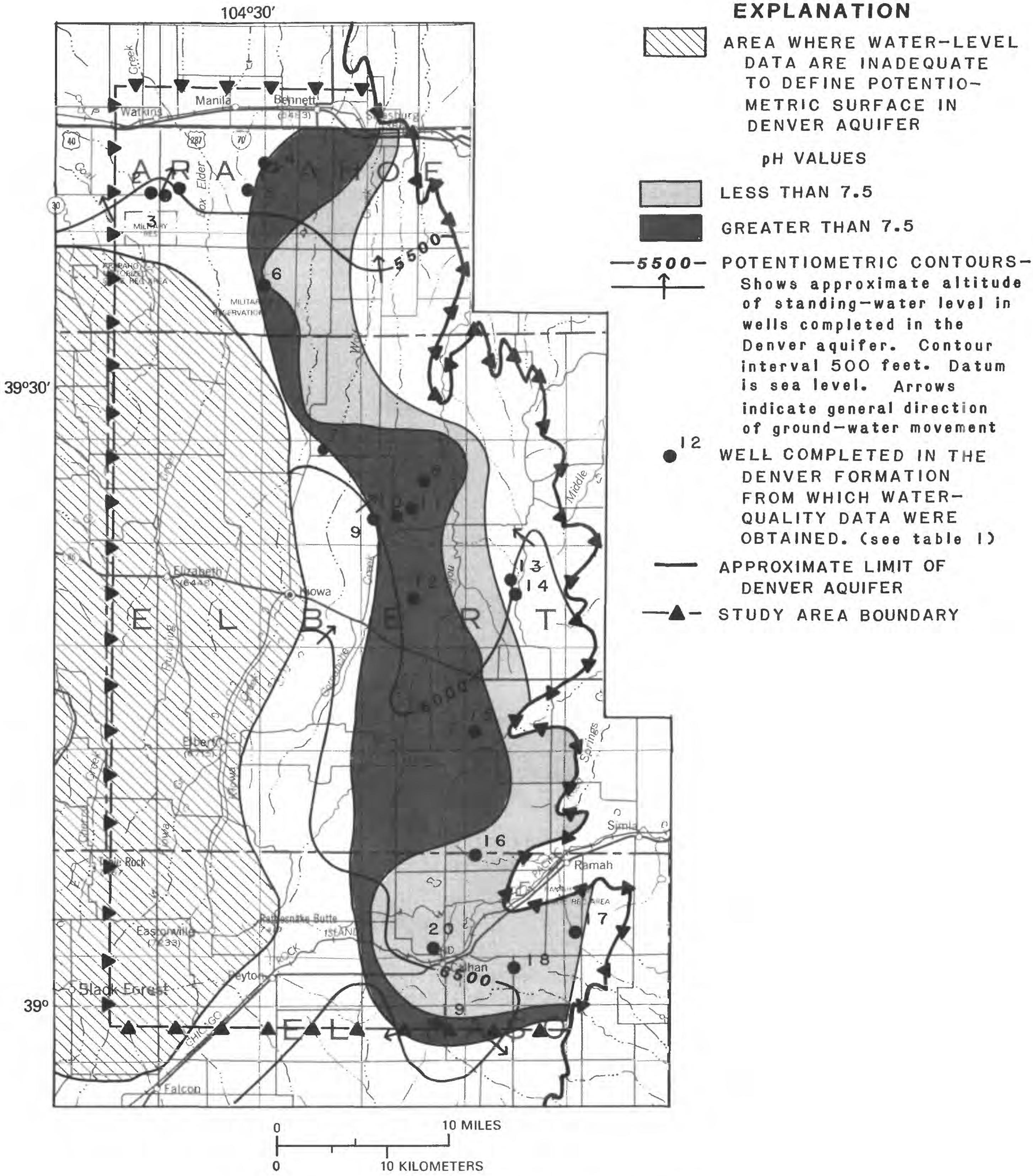


Figure 17.--pH values and potentiometric contours in the Denver aquifer.

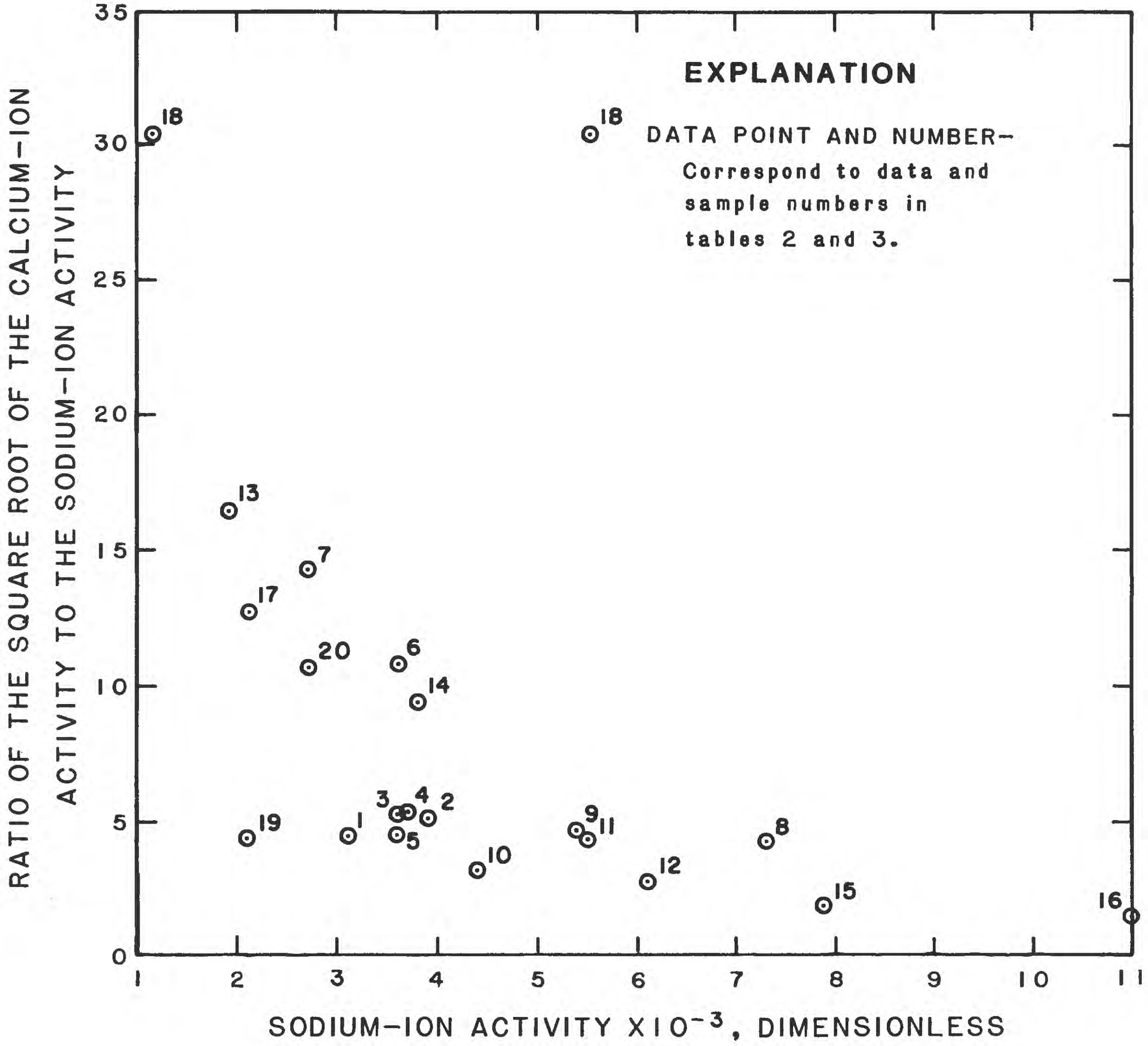


Figure 18.--Ratio of the square root of the calcium-ion activity to the sodium-ion activity as a function of the sodium-ion activity.

Conditions Before Mining

Because a variety of geologic and hydrologic conditions can exist in the study area to be mined, a sample set of premining conditions has been selected to illustrate the possible impacts of mining on an aquifer system. This set is as follows:

1. A sandstone and siltstone unit directly overlies a lignite unit. No intervening confining layers are present.
2. The sandstone, siltstone, and lignite units comprise a single, continuous aquifer.
3. The aquifer is unconfined.
4. The aquifer discharges into a stream downgradient from the area to be mined.

Premining conditions 1, 2, and 3 above are depicted in figure 19; these conditions can be used to assess the impacts of mining on the hydrologic system in the proposed mine area.

Conditions During Mining

Strip mining of lignitic coal can affect ground-water quantity locally. Aquifer disruption during mining and disturbance of the recharge areas are the primary means by which ground-water flow paths and ground-water quantity are changed. Aquifers penetrated by a surface mine will drain into the open pit. Dewatering of the mine further reduces the quantity of water within and surrounding the mine area. The effects of dewatering on water levels need to be determined.

Distance-drawdown curves are one useful and relatively simple management tool for approximately estimating the effects of mine dewatering. Five diagrams showing water-level drawdown with distance for the Denver aquifer (figs. 7 through 11) depict the drawdown curves that can be used to estimate the effects of dewatering the mines.

To apply the curves to the hypothetical mine area shown in figure 19, the assumption is made that the transmissivity of the aquifer at this site is 160 feet squared per day, and the saturated thickness is about 50 feet. If the aquifer to be dewatered is unconfined, the resource manager would use figure 7 to estimate drawdowns. The distance-drawdown curves, thereby, help to generally determine the range of drawdowns due to dewatering the mine.

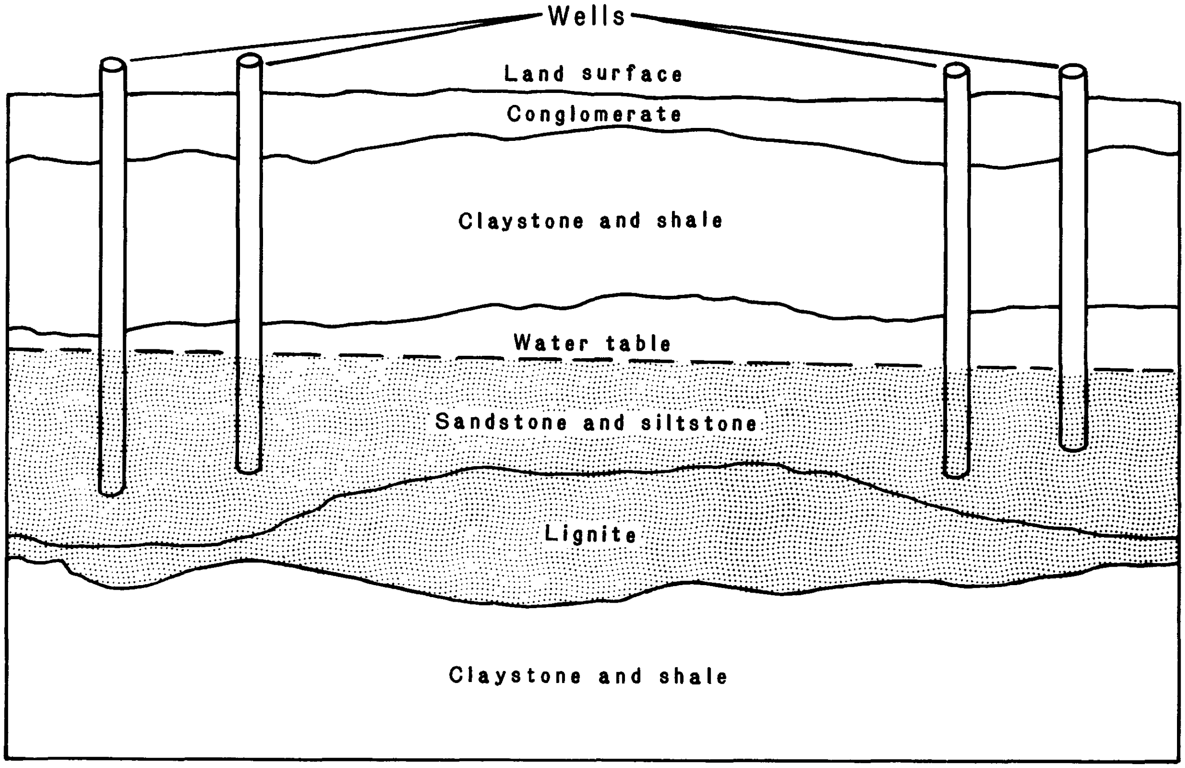
The probable outcome of the dewatering would be that domestic and stock wells within the cone of depression would either go dry or would have lower water levels (fig. 19B). Possibly this reduction in water supply would necessitate finding alternative supplies of surface water, drilling deeper wells, or lowering the pump intake. A second possible effect from dewatering might be that water levels would decline in streams and alluvial aquifers supplied by the bedrock aquifer within the cone of depression. Although water levels would decline during the mining operation, water quality in the aquifer would not change significantly at this stage of the operation.

Conditions After Mining

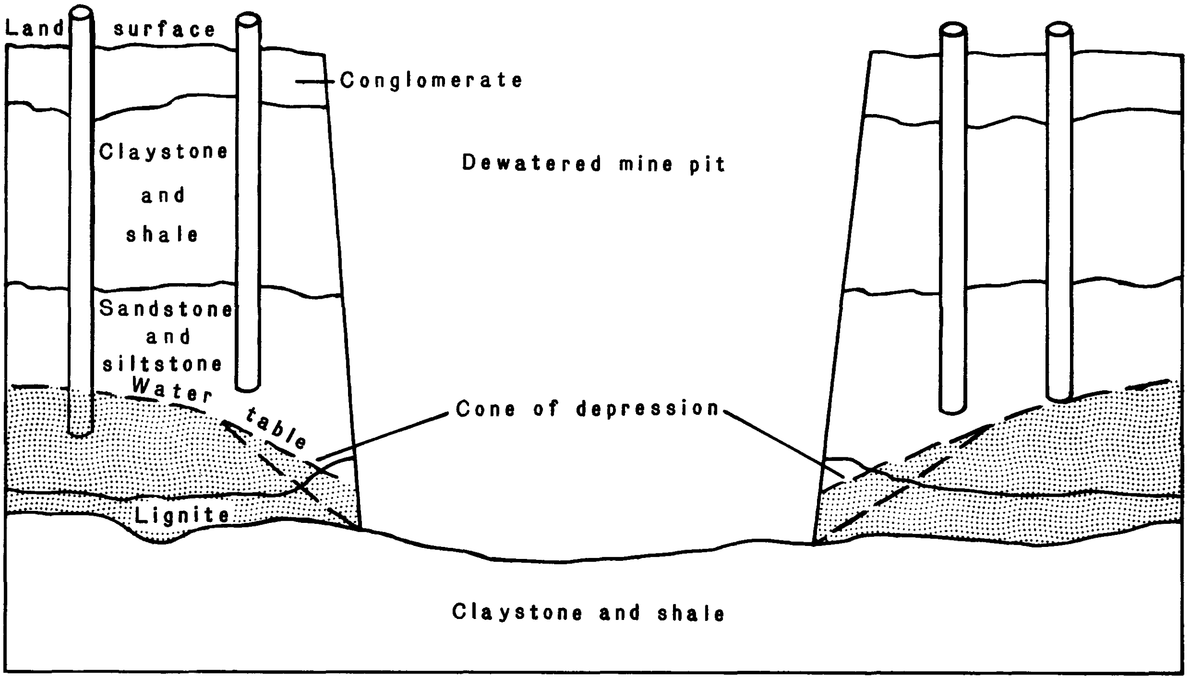
Both ground-water quantity and quality can be affected by postmining conditions. The types of spoils are a primary factor determining these effects.

Types of Spoils

As mining progresses, the spoil material is replaced in the mine pit and recontoured to approximate premining conditions. Depending upon the reclamation techniques and the local spoil material, several types of spoils may exist in a backfilled pit. The spoil may consist of highly permeable



A. Conditions before mining



B. Conditions during mining

Figure 19.--Idealized sections showing the effects of mining on the Denver aquifer: A, Conditions before mining, and B, Conditions during mining.

material, less-permeable clay overlying rubble of sandstone and siltstone, or other types of rock.

Characteristics of the Permeable Spoil

Permeable spoil could be a heterogeneous mixture of siltstone, sandstone, claystone, and shale through which water easily percolates (fig. 20). After reclamation of the mined area, water in the aquifer in the spoil will return to approximately its premining level. However, because the spoil locally may increase infiltration and percolation, the postmining hydrostatic condition will alter. Increased infiltration and percolation through the spoil could cause recharge and leaching of ions to increase and surface flow to decrease. This ultimately may result in the formation of a ground-water mound under the abandoned mine site. The mound would locally raise the water table in all directions. The effects on the aquifer of the ground-water mound would be a function of the extent of the surface mine spoils and localized geologic and hydrologic factors.

As spoil material is replaced, ground-water quality can be affected locally by ions leached from replaced overburden. During mining, the overburden is scraped, hauled, or dragged to the outside of the mine pit. The overburden is broken, mixed, and exposed to the air during this process. While on the surface, some of the overburden is exposed to weathering. When the overburden is replaced in the mine pit during reclamation, further breakage and mixing occur. Therefore, these newly exposed or slightly weathered rock surfaces of the rubble in the pit are probably more susceptible to leaching of their ions when they are in contact with water. As water from rain and overland flow percolates through these newly exposed surfaces in the permeable spoil, minerals from the overburden can be dissolved in the water; then, that water joins with water from the aquifer. As a result, the dissolved-solids concentration of the water in the spoil could increase. The water will move away from the mound, joining the regional flow path of the Denver aquifer. Therefore, dissolved-solids concentration could increase in a northeasterly direction from the spoil. Further discussion on this topic is in the section, Potential Impacts Common to Both Types of Spoils.

Characteristics of the Clay Spoil

The second type of spoil consists of a less-permeable clay overlying sandstone and siltstone rubble (fig. 20). Claystones and shales are assumed to be relatively soft so that they can be compacted into a unit with low permeability. This clay spoil may form as a result of sorting due to gravity. Larger boulders in the sandstone and siltstone overburden at the edge of the pit roll to the base of the pit during reclamation of the site. Then the claystone and shale overburden, which forms 70 percent of the Denver Formation, forms a less-permeable barrier on top.

There could be little or no infiltration from the surface of the spoil into the spoil under these conditions. The clay barrier could locally cause an increase in overland flow, a decrease in leaching, and a decrease in recharge.

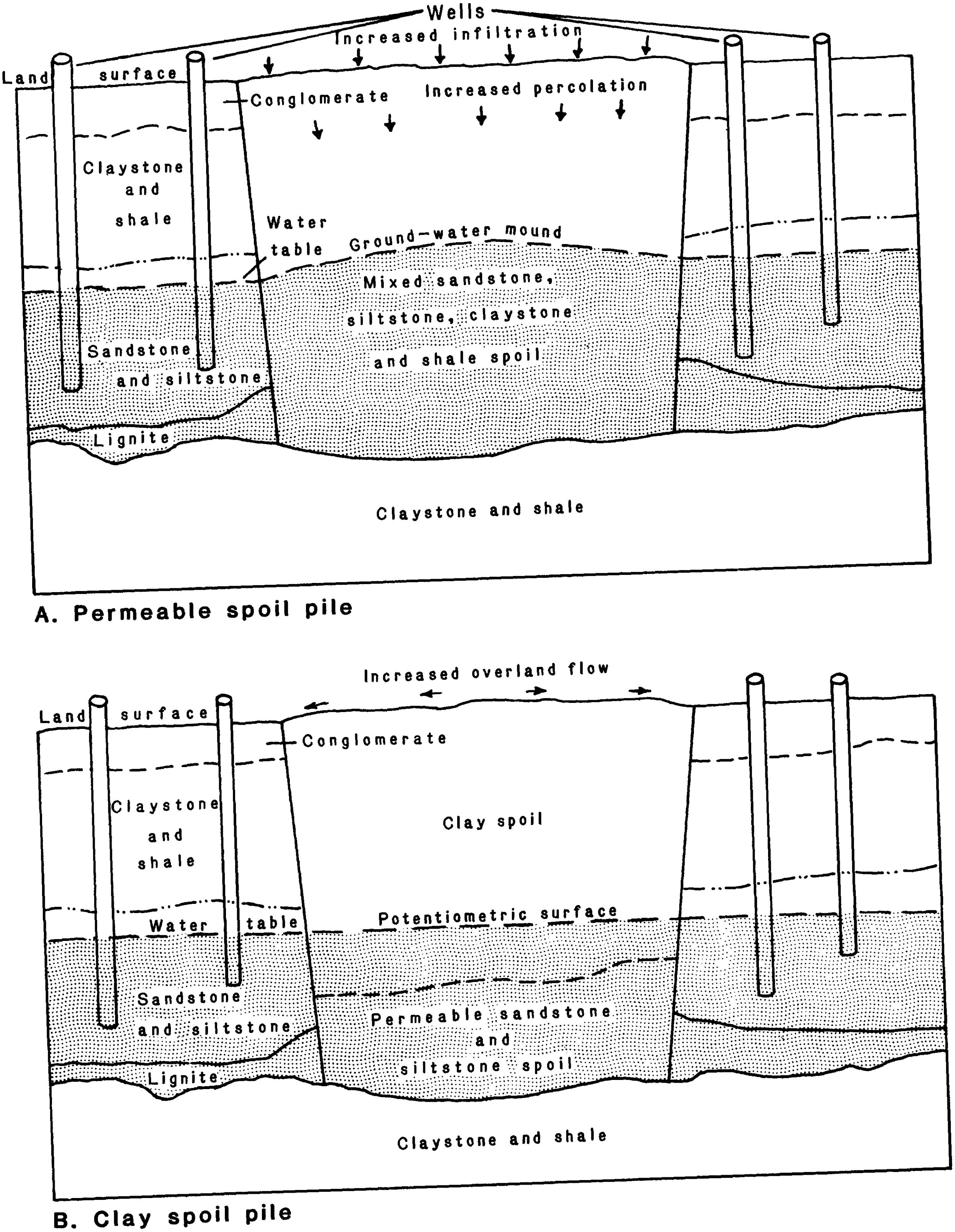


Figure 20.--Idealized sections of two spoil piles and associated ground-water conditions: A, Permeable spoil pile, and B, Clay spoil pile.

Because little or no water could flow through the clay barrier, the postmining flow path of the aquifer would differ from the premining flow path. Water would be forced to flow around the clay barrier. Water would flow through the sandstone and siltstone rubble at the base of the spoil pile. Water levels in the water-table aquifer adjacent to the clay barrier would ultimately return to the premining level, and a confined aquifer could be formed at the base of the spoil.

The downgradient water quality of the aquifer could be affected significantly. The sandstone and siltstone rubble, which was broken and weathered on the surface during mining and further broken during reclamation as it tumbled to the base of the pit, contains newly exposed or slightly weathered surfaces that are vulnerable to leaching. As water from the aquifer flows through the rubble, the water could dissolve minerals on the exposed surfaces, and dissolved-solids concentrations of the water could increase downgradient from the rubble spoil.

Potential Impacts Common to Both Types of Spoils

Water quality downgradient from the permeable spoils and the clay spoils possibly could exhibit the same general pattern. Because water from the aquifer could flow through both types of spoils, the only difference in the dissolved-solids loads probably would be from the addition of water percolating from the surface to the permeable spoil.

The primary constituents that would be introduced to the water from the spoils are sulfate and calcium. If the mine is in an area where the aquifer is supersaturated with calcite, further dissolution of calcite would be minimal. Calcite could be a large contributor to downgradient dissolved solids if water in the aquifer in the mine area is undersaturated with calcite or gypsum. The sulfates, which are consistently undersaturated in the water in the aquifer, would probably be the major contributors of ions to the system. Downgradient geochemical reactions also may affect equilibrium conditions of water flowing from the mine site.

According to studies at reclaimed surface coal mines in mountainous and high-plains areas, the concentration of dissolved solids increases from 700 to 800 mg/L in an undisturbed aquifer to 2,000 to 2,200 mg/L in a spoil pile aquifer (R.S. Williams, Jr., U.S. Geological Survey, unpublished data, 1984). Although the mountainous areas and the study area may or may not undergo similar increases, change at reclaimed surface coal mines has occurred in other areas, and the potential for change exists. Because water in the undisturbed aquifer flows from the southwest to the northeast, dissolved solids from the spoil should form a plume in that direction. The extent of the dissolved-solids plume depends on the boundaries of the aquifer, fractures in the formation, permeability of the material, mineral-solubility equilibrium in the undisturbed aquifer, and the area of discharge. Additional factors may also affect a mine impact on local and regional hydrology. For example, a mine may be in an area of recharge or discharge, which may affect the areal extent of a mine impact. The method of spoil-pile reclamation and revegetation can affect infiltration, percolation, and migration of solutes.

Also, as mentioned in a previous section, dewatering of the mine site may result in a change of direction of the aquifer flow path.

If the area of discharge is within the boundaries of the dissolved-solids plume, stream water and alluvial aquifers in the discharge area might be affected. Dissolved-solids loads might increase in the gaining stream and alluvial aquifer. The quantity and quality of water in the stream and alluvial aquifer would determine the effects of water from the discharging bedrock aquifer on the alluvial system. Because streams in the area are intermittent, the diluting effect of existing streamflow may be minimal.

SUMMARY AND CONCLUSIONS

This study interpreted the hydrology of the Denver aquifer in areas where surface mining of lignite could occur. The primary hydraulic characteristics of the Denver aquifer in the study area are: (1) Small transmissivities, ranging from 15 to 160 feet squared per day; and (2) the major direction of the movement of water from southwest to northeast. Dissolved-solids concentrations increase from 145 to 1,000 mg/L to the northeast in the study area as hydraulic head decreases from 6,600 to 5,400 feet. The dominant ions of the Denver aquifer in these minable areas are sodium, bicarbonate, calcium, and sulfate. In certain locations of the minable parts of the Denver aquifer, the water is supersaturated with calcite.

The Denver aquifer is likely to be affected locally by surface mining of lignite. Aquifer disruption during mining and disturbance of the recharge areas are primary means by which the ground-water flow paths and quantity are changed. Dewatering of the mine further reduces the quantity of water within and surrounding the mine area. Distance-drawdown curves provide an estimate of the extent of the area impacted by dewatering.

The probable outcome of the dewatering would be that domestic and stock wells within the cone of depression would either go dry or would have lower water levels. A second possible effect from dewatering might be that the water levels would decline in streams and alluvial aquifers supplied by the bedrock aquifer within the cone of depression.

After reclamation of the lignite mine pit, flow through the lignite-spoil pile may increase the dissolved-solids concentrations in the Denver aquifer. This increase could occur because, as water from rain and overland flow percolates through the newly exposed rock surfaces in the spoil material, minerals from the overburden can be dissolved in the water; this water then joins with water from the aquifer.

According to studies of reclaimed surface coal mines in mountainous and high-plains areas, dissolved-solids concentrations can increase from about 750 mg/L in the undisturbed aquifer to about 2,100 mg/L in the spoil-pile aquifer. Because water in the undisturbed aquifer flows from the southwest to the northeast in the study area, the dissolved solids from the spoil should form a plume in that direction unless pumping or mine-dewatering significantly affects the local flow system. In any case, water from wells in the plume path could be affected.

The primary constituents that would be introduced to the water from the lignite spoils are sulfate and calcium. Calcite could be a large contributor to downgradient dissolved solids if water in the aquifer in the mine area is undersaturated with calcite or gypsum. The sulfates, which are consistently undersaturated in the aquifer, would probably be the major contributors of ions to the system.

REFERENCES

Davis, S.N., and DeWiest, R.J., 1966, Hydrogeology: New York, Wiley, 463 p.

Hansen, W.R., Chronic, John, and Matelock, John, 1978, Climatography of the Front Range Corridor and vicinity, Colorado: U.S. Geological Survey Professional Paper 1019, 59 p.

Kharaka, Y.D., and Barnes, Ivan, 1973, SOLMNEQ-solution-mineral equilibrium computations: Menlo Park, Calif., U.S. Geological Survey Computer Contributions, available only from U.S. Department of Commerce, National Technical Information Service, Springfield, Va. 22151, as Report PB-215 899, 81 p.

Kirkham, R.M., 1978, Coal mines of the Denver and Cheyenne basins, Colorado: Denver, Colorado Geological Survey Open-File Report 78-9, 104 p.

Kirkham, R.M., and Ladwig, L.R., 1979, Coal resources of the Denver and Cheyenne basins, Colorado: Denver, Colorado Geological Survey Resource Series No. 5, 70 p.

_____1980, Energy resources of the Denver and Cheyenne basins, Colorado: Denver, Colorado Geological Survey Environmental Geology No. 12, 258 p.

McLaughlin, T.G., 1946, Geology and ground-water resources of parts of Lincoln, Elbert, and El Paso Counties, Colorado: Denver, Colorado Water Conservation Board Ground-Water Series Bulletin 1, 139 p.

Robson, S.G., 1983, Hydraulic characteristics of the principal bedrock aquifers in the Denver basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas, HA-659, scale 1:500,000, 3 sheets.

Robson, S.G., and Romero, J.C., 1981, Geologic structure, hydrology, and water quality of the Denver aquifer in the Denver basin, Colorado: U.S. Geological Survey Hydrologic Investigations Atlas, HA-646, scale 1:500,000, 3 sheets.

Romero, J.C., 1976, Ground-water resources of the bedrock aquifers of the Denver basin, Colorado: Denver, Colorado Division of Water Resources, 109 p.

Soister, P.E., 1972, Preliminary geologic map and lignite deposits of the Strasburg NW quadrangle, Arapahoe and Adams Counties, Colorado: U.S. Geological Survey Open-File Report 72-753, 2 sheets, scale 1:24,000.

_____1974, A preliminary report on a zone containing thick lignite beds, Denver basin, Colorado: U.S. Geological Survey Open-File Report 74-27, 46 p.

_____1981, Colorado lignite for underground coal gasification: Englewood, Colo., Maverick Exploration Co., 1 v.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: American Geophysical Union Transactions, pt. 2, p. 520.

U.S. Department of Commerce, Bureau of the Census, 1980, 1980 census of population and housing, Colorado, 15 p.

U.S. National Oceanic and Atmospheric Administration, 1982, Climatological data, annual summary, Colorado, 1982, 28 p.

GPO 851-632