AVAILABILITY AND QUALITY OF WATER FROM THE BEDROCK AQUIFERS IN THE RAPID CITY AREA, SOUTH DAKOTA

By Kathy D. Peter

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CONVERSION FACTORS

For use of readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply inch-pound units	By	To obtain SI units
foot (ft)	0.3048	meter
foot squared per day (ft^2/d)	0.0929	meter squared per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.0630	liter per second
inch	25.40	millimeter
inch per year (in/yr)	25.40	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre	4,047	square meter
foot per mile (ft/mi)	0.1894	meter per kilometer

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}F = 1.8^{\circ}C + 32$$

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, called NGVD of 1929, is referred to as sea level in this report.

AVAILABILITY AND QUALITY OF WATER FROM THE BEDROCK AQUIFERS IN THE RAPID CITY AREA, SOUTH DAKOTA

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ABSTRACT

An evaluation made in cooperation with the U.S. Bureau of Reclamation of the availability and quality of water from the bedrock aquifers in the Rapid City area, South Dakota, concluded that the Madison aquifer has the greatest potential for additional development of the three major aquifers investigated (the Inyan Kara of Cretaceous age, the Minnelusa of Pennsylvanian and Permian age, and the Madison of Mississippian age). Ground-water availability was evaluated on the basis of unit thickness and depth, potentiometric-surface altitudes and gradients, estimated recharge and discharge rates, estimated aquifer transmissivities and storage coefficients, and reported yields of wells. Ground-water quality was evaluated on the basis of the concentrations of ions in the water that may affect its use as a community supply. The Inyan Kara aquifer, though less than 1,900 feet below land surface and the shallowest aquifer in the eastern part of the study area, has the least potential for additional development because of small reported well yields (less than 200 gallons per minute), the proximity of the outcrop, and concentration of radium-226 that exceeds 5 picocuries per liter. The Minnelusa aquifer is suitable for development in the western one-third of the study area. In the eastern two-thirds of the area, the quality of water in the Minnelusa is unsatisfactory because the concentration of dissolved solids exceeds 500 milligrams per liter and the concentration of sulfate exceeds 250 milligrams per liter, the recommended maximum levels for community supplies. The Madison aquifer has the greatest potential of the three aquifers for additional development because it has areas with significant fracture permeability, is known to yield more than 500 gallons per minute to wells, is deep enough to sustain the large water-level drawdowns needed for large yields, and has satisfactory water quality, though it is hard (hardness 120 to 180 milligrams per liter) to very hard (hardness greater than 180 milligrams per liter). The Madison aquifer also has the greatest potential to increase recharge by capturing additional streamflow.

INTRODUCTION

In 1983, the U.S. Bureau of Reclamation began a study to determine the long-range, multiple-purpose, water-supply needs of the metropolitan and regional Rapid City area and to assess the capability of presently available supplies to meet the long-term needs. The purpose of this investigation by the U.S. Geological Survey was to provide the Bureau with information on the availability and quality of water from the bedrock aquifers in the area and evaluate the potential for developing community water supplies from the bedrock aquifers. The study area, located on the eastern edge of the Black Hills, is shown in figure 1. This report describes the results and conclusions of the Geological Survey investigation.

The Inyan Kara Group, Minnelusa Formation, and Madison Limestone are major suppliers of ground water in the Rapid City area. Their relative stratigraphic positions in order of increasing age are shown in table 1. Though there are other units that

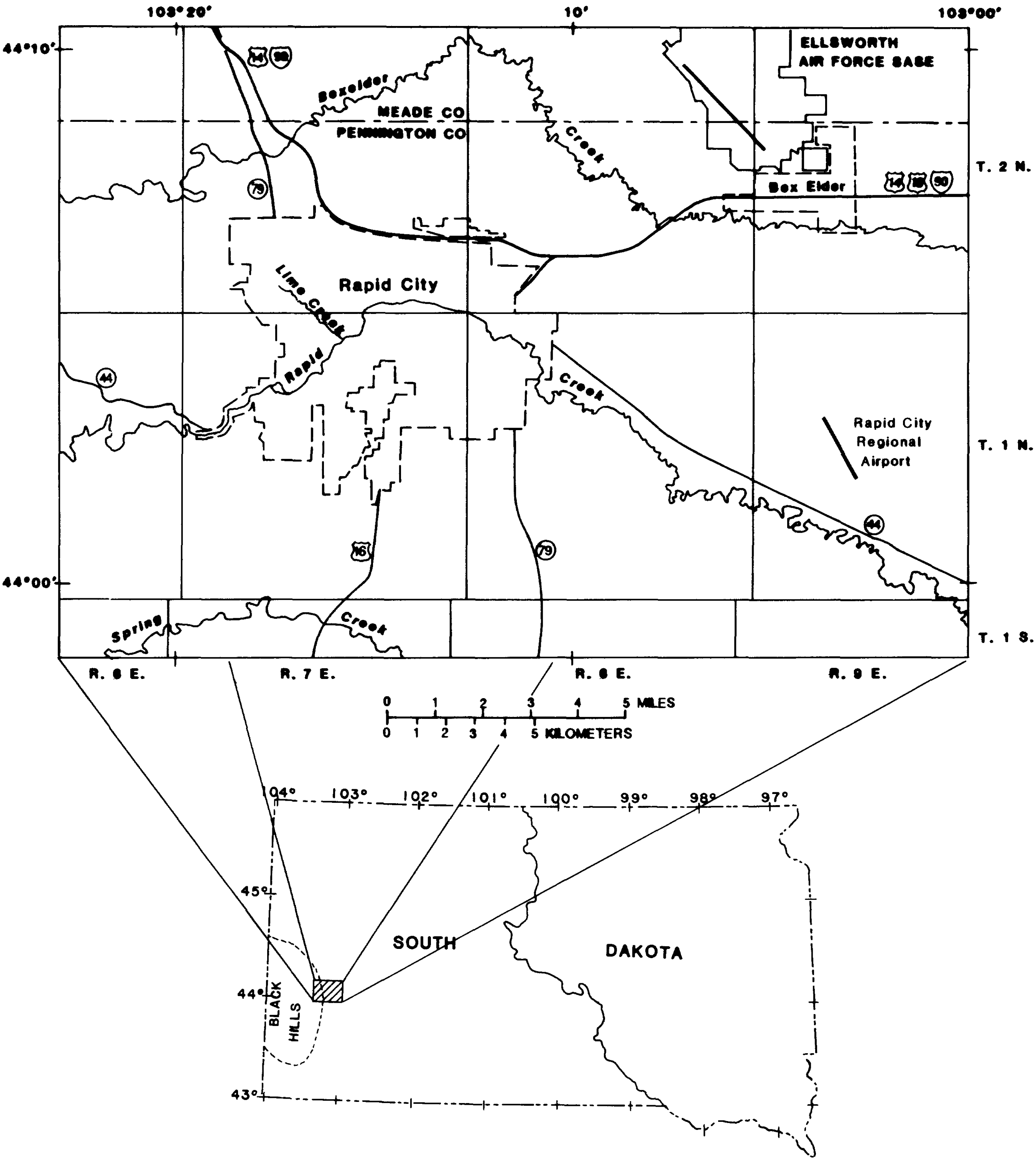


Figure 1.--Location of the study area.

Table 1.—Bedrock formation and aquifers (modified from Brown, D. L. and others, 1982, Robinson, C. S. and others, 1964, and Cattermole, J. M., 1969 and 1972)

Era	System	Series	Geologic unit		Hydrologic unit
Mesozoic	Cretaceous	Upper		Pierre Shale	Confining beds
				Niobrara Formation	
				Carlile Shale	
				Greenhorn Formation	
				Belle Fourche Shale	
		Lower		Mowry Shale	
				Newcastle Sandstone	Newcastle aquifer 1/
				Skull Creek Shale	Confining bed
			Inyan Kara Group	Fall River Formation or Sandstone	Inyan Kara aquifer
				Lakota Formation	
	Jurassic	Upper		Morrison Formation / Unkpapa Sandstone 2/	Confining beds
		Middle		Sundance Formation	
				Gypsum Spring Formation 3/	
	Triassic			Spearfish Formation	
Paleozoic	Permian			Minnekahta Limestone	
				Opeche Formation or Shale	
	Pennsylvanian			Minnelusa Formation	Minnelusa aquifer
					Confining beds
	Mississippian			Madison Limestone or Pahasapa Limestone	Madison aquifer
	Devonian			Englewood Formation	Confining beds
	Silurian			Not present	
	Ordovician			Whitewood Dolomite	
				Winnipeg Formation	
	Cambrian			Deadwood Formation	Deadwood aquifer 1/
	Precambrian				Base of hydrologic system

1/ Minor source of supply in the study area.
2/ Only in the southern and eastern Black Hills.
3/ Only in the northern and western Black Hills.

provide small quantities of ground water, the Inyan Kara, Minnelusa, and Madison aquifers were studied in detail in this investigation because they are the most extensively developed and have the greatest known potential for future development by Rapid City. The outcrop areas of these three aquifers are shown in figure 2.

Approach

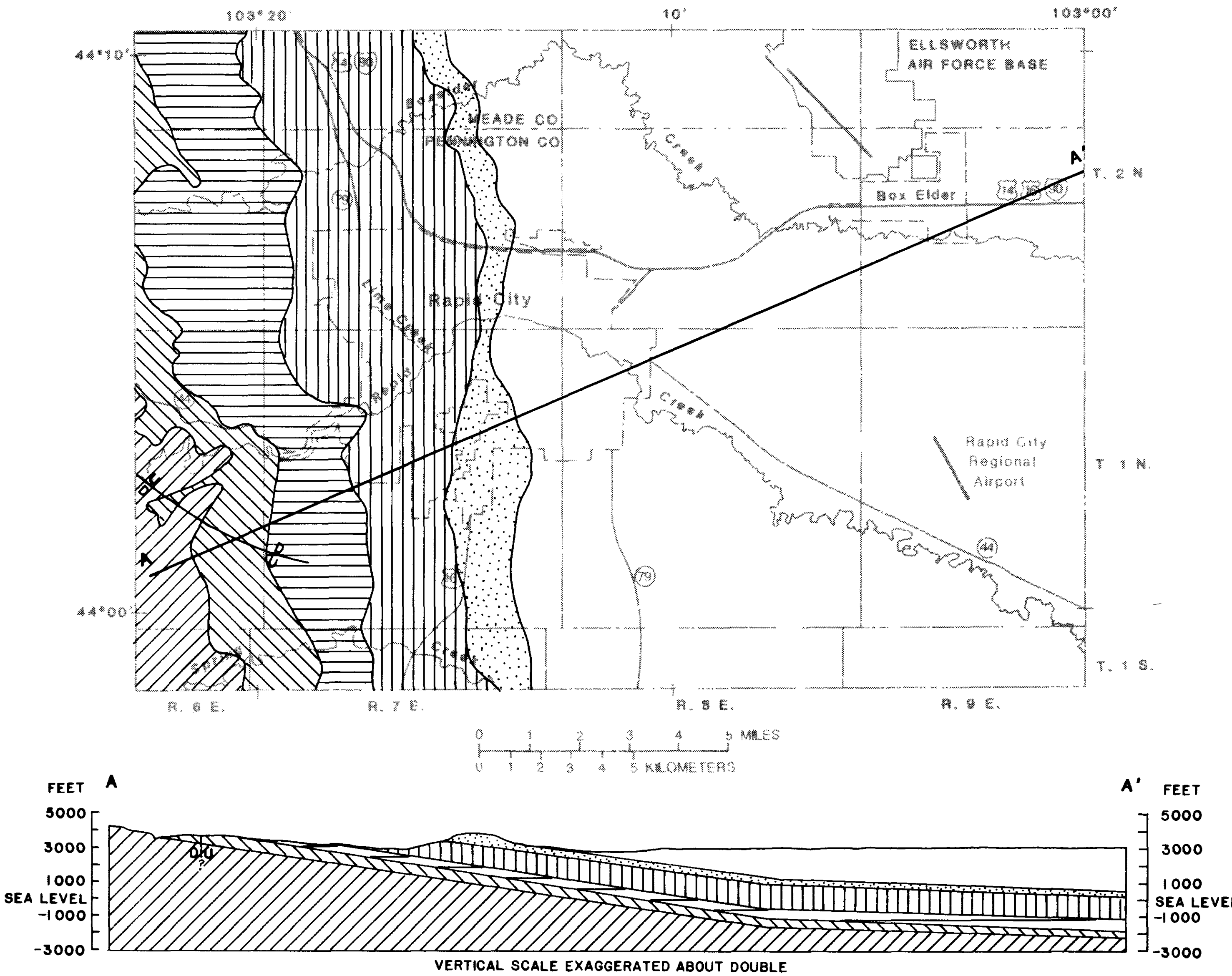
The availability of water in the three major bedrock aquifers was evaluated on the basis of unit thickness and depth, potentiometric surface altitudes and gradients, estimated recharge and discharge rates, estimated transmissivities and storage coefficients, and reported yields of wells. Ground-water quality was evaluated on the basis of the concentrations of ions in the water that may affect its use as a community supply.

This investigation relied solely on well records on file at the U.S. Geological Survey office in Rapid City, S. Dak. No new wells or test holes were drilled. As a result, some interpretations are based on the best possible use of inadequate, though useful, data. In general, the deeper the aquifer, the less is known about it. Water wells generally are drilled only deep enough to obtain an adequate supply for the intended use. As a result, little is known about the Madison and the Minnelusa aquifers in the eastern one-half of the study area. Because shallower supplies are available, few wells have been drilled to these aquifers in this area. Only three wells are completed in the Madison aquifer in the eastern one-half of the study area. Of these, one has been destroyed, one is inaccessible, and all three are within a mile of the city of Box Elder. Only inferences about the availability of water from the Madison and Minnelusa aquifers can be made from the little information available from deep wells and observations near the outcrop.

Approximately 80 lithologic and geophysical logs of the area were compiled and examined and aquifer tops and bottoms identified. A map of the altitude of the top of the Minnelusa aquifer was prepared because it is the most extensive of the aquifers for which sufficient data existed to allow adequate map preparation. Though formation thicknesses were recorded on maps, the data was not contoured or included in this report because the relatively small variations in thickness and small amount of data did not provide sufficient information for interpretation. The variability of the potentiometric surfaces were evaluated using approximately 180 water-level measurements, current and historic. Maps of the potentiometric surfaces in 1983 of all three aquifers were prepared. Previous investigations on the hydrology of the three aquifers provided estimates of recharge and discharge rates, and of transmissivities and storage coefficient. Recharge from infiltration of streamflow was evaluated from approximately 35 years of record for Rapid Creek and 4 years of record for Boxelder Creek. Records of reported well yields were compiled. Analyses of water from about 45 wells were compiled and compared with standards for community water supplies set by the U.S. Environmental Protection Agency (1975-80, 1979).

Well-Numbering System

Each well tabulated in this report has been assigned a number based on its location, according to the Federal land-survey system used in western South Dakota. The number consists of the township, range, and section numbers; three or four letters after the section number indicate respectively the quarter section (160 acres), quarter-quarter section (40 acres), quarter-quarter-quarter section (10 acres), and quarter-quarter-quarter-quarter section (2.5 acres), in which the well, spring, or test



EXPLANATION

CRETACEOUS CONFINING BEDS--Shale with lesser amounts of limestone. Some sandstone, including the Newcastle Sandstone. Generally gray to dark gray in color.

INYAN KARA GROUP--Sandstone, shale, and siltstone. Gray brown, buff, and red in color.

PERMIAN-TRIASSIC-JURASSIC CONFINING BEDS--Shale with lesser amounts of limestone, siltstone, and sandstone. Lower one-half is mostly red, upper one-half is green, gray, and buff in color.

MINNELUSA FORMATION--Sandstone and dolomitic limestone. Light brown to gray in color.

MADISON LIMESTONE--Limestone and dolomite. Buff or brown in color.

ENGLEWOOD LIMESTONE, DEADWOOD FORMATION, AND PRECAMBRIAN ROCKS--Schist, sandstone, shale, and limestone. Brown, red, and pink in color.

U/D FAULT - U indicates upthrown side
D indicates downthrown side

Figure 2.--Bedrock geology. (Geology modified from Darton and Paige, 1925, and Cattermole, 1969 and 1972.)

hole is located. For example, 2N7E17BACA is in the NE¼SW¼NE¼NW¼ sec. 17, T. 2 N., R. 7 E. (fig. 3). The number of lowercase letters indicates the accuracy of each location; if it can be located within a 10-acre tract, three lowercase letters are shown in the number. If two or more locations are within the same tract, consecutive numbers, beginning with 1, are added as suffixes to designate more than one well in the same tract.

WATER AVAILABILITY

Each of the three aquifers, the Inyan Kara, Minnelusa, and Madison, is unique. The availability of water from each aquifer was evaluated on the basis of their characteristics: unit thickness and depth, potentiometric surface altitudes and gradients, estimated recharge and discharge rates, estimated transmissivities and storage coefficients, and reported yields of wells.

Inyan Kara Aquifer

The Inyan Kara Group of Early Cretaceous age consists of the Fall River and Lakota Formations. The sandstone beds in these units form the Inyan Kara aquifer. The Fall River Formation is about 125 ft thick and the Lakota Formation is about 225 to 375 ft thick (Cattermole, 1972). Cattermole interpreted the erratic thickness of the Lakota as an indication of channeling into the underlying Morrison Formation; however, there are not enough logs of wells penetrating the entire thickness of the Lakota to allow mapping of these channels. The Fall River Formation and the Lakota Formation are composed of beds of sandstone, shale, and siltstone. The outcrop of these beds form a hogback dividing east and west Rapid City. The top of the Fall River Formation, shallowest of the two formations, is at a depth of about 1,900 ft in the city of Box Elder. Most wells in the eastern two-thirds of the study area are completed in either the Fall River or the Lakota or both, because these two formations are the shallowest bedrock aquifers east of the Inyan Kara outcrop.

The altitude of the potentiometric surface of the Inyan Kara aquifer ranges from about 2,600 to 3,800 ft above sea level (fig. 4). Wells completed in the Inyan Kara aquifer do not flow in the study area. The gradient of the potentiometric surface ranges from 30 ft/mi in the northeastern part of the study area to 350 ft/mi near the outcrop south of Rapid City. The steeper gradient near the outcrop may be misleading. Wells in the outcrop are shallow and may not be representative of regional flow because of the significant vertical flow in the aquifer near the outcrop. Normally, it is assumed that flow in the aquifer is horizontal when constructing potentiometric maps using existing wells.

Recharge to the Inyan Kara in the study area probably is less than recharge to the other two aquifers because infiltration of precipitation provides most of the recharge to the Inyan Kara aquifer; whereas infiltration from streams may provide significant recharge to the other aquifers. Infiltration of precipitation on the outcrop recharges the Inyan Kara aquifer at a rate of about 1 ft^3/s, if it is assumed that, of the approximately 18 inches of annual precipitation (U.S. Department of Commerce, 1976-83), 2 in/yr infiltrates the outcrop, which is about 10 mi^2 in area. It is not known how much recharge may be leaking upward from the Minnelusa aquifer. Gain-loss measurements on Rapid Creek indicate there is no significant change in flow of the creek across the Inyan Kara outcrop. Most of the year Box Elder Creek and Spring Creek are dry where they cross the outcrop of the Inyan Kara aquifer and do not recharge the aquifer.

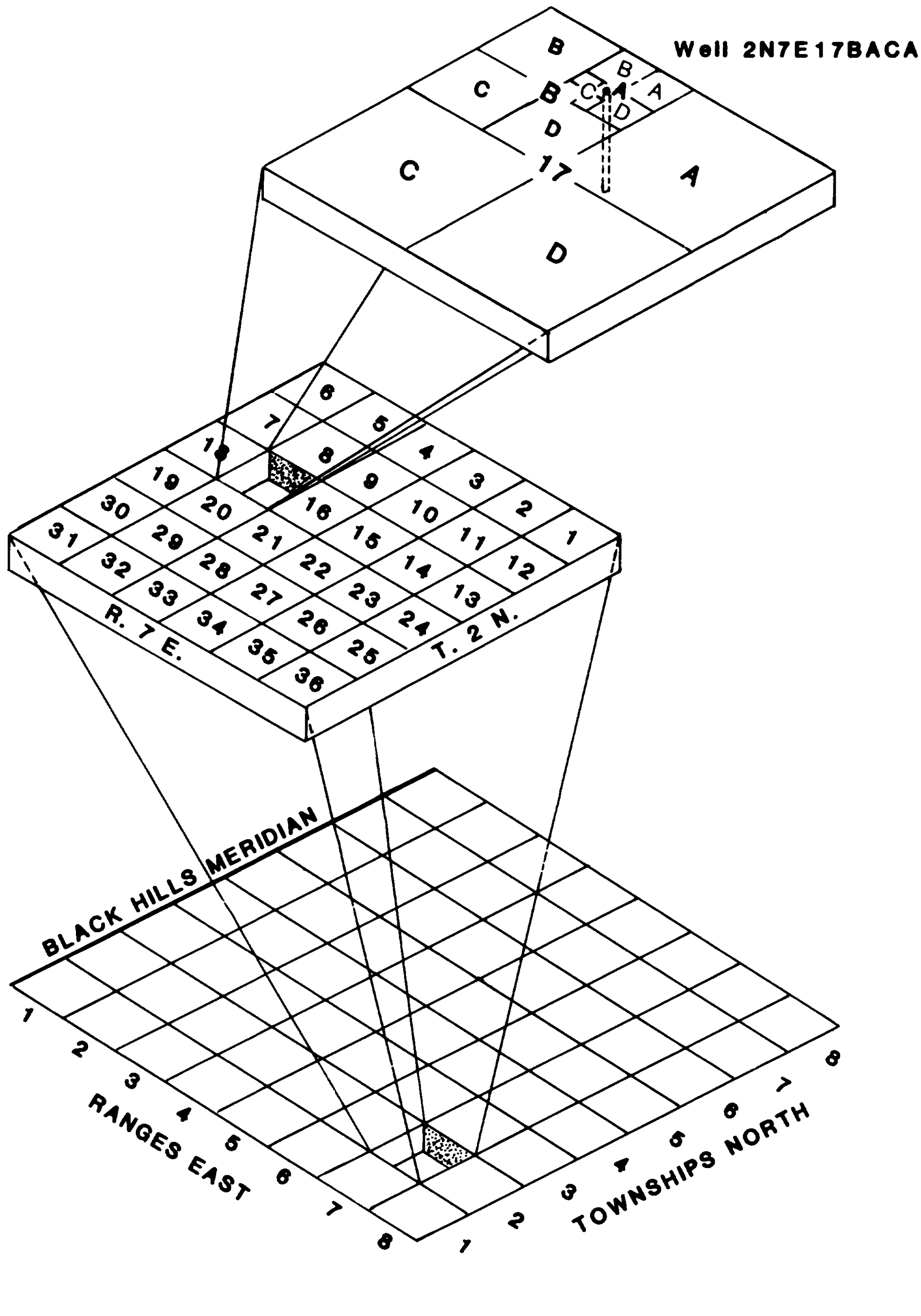
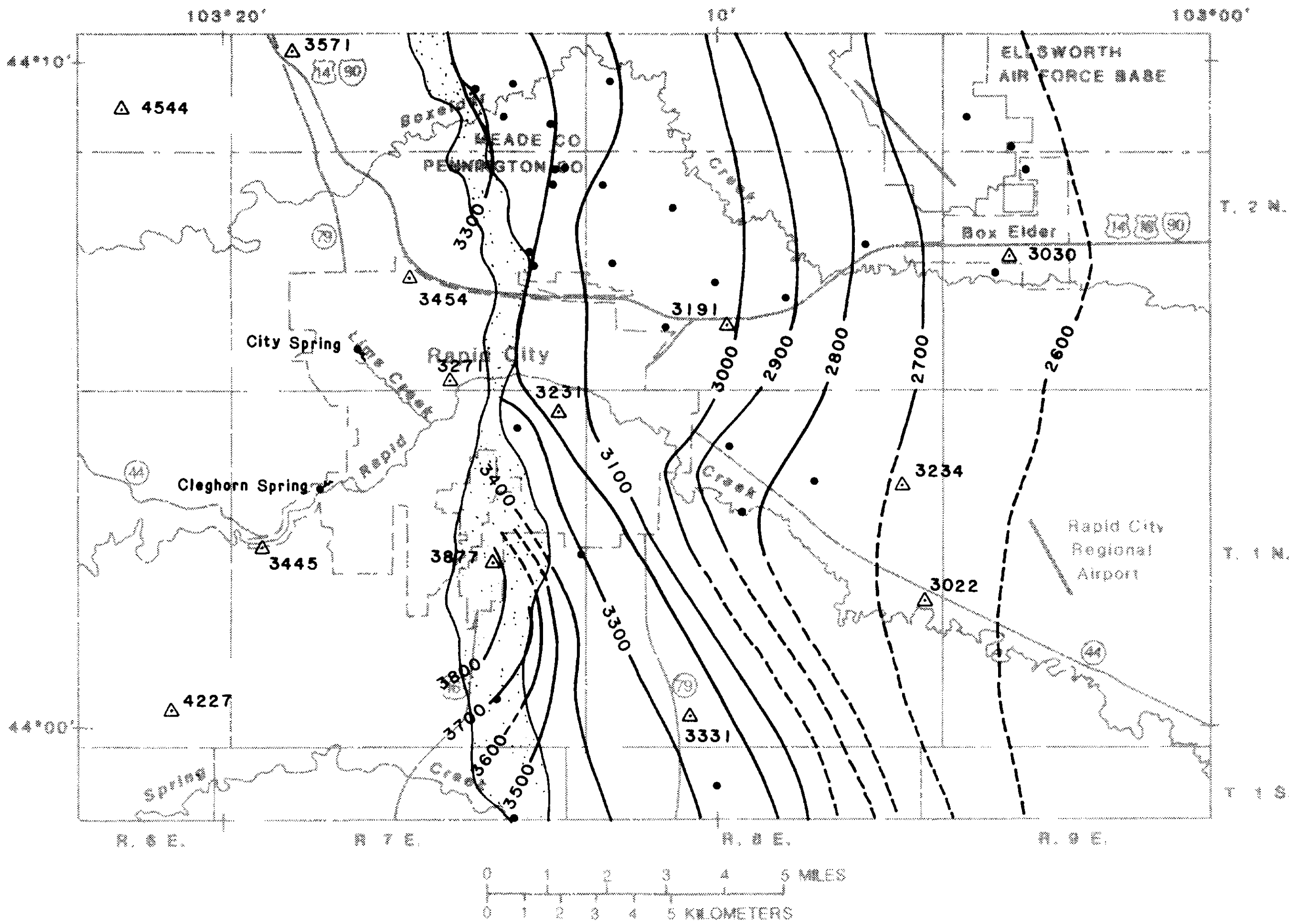


Figure 3.--Well-numbering system.



EXPLANATION

OUTCROP OF THE INYAN KARA GROUP

—— 3100 - - - POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, 1983. Dashed where approximately located. Contour interval 100 feet. National Geodetic Vertical Datum of 1929.

• WELL COMPLETED IN THE INYAN KARA AQUIFER

△3022 LAND SURFACE ALTITUDE--Shows altitude of land surface in feet above National Geodetic Vertical Datum of 1929.

Figure 4.--Potentiometric surface of the Inyan Kara aquifer.

Discharge from the Inyan Kara aquifer from the area is by underflow and by well withdrawals. Subsurface outflow is estimated to be about 4 ft^3/s across the eastern boundary of the study area. Withdrawals of water from wells are estimated to be less than 1 ft^3/s.

The difference in recharge and discharge rates represents the variability of the measurements used in the approximations, leakage from the Minnelusa aquifer, and possibly leakage from the overlying shales and the underlying Jurassic-age rocks. Appraisal of the shales and Jurassic-age rocks was beyond the scope of this study because the lack of data would require drilling of test holes and wells.

There are no aquifer-test data for the Inyan Kara aquifer in the Rapid City area; therefore, the aquifer transmissivity and storage coefficient are unknown. Estimates from regional studies of the aquifer (Joe S. Downey, U.S. Geological Survey, written commun., 1982; H. Lee Case III, U.S. Geological Survey, written commun., 1982; and the author) indicate that the aquifer transmissivity may range from 300 to 3,800 ft^2/d and that the storage coefficient may range from $1.2X10^{-4}$ to $2.3X10^{-5}$.

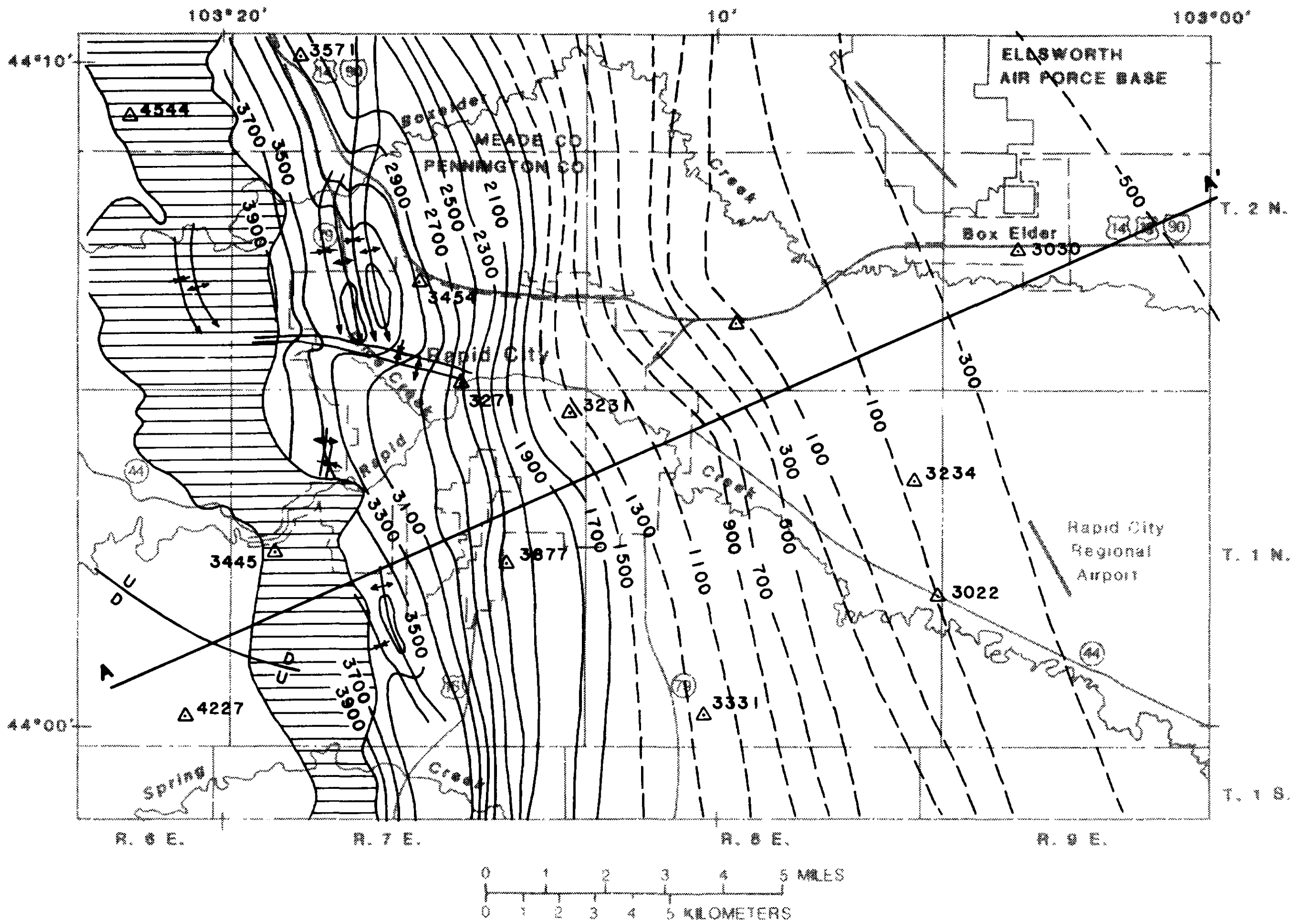
Reported yields of wells completed in the Inyan Kara aquifer in the study area are as much as 200 gal/min. Yields are related to the thickness, grain size, and degree of cementation of sandstone beds the well penetrates. A well outside the study area produced 500 gal/min from a poorly cemented, coarse-grained sandstone bed in the Lakota.

Large-scale development of the Inyan Kara aquifer may be impractical because it is the least extensive of the three aquifers in the study area. The Inyan Kara is the shallowest of the three aquifers and may not be able to sustain the large drawdowns required for large well yields. Streamflow from Rapid Creek may be captured because of the drawdown of the potentiometric surface; however, the narrowness of the outcrop would limit the volume of water the aquifer could take from the creek.

Minnelusa Aquifer

The Minnelusa Formation of Permian and Pennsylvanian age is about 560 to 640 ft thick (Cattermole, 1969). The upper 200 to 300 ft of the Minnelusa is mostly fine to medium-grained sandstone and is an aquifer. The lower part is interbedded sandstone and dolomitic limestone and is a confining or semi-confining layer separating the Minnelusa aquifer from the Madison aquifer. The hills west of Rapid City are formed by the outcrop of the Minnelusa. In the Box Elder area, the Minnelusa contains beds of anhydrite, a calcium-sulfate mineral that is the anhydrous form of gypsum. In the city of Box Elder, the top of the Minnelusa is at a depth of about 3,460 ft. A structure map with contours on the top of the Minnelusa is shown in figure 5. The sandstone beds in the upper part of the Minnelusa are the most-utilized aquifer in the eastern Black Hills.

The altitude of the potentiometric surface of the Minnelusa aquifer ranges from about 3,250 to 3,650 ft above sea level (fig. 6). Because there are only two wells completed in the Minnelusa in the eastern one-half of the study area, the potentiometric surface is approximated for this area. The Box Elder city well number 4 flowed when it was open to the Minnelusa during drilling, as do wells completed in the Minnelusa in Rapid City. This indicates that the potentiometric surface of the Minnelusa may be above land surface in the eastern two-thirds of the study area. The



EXPLANATION

OUTCROP OF THE MINNELUSA FORMATION

ANTICLINE--Showing trace of crestal plane and direction of plunge.

SYNCLINE--Showing trace of trough plane and direction of plunge.

MONOCLINE--Showing trace.

Anticlinal

Synclinal

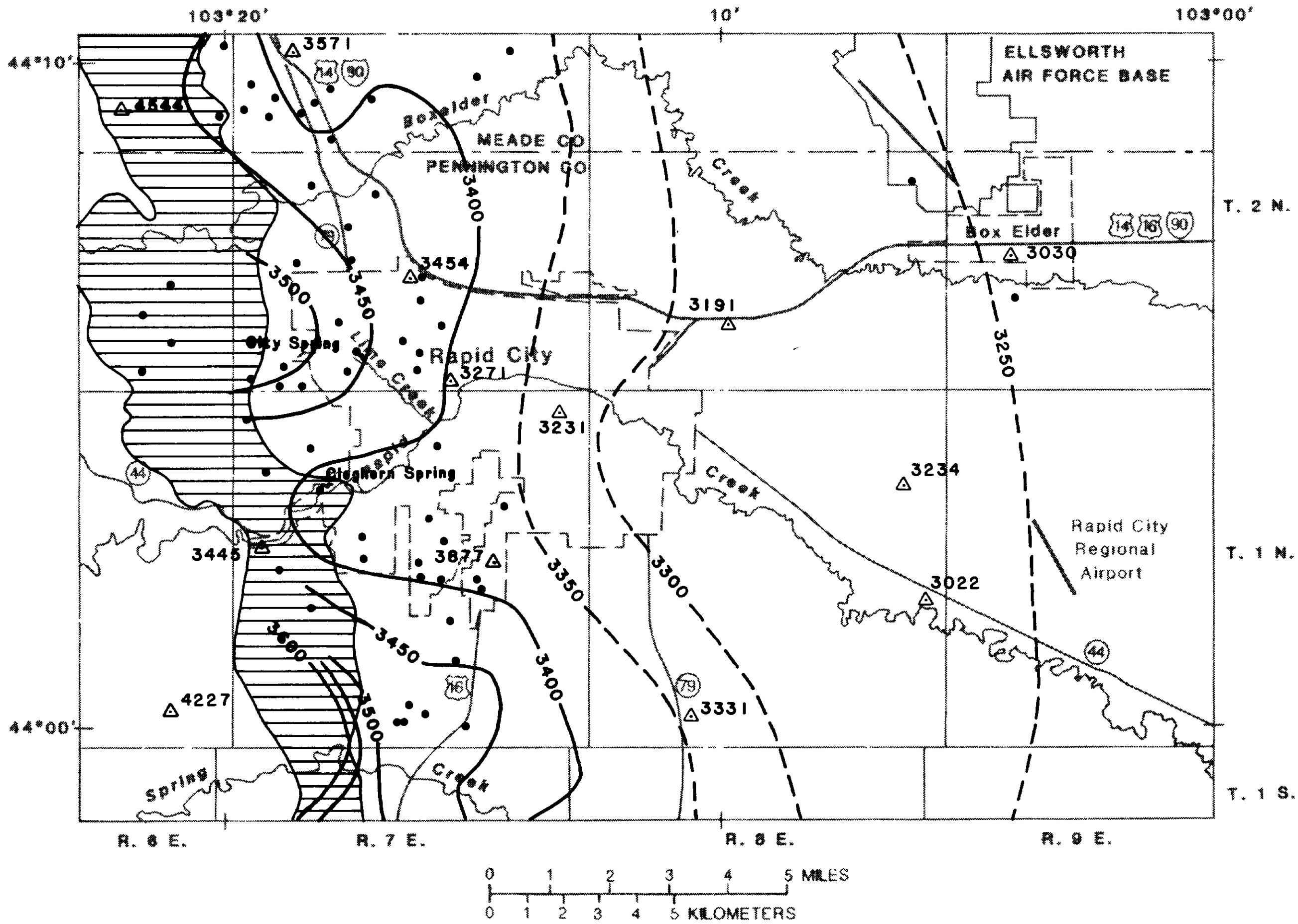
U / D FAULT --U indicates upthrown side
D indicates downthrown side

2100 — — STRUCTURAL CONTOUR--Shows altitude of the top of the Minnelusa Formation. Dashed where approximately located. Contour interval 200 feet. National Geodetic Vertical Datum of 1929.

A —— A' LINE OF CROSS SECTION--Shown with map of bedrock geology.

△3022 LAND SURFACE ALTITUDE--Shows altitude of land surface in feet above National Geodetic Vertical Datum of 1929.

Figure 5.--Geologic structures and altitude of the top of the Minnelusa Formation. (Structures from Cattermole, 1969.)



EXPLANATION

OUTCROP OF THE MINNELUSA FORMATION

—— 3400 — — POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, 1983. Dashed where approximately located. Contour interval 50 feet. National Geodetic Vertical Datum of 1929.

• WELL COMPLETED IN THE MINNELUSA AQUIFER

SPRING ISSUING FROM THE MINNELUSA AQUIFER

△3022 LAND SURFACE ALTITUDE--Shows altitude of land surface in feet above National Geodetic Vertical Datum of 1929.

Figure 6.--Potentiometric surface of the Minnelusa aquifer.

gradient of the potentiometric surface ranges from 10 ft/mi in the eastern part of the study area to 200 ft/mi in the outcrop southwest of Rapid City. Water in the aquifer generally moves from west to east. The steeper gradient in the outcrop may be a misinterpretation of water levels in wells, because there may be significant vertical flow in the aquifer in the outcrop and it was assumed in constructing the potentiometric maps that flow was mainly horizontal.

Recharge to the Minnelusa aquifer in the study area is from infiltration of precipitation and streamflow on the outcrop, and upward leakage from the Madison aquifer. Infiltration of precipitation on the outcrop recharges the Minnelusa aquifer, at a rate of about 2 ft^3/s, if it is assumed of the 18 to 20 inches of annual precipitation about 2 in/yr infiltrates the aquifer outcrop, which has an area of about 15 mi^2. Of the three creeks in the area, Boxelder, Rapid, and Spring, only Rapid flows perenially across the Minnelusa outcrop. Based on measurements of stream discharge on the upstream and downstream side of the Minnelusa outcrop, less than 1 ft^3/s of the flow in Rapid Creek infiltrates the outcrop of the Minnelusa aquifer. Boxelder and Spring Creeks flow across the outcrop during high flow, usually in May and June.

In the western part of the study area, the Minnelusa potentiometric surface is about 30 to 60 ft lower than that of the Madison, therefore, the potential exists for flow from the Madison to the Minnelusa. The similarity of the configurations of the potentiometric surfaces in this area implies the Minnelusa and Madison may be hydraulically connected, perhaps because the vertical permeability of the lower Minnelusa has been increased along the geologic structures shown in figure 5. The vertical movement of water is confirmed by field observations. Cleghorn Spring issues from alluvium directly overlying the Minnelusa and City Spring issues from the Minnekahta Limestone, a shallower formation (see table 1 and fig. 5). The potentiometric maps prepared for this study and dye tests reported by Rahn and Gries (1973), show that both springs are partly fed by water from the Madison, perhaps because the permeability of the lower Minnelusa has been increased by fracturing. The relative altitudes of the potentiometric surfaces indicate that water leaks into the Minnelusa from the Madison in the western one-third to one-half of the study area, but the rate of leakage is unknown.

Water discharges from the Minnelusa aquifer in the study area by spring flow, underflow, withdrawals from wells, and possibly leakage to other aquifers. Water from the Madison and the Minnelusa discharges from Cleghorn and City Springs, but it is not known what proportion is from each aquifer. About 5 ft^3/s flows out of the study area through the Minnelusa in the subsurface, assuming a transmissivity of 780 ft^2/d. About 2 ft^3/s is withdrawn by wells. In the eastern part of the study area, water may be leaking from the Minnelusa to both the Inyan Kara and Madison aquifers. At the city of Box Elder, the Minnelusa potentiometric surface probably is 400 to 600 ft above the Madison potentiometric surface and the Inyan Kara potentiometric surface. In the eastern two-thirds of the study area, there are fewer geologic structures than in the western one-third. Therefore, there may be less fracturing. This, combined with the presence of anhydrite in the Minnelusa, may result in less permeability in the confining beds in the eastern part of the study area and, therefore, the larger hydraulic gradient between aquifers.

There are no aquifer-test data for the Minnelusa aquifer in the Rapid City area; therefore, the aquifer transmissivity and storage coefficient are unknown. Estimates from regional studies of the aquifer (Joe S. Downey, U.S. Geological Survey, written commun., 1982, and the author) indicate the aquifer transmissivity may range from

700 to 1,000 ft^2/d. There are no estimates of storage coefficient, though if it is assumed the storage coefficient is about 10^{-6} per foot of thickness, as is typical for confined aquifers (Lohman, 1979, p. 8), then the storage coefficient ranges from $2X10^{-4}$ to $3X10^{-4}$.

Yields of as much as 150 gal/min have been reported for wells completed in the Minnelusa aquifer. As with any sandstone aquifer, the yields are affected by the thickness, grain size, and degree of cementation of the sandstone beds the well penetrates. Near the outcrop, where there are more geologic structures and anhydrite beds have been dissolved, the permeability of the Minnelusa is increased, particularly in brecciated zones where the unit has collapsed. Potential yield from the Minnelusa may be greater in areas where the dolomitic beds in the lower part of the aquifer are fractured and more permeable. Most of the wells in the study area do not penetrate this interval so an evaluation of its potential is not possible.

It is not known how much water flows between the Minnelusa and Madison aquifers. The effect of development of one aquifer on the potentiometric surface of the other is not known quantitatively. Increased development in the Minnelusa in the western part of the study area may increase leakage from the Madison. Lowering the potentiometric surface of the Minnelusa near the outcrop area would decrease spring flow.

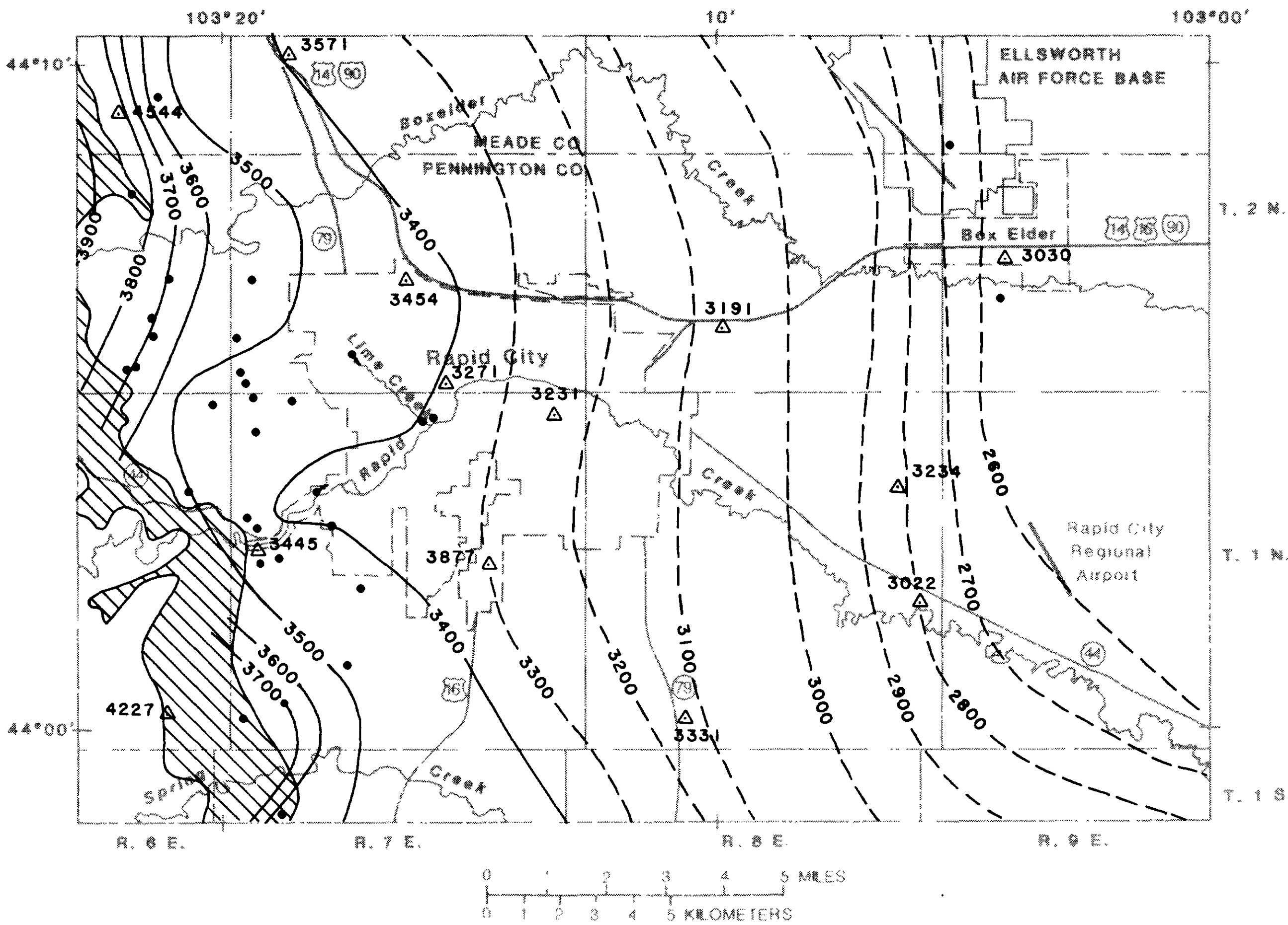
Madison Aquifer

The Madison Limestone of Mississippian age (also called the Pahasapa Limestone in the Black Hills) is a massive limestone and dolomite about 300 to 400 ft thick (Cattermole, 1969). It is cavernous in the upper one-half and contains numerous fractures in outcrops near structural flexures and faults. The Madison is an aquifer in the study area, bounded on the bottom by the Englewood Formation. The plateau on the western boundary of the study area is formed by the outcrop of the Madison. In the city of Box Elder, the top of the Madison is at a depth of about 4,150 ft. Throughout the study area, the top of the Madison aquifer is about 560 to 640 ft below the top of the Minnelusa aquifer and the geologic structures are similar to those shown in figure 5. Most wells completed in the Madison are in areas where the Minnelusa is either dry or does not provide a sufficient supply, or in areas where the Minnelusa contains saline water.

The altitude of the potentiometric surface of the Madison aquifer ranges from about 2,600 to 3,900 ft above sea level (fig. 7). Because there are very few wells completed in the Madison in the eastern two-thirds of the study area, the potentiometric surface is approximated in this area.

The gradient of the potentiometric surface ranges from 30 ft/mi in the central part of the study area to 200 ft/mi near the outcrop southwest of Rapid City. Water in the aquifer generally flows from west to east. As explained previously, the steep gradient near the outcrop may be misinterpretation of the data because of significant vertical flow in the aquifer near the outcrop. However, the steeper gradient east of Rapid City may be the result of a change in transmissivity.

The steep gradient between Rapid City and Box Elder, though previously suspected, was confirmed by water-level measurements of the Box Elder well number 4, drilled in 1983 and the first new well penetrating the Madison in the study area east of the Inyan Kara outcrop in nearly 40 years. The Box Elder city well



EXPLANATION

OUTCROP OF THE MADISON LIMESTONE

3100 — — POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, 1983. Dashed where approximately located. Contour interval 100 feet. National Geodetic Vertical Datum of 1929.

• WELL COMPLETED IN THE MADISON AQUIFER

SPRING ISSUING FROM THE MADISON AQUIFER

3022 △ LAND SURFACE ALTITUDE--Shows altitude of land surface in feet above National Geodetic Vertical Datum of 1929.

Figure 7.--Potentiometric surface of the Madison aquifer.

number 4, which flowed when it penetrated the Minnelusa, was deepened and completed with about 320 ft of open hole in the Madison. After the Minnelusa was sealed off by casing, the water level was 480 ft below land surface. The steep gradient between western Rapid City and Box Elder (averaging 75 ft/mi) indicates a decrease in transmissivity in the Madison somewhere between the two cities. It is known from dye tests (Rahn and Gries, 1973) in the western part of the study area that the Madison is very permeable near the outcrop. Because the Madison is not known or expected to be thinner in the eastern part of the study area, the most logical explanation for the steep gradient is that the aquifer is less permeable in the eastern part of the study area. However, the reversal of the direction of flow and decrease of the volumetric rate of flow between the Madison and Minnelusa also may be affecting the gradient in each aquifer.

Recharge to the Madison aquifer in the study area is from infiltration of precipitation and streamflow on the outcrop, inflow, and possibly leakage from other aquifers. Infiltration of precipitation on the outcrop recharges the Madison aquifer at a rate of about 1 ft^3/s, if it is assumed 2 in/yr of the annual 20 inches of precipitation infiltrates the outcrop, which is about 9 mi^2 in area. Practically all the stream losses, about 25 ft^3/s from Boxelder, Rapid, and Spring Creeks, recharges the Madison. The potentiometric surface indicates the water flows from these recharge areas toward Cleghorn and City Springs. About 0.5 ft^3/s may be entering the southeastern part of the study area as underflow through the aquifer. There may be leakage from the Minnelusa in the eastern part of the study area, but the quantity is unknown.

Discharge from the Madison in the area is as spring flow, underflow, withdrawals from wells, and leakage to other aquifers. It is unknown what proportion of the approximately 15 ft^3/s discharged by Cleghorn and City Springs is from the Madison, but it is known from dye tests (Rahn and Gries, 1973) that part and possibly most of the water has flowed through the Madison. About 2 ft^3/s flows across the eastern boundary of the study area. Less than 0.5 ft^3/s is withdrawn by wells. The quantity of leakage from the Madison to the Minnelusa, or possibly to the deeper Deadwood Formation, is unknown.

Estimates from regional studies of the aquifer by Downey (1982) and the author indicate the transmissivity may range from 86 to 25,000 ft^2/d within the study area. The storage coefficient may range from $1X10^{-6}$ to $1X10^{-4}$ (Joe S. Downey, U.S. Geological Survey, written commun., 1982).

Reported well yields from the Madison aquifer range from 22 to more than 500 gal/min. The permeability of the Madison, a carbonate aquifer, is mainly a result of fracturing and subsequent solution channel development. Therefore, large yields may be obtained by locating wells near geologic structures where fracturing is expected, such as near folds or faults. The location of such structual features in the western one-third of the area is shown in fig. 5. City Spring and the wells with the greatest reported yields are located near folds in T. 2 N., R. 7 E. The monocline that extends eastward through the southwest corner of T. 2 N., R. 7 E. (fig. 5) appears to extend further east, into an area where there are no wells. Possibly Rapid Creek partly follows the trace of this feature. In central and eastern Rapid City this monocline, which is a subtle flexure, may have increased the permeability of the Madison by fracturing, as the folds in T. 2 N., R. 7 E. apparently have. The large yields produced by some wells in the Madison indicate this aquifer has the greatest potential for additional development of the three studied. However, lowering of the potentiometric surface in the outcrop and in the vicinity of springs could increase the rate of stream loss and decrease the flow from springs.

Preliminary estimates of the potential drawdown for a given discharge of a well completed in the Madison aquifer can be made by estimating values of hydraulic variables, such as transmissivity, storage, and areal extent, and applying them in the Theis equation for nonsteady radial flow without vertical movement (Lohman, 1979). However, the following assumptions are required: (1) The aquifer is homogeneous and isotropic, (2) the boundaries are beyond the effects of the well in the time considered, (3) the discharging well penetrates the entire thickness of the aquifer, (4) the well has an infinitesimal diameter, and (5) the water removed from storage is discharged instantaneously with the decline in head. The version of the Theis equation that is appropriate for estimating discharge given drawdown in a well, is:

$$Q = \frac{4\pi Ts}{W(u)} \frac{1}{(86{,}400)} \qquad (1)$$

where

$$u = \frac{Sr^2}{4Tt} \qquad (2)$$

and Q is well discharge, in cubic feet per second;
W(u) is well function of u, dimensionless;
T is transmissivity, in feet squared per day;
s is drawdown, in feet;
S is storage coefficient, dimensionless;
r is radial distance from well, in feet; and
t is time since discharge began, in days.

Not all of the assumptions required by the Theis equation may be reasonably met by the Madison aquifer in the Rapid City area. The aquifer is not homogeneous or isotropic, though it may be sufficiently fractured in some areas to behave as if it were. It is likely the radius of influence of a well would intercept boundaries such as the aquifer outcrop, faults, and streams. Boundaries may increase drawdown by being impermeable obstructions to ground-water flow or may decrease drawdown by providing additional water as flow from discharge points, such as springs, is captured. Furthermore, values of transmissivity and storage coefficient can only be approximately estimated from regional digital model studies, because there is no aquifer test data for transmissivity and storage coefficient in the Rapid City area.

Although more detailed analysis would be beneficial for selecting well location and design, preliminary estimates of discharge-drawdown ratios can be made using the Theis equation.

For example, if it is assumed t = 60 days and r = 1 ft, and the above equations applied, discharge-drawdown ratios can be calculated using tables of W(u) and u (Lohman, 1979, p. 16) for different values of T and S. The relationship of discharge-drawdown ratios to transmissivity and storage coefficient, neglecting well losses, for the assumed conditions are shown in figure 8, which can be used to estimate drawdown for various values of T, S, and Q for the above assumed conditions. For example, if T = 1,000 ft^2/d, S = 0.0001, and the assumptions of the Theis equation are met, Q/s would be about 0.0072 ft^2/s (fig. 8) and a well discharging about 4 ft^3/s in central Rapid City for 60 days would draw the potentiometric surface down about 550 ft near the well. However, by assuming s = 1 ft, solving equation 1 for W(u), determining the corresponding value of u from Lohman (1979, p. 16), and solving for r from equation 2, it is found the radius of influence of a well pumping 15 ft^3/s would extend more than 15 miles, given T = 1,000 ft^2/d and S = 0.0001, and the assumption that any boundary conditions would be beyond the effect of the well would not be met if the well is in Rapid City.

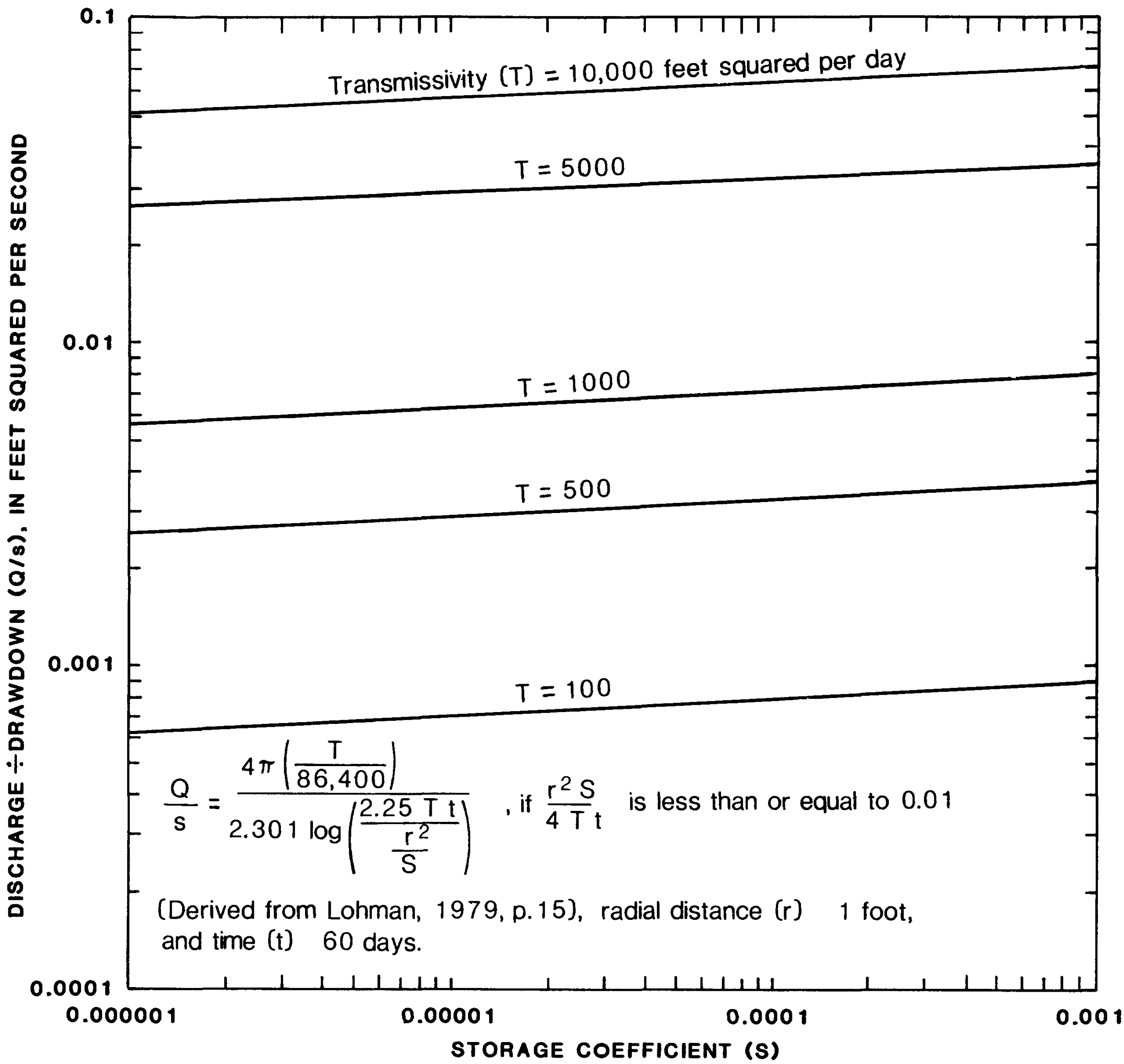


Figure 8.--Hypothesized relationship of drawdown-discharge ratios to transmissivity and storage coefficient for a well fully penetrating the Madison aquifer, assuming nonsteady radial flow without vertical movement.

If the following reasonable values are assumed for the hydraulic properties of the Madison aquifer and for typical public supply pumping rate:

$Q = 10\ ft^3/s$,
$T = 1,000\ ft^2/d$,
$S = 0.0001$, and
$t = 60$ days,

values for u can be calculated for given values of r, W(u) can be determined from tables of W(u) and u (Lohman, 1979, p. 16) and s then can be calculated. The relationship of drawdown and radial distance for the above assumptions is shown in figure 9. It is estimated, using this approach, that if a well discharges 10 ft^3/s for 60 days from the Madison aquifer, the drawdown about 700 ft from the well would be about 550 ft. About 10,000 ft from the well, the drawdown would be about 180 ft. Thus the radius of influence of the well would exceed 2 mi and it is expected that boundary conditions would have an effect on similar large-capacity wells in the Rapid City area.

Using these approximations and reported well yields, it is estimated that 5 to 10 ft^3/s of water could be supplied by less than 5 wells, if they were constructed similarly to the existing wells, which yield more than 500 gal/min, or 1 ft^3/s. A major consideration in the design and location of a well field will be a large enough well spacing so that well interference is minimized as much as practical. An optimal well-field design would require a more specific evaluation of the effect of known boundary conditions, transmissivity, storage coefficient, and estimated pumping rates.

The variability of the transmissivity of carbonate aquifers, such as the Madison aquifer, complicates planning of ground-water development. As shown by figure 8, Q/S may vary from less than 0.0007 to greater than 0.1 within the Rapid City area. As discussed previously, locating wells near folds in the rock where fractures may have increased the aquifer transmissivity may increase the likelihood of obtaining larger well yields.

WATER QUALITY

The quality of water from bedrock aquifers in the Rapid City area generally is acceptable for community use, with the concentrations of most ions less than the maximum permissible and recommended levels allowed by the Environmental Protection Agency (1975-80, 1979) for community water systems. A summary of water-quality analyses for samples from the Inyan Kara, Minnelusa, and Madison as related to mandatory and recommended standards established by the U.S. Environmental Protection Agency (1975-80, 1979) for community water supplies is presented in table 2.

The National Interim Primary Drinking Water Regulations (U.S. Environmental Protection Agency, 1975-80) are mandatory criteria for public water systems establishing the maximum permissible levels of contituents known to be either toxic or injurious to health. The constituents listed under the heading of "primary" in table 2 are in this category. All may be toxic to humans at levels in excess of the maximum permissible level established by the U.S. Environmental Protection Agency, except fluoride. Excessive concentrations of nitrate in water, though not toxic to adults, can cause methemoglobinemia or blue baby disease if ingested by infants. Excessive concentration of fluoride produces objectionable dental fluorosis, or mottling of teeth.

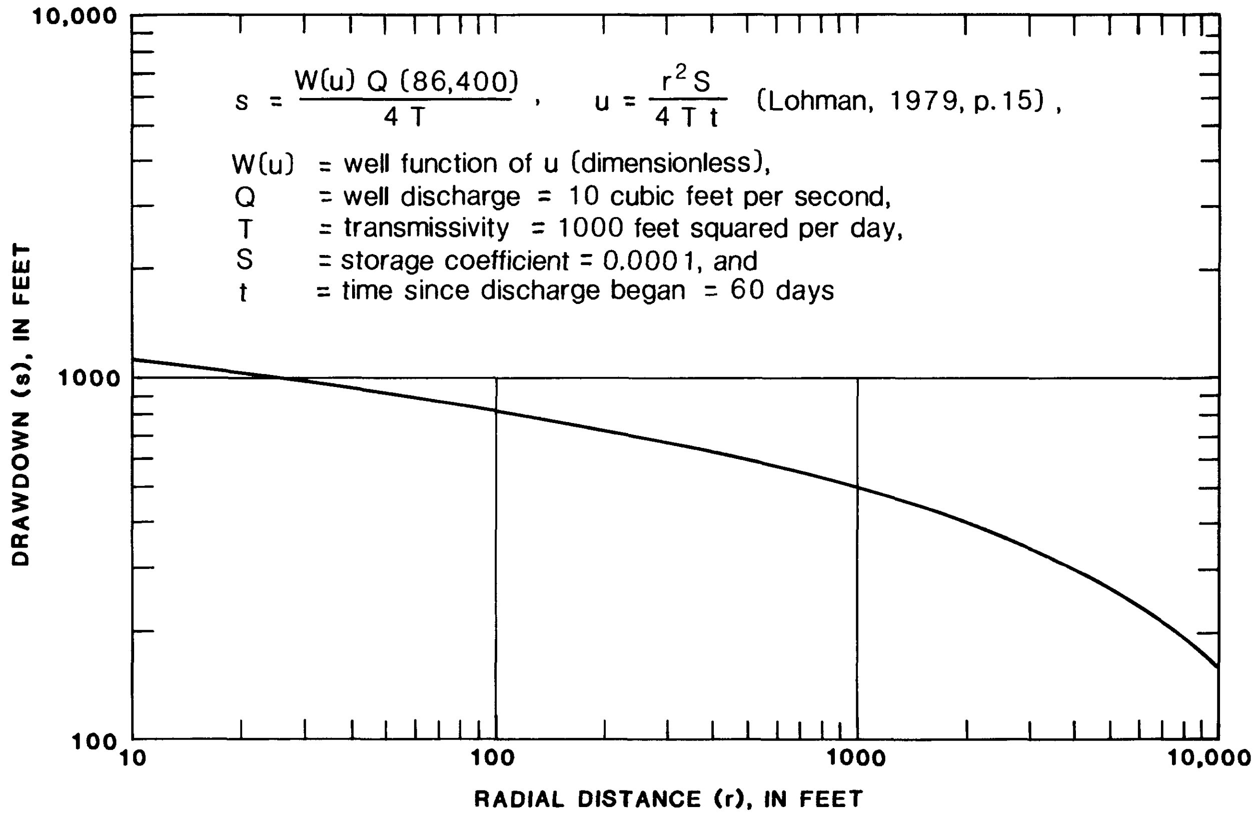


Figure 9.--Hypothesized drawdown for a well fully penetrating the Madison aquifer, assuming nonsteady radial flow without vertical movement.

Table 2.--Concentrations of constituents and values of properties that may affect use of water from the bedrock aquifers for community supply

[Concentrations in micrograms per liter except as indicated. <1, less than 1; ≤30, less than or equal to 30]

Constituent or property	Maximum permissible or recommended level for community water systems[1]	Range of concentrations or values (number of analyses given in parentheses; concentrations exceeding the maximum levels are underlined)					
		Inyan Kara		Minnelusa		Madison	
Primary (Permissible)							
Arsenic	50	≤1	(4)	4	(1)	3	(1)
Barium	1,000	10-20	(4)	10-100	(2)	100	(1)
Cadmium	10	≤1	(4)	<1	(2)	<1	(1)
Chromium	50	10-<50	(4)	<50	(2)	0	(1)
Fluoride, milligrams per liter	2.4	.0-.8	(9)	.2-1.5	(17)	<.1-1.4	(7)
Lead	50	<30	(4)	<30	(2)	2	(1)
Mercury	2	.0-<.1	(4)	.1	(2)	.0	(1)
Nitrate as nitrogen (N), milligrams per liter	10	<.3	(8)	.2-1.0	(16)	.0-.5	(8)
Radium-226, milligrams per liter	[2] 5	.3-24	(5)	.3-.5	(4)	.5-<2	(3)
Selenium	10	1-10	(4)	4	(2)	1	(1)
Silver	50	10	(1)	<10	(1)	No analyses	

Secondary (Recommended)							
Chloride, milligrams per liter	250	.1-2.7	(9)	< 1-12	(18)	1.5-40	(10)
Copper	1,000	.4-2	(4)	< 30	(6)	6-30	(4)
Dissolved solids, milligrams per liter	500	340-630	(7)	150-2,260	(18)	190-490	(9)
Iron	300	0-1,800	(8)	0-2,800	(17)	5-300	(8)
Manganese	50	3-60	(6)	1-60	(10)	<50	(5)
pH, units	6.5-8.5	7.0-8.1	(9)	7.3-7.9	(17)	6.8-8.0	(9)
Sulfate, milligrams per liter	250	3.3-290	(9)	5-1,330	(18)	10-210	(10)
Zinc	5,000	20-1,000	(4)	9-110	(6)	20-230	(4)
Constituents that may affect use, but for which there is no maximum permissible or recommended level							
Hardness as $CaCO_3$, milligrams per liter		19-420	(9)	190-1,620	(18)	140-360	(10)
Uranium		3.9-7.1	(4)	1.1-3.7	(2)	.1-6.4	(2)

1/ From Environmental Protection Agency, 1975-80 and 1979.

2/ Maximum permissible level is 5 picocuries per liter for radium-226 and radium-228 combined.

The National Secondary Drinking Water Regulations (U.S. Environmental Protection Agency, 1979) are recommended criteria for public water systems. The maximum recommended levels of the constituents listed under the heading of "secondary" in table 2 were established because excessive concentrations are undesirable, although not toxic. Excessive concentration of chloride, copper, iron, or zinc imparts an undesirable taste to water. Iron or manganese in excessive concentrations stains porcelain and laundry. If the pH of water is outside the recommended range, it can be corrosive to pipes and interfere with water treatment. Excessive concentration of sulfate is undesirable because it can have a laxative effect on people not accustomed to drinking the water. Water with a concentration of dissolved solids exceeding the maximum recommended level generally has a concentration of a specific constituent, such as sulfate, which exceeds the maximum permissible or recommended level. Also included in table 2 are data for hardness and uranium. Although no standards have been established for these constituents, they may affect the use of the water for community supplies.

Constituents that exceeded the maximum permissible or recommended levels in at least one analysis were radium-226, dissolved solids, iron, manganese, and sulfate. Though the concentration of dissolved solids in water from the Inyan Kara and Minnelusa aquifers exceeded the maximum recommended level in some areas, the actual deterrent to use of the water is the concentrations of specific constituents, discussed individually below.

The maximum concentration of radioactivity from radium-226 and radium-228 combined allowed in water used by community supplies is 5 picocuries per liter (U.S. Environmental Protection Agency, 1975-80) because of the toxicity of radium. This concentration was exceeded in water from the Inyan Kara aquifer in some parts of the study area, as well as in other areas of western South Dakota. Both aquifers are uraniferous and it can be expected that radium-226, a daughter product of uranium radioactive decay, will be found in the water. Though the concentrations of radium-226 in water from the Madison in other areas of South Dakota exceeds the maximum permissible level allowed for community supplies, in the Rapid City area the concentration is less than the maximum permissible level.

The concentrations of iron and manganese in water from the Inyan Kara and Minnelusa aquifers exceeds the maximum recommended levels set by the U.S. Environmental Protection Agency (1979). At concentrations greater than the maximum recommended levels, these two metals will stain porcelain and laundry and impart undesirable tastes to beverages made using the water. Because metal well casings and iron bacteria may increase the concentration of iron in water, it is difficult to evaluate the origins of iron in ground water. Undesirable concentrations of iron in water from the Inyan Kara has been reported in other areas in the Black Hills. The water from the Minnelusa generally does not have large concentrations of iron and manganese in other areas of the Black Hills. Water from the Madison aquifer does not have undesirable concentrations of iron or manganese in the Rapid City area.

Sulfate concentration exceeds the maximum recommended level of 250 mg/L (milligrams per liter) established by the U.S. Environmental Protection Agency (1979) in water from the Inyan Kara and Minnelusa aquifers within the study area and in other areas of the Black Hills. Water having a sulfate concentration exceeding 250 mg/L may have a laxative effect, particularly on people unaccustomed to drinking the water. The source of the sulfate in the Inyan Kara aquifer may be leakage of water through underlying gypsiferous units or oxidation of sulfide minerals. The areas where sulfate concentration is excessive in the water from the Inyan Kara are not delineated by the available data. The Minnelusa Formation in the eastern part of the study area is partly composed of beds of anhydrite, a calcium-sulfate mineral. In the western part of the study area, near the Minnelusa outcrop, the anhydrite has been dissolved and removed long ago. As a result, water from the Minnelusa near the outcrop has a sulfate concentration less than 100 mg/L. The approximate area where sulfate concentration in water from the Minnelusa exceeds or probably exceeds 250 mg/L is shown in figure 10. If the drawdown of the potentiometric surface of the Minnelusa in the western study area were sufficient to reverse the gradient, forcing water to flow to the west, water containing an undesirable sulfate concentration could move westward. Sulfate concentration in water from the Madison in the Rapid City area is less than 250 mg/L.

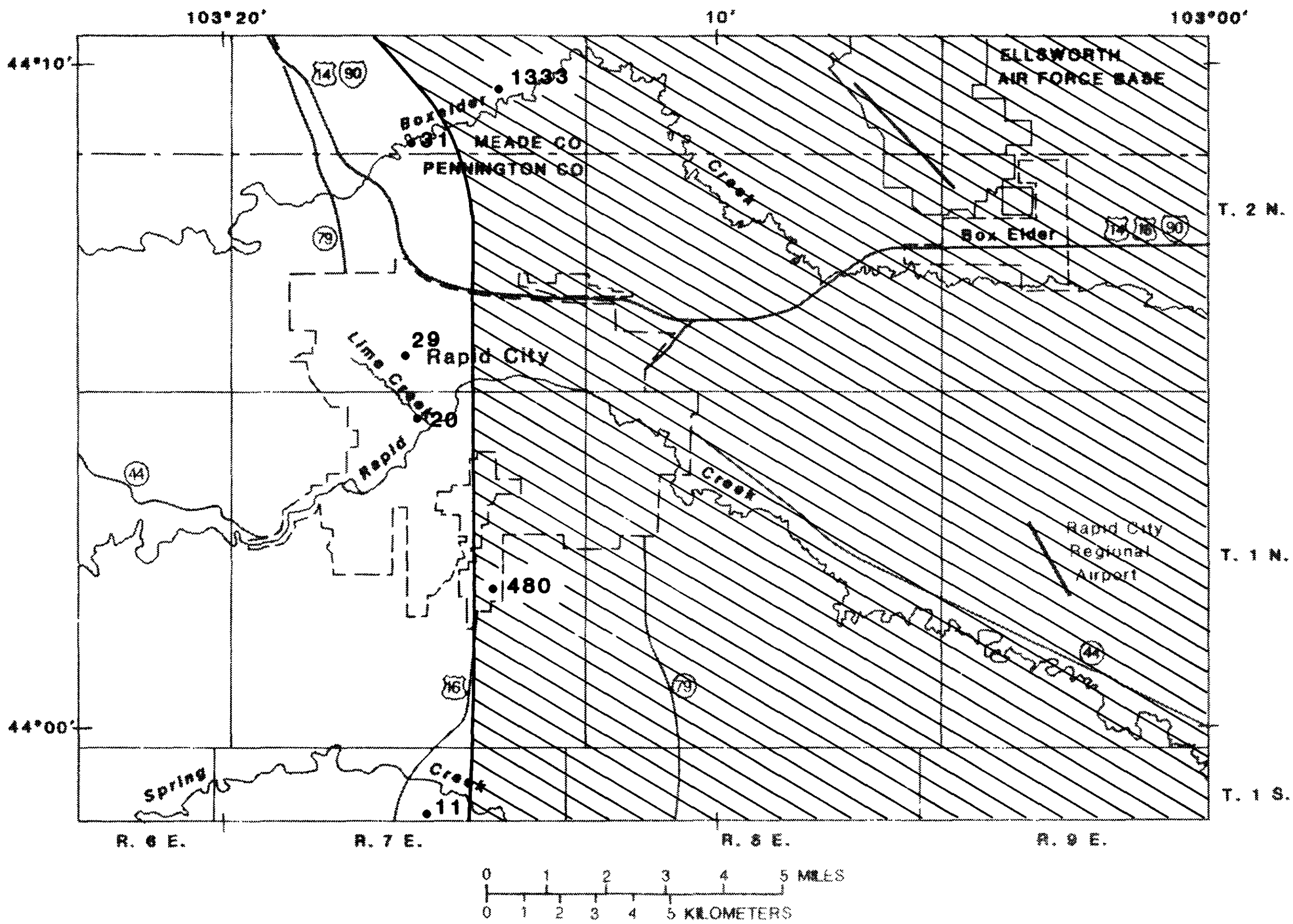
Most of the ground water in the Rapid City area is hard (hardness 120 to 180 mg/L) to very hard (hardness greater than 180 mg/L). Excessive hardness in water causes encrustation of pipes and water tanks and reduces the lathering capacity of soaps and detergents. Hardness is mainly caused by calcium and magnesium dissolved in the water. The Minnelusa and Madison aquifers are composed of minerals, mainly calcite, dolomite, and anhydrite, which contain calcium, magnesium, or both. Typically, hardness as calcium carbonate exceeds 100 mg/L in water from the Madison and Minnelusa aquifers. The Inyan Kara aquifer has calcite cement in the sandstone and does have hard water in the western part of the study area. Water from the Inyan Kara aquifer in the eastern part of the study area is soft (hardness less than 60 mg/L) because the calcium has been removed and replaced by sodium by the natural softening ability of clay minerals in the Inyan Kara Group.

The U.S. Environmental Protection Agency has not established either a maximum permissible or recommended level for dissolved uranium in community supplies. Because two of the aquifers in the Rapid City area are uraniferous, data on concentrations of uranium were included in table 3 so evaluations can be made when a maximum permissible or recommended level is established.

All the ground water in the Rapid City area has less than the maximum concentration of fluoride established by the U.S. Environmental Protection Agency (1975-80). Fluoride at optimum levels in drinking water has been shown to have beneficial effects in reducing the occurrence of tooth decay (U.S. Environmental Protection Agency, 1975-80).

Because the aquifers in the eastern part of the study area are deeply buried, the ground water is hotter than the average annual air temperature, about 8°C in Rapid City (U.S. Dept. of Commerce, 1976), which is the typical temperature of water at shallow depths. The temperature gradient in Box Elder well number 4, which is 4,480 ft deep, is about 1°C per 100 ft. The bottom-hole temperature is 46.5°C. Water from deep wells in the study area may require some kind of cooling before consumption. The available heat stored in the ground water may be used in some way, particularly if the water quality is acceptable for use as a community supply.

Based on the chemical analyses used to prepare table 2, the Madison aquifer is the only aquifer in the Rapid City area containing water that is acceptable for community supply without treatment throughout the area.



EXPLANATION

AREA WHERE CONCENTRATION OF DISSOLVED SULFATE EXCEEDS OR PROBABLY EXCEEDS 250 MILLIGRAMS PER LITER IN WATER FROM THE MINNELUSA AQUIFER

• 11 WELL--Number is the concentration of sulfate, in milligrams per liter in the water from the well.

Figure 10.--Area where the concentration of sulfate in water in the Minnelusa aquifer may exceed 250 milligrams per liter.

HYDROLOGIC BUDGET

As Bredehoeft, Papadopulos, and Cooper stated (1982, p. 51), "Perhaps the most common misconception in groundwater hydrology is that a water budget of an area determines the magnitude of possible groundwater development." As mentioned in the previous discussion of drawdown-discharge relationships, the availability of water is determined by transmissivity, storage coefficient, the proximity of wells to boundaries, and the nature of those boundaries. In the Rapid City area, the magnitude of sustained pumpage may depend on how much water can be captured by increasing leakage from other aquifers, increasing infiltration of streamflow from Rapid Creek, or decreasing spring flow. Furthermore, the maximum sustained yield of a well usually is dictated not by the aquifer properties so much as the impacts of ground-water withdrawal, such as drawdown or decreased spring flow, that can be tolerated by the users.

However, a general appraisal of the volumetric rate of water moving through the aquifer system composed of the Inyan Kara, Minnelusa, and Madison aquifers and the intervening confining layers is beneficial to understanding the aquifer system and well production and can be made from estimates of recharge and discharge, and assumptions about the geologic and hydrologic properties of individual aquifers in the system.

A hydrologic budget is a numerical estimate of the quantity of water entering and leaving an aquifer or group of aquifers. If recharge and discharge are equal, there is no change in the quantity of water in storage and the system is described as being at steady state. Actually, at any one time recharge and discharge may not be equal and water may be removed from or added to storage, hence the seasonal fluctuations of water levels in wells, particularly near aquifer outcrops. However, after long periods these fluctuations tend to cancel each other out. If there is a long-term inbalance between recharge and discharge in the system, the changes in the quantity of water in storage will be discernible by long-term changes in the potentiometric surface as measured by the water level in observation wells.

Measurements of water levels during the last 20 years were examined to ascertain if the ground-water system is in equilibrium in the study area. Though there were fluctuations, usually within a range of 30 ft, water levels generally have not declined.

The only significant decline in water levels has been in wells completed in the Inyan Kara aquifer near the city of Box Elder. Though the wells were drilled as early as the 1940's, continuous monitoring of water levels was not begun until 1983. During 6 months in 1983, the water level in an observation well on Ellsworth Air Force Base declined nearly 60 ft. Drawdowns in this area may be significant during the summer months when pumpage in Box Elder is at its maximum. It appears, based on measurements made in the fall of 1983, that water levels rise during the winter. At this time, 1984, there is no long-term record for water levels in the area of Box Elder that would show if there was a declining trend in water levels near Box Elder.

If it is assumed the ground-water system, defined as the three major bedrock aquifers within the study area, is at steady state, then after long periods, recharge and inflow to the system balance natural discharge, withdrawals, and outflow. The components of a hydrologic budget for the system and estimates of their values are shown in fig. 11. The principal source of ground-water recharge is the water that Rapid, Boxelder, and Spring Creeks lose when they cross outcrops of the Madison and Minnelusa aquifers. Average stream loss from Rapid Creek as it crosses the Madison

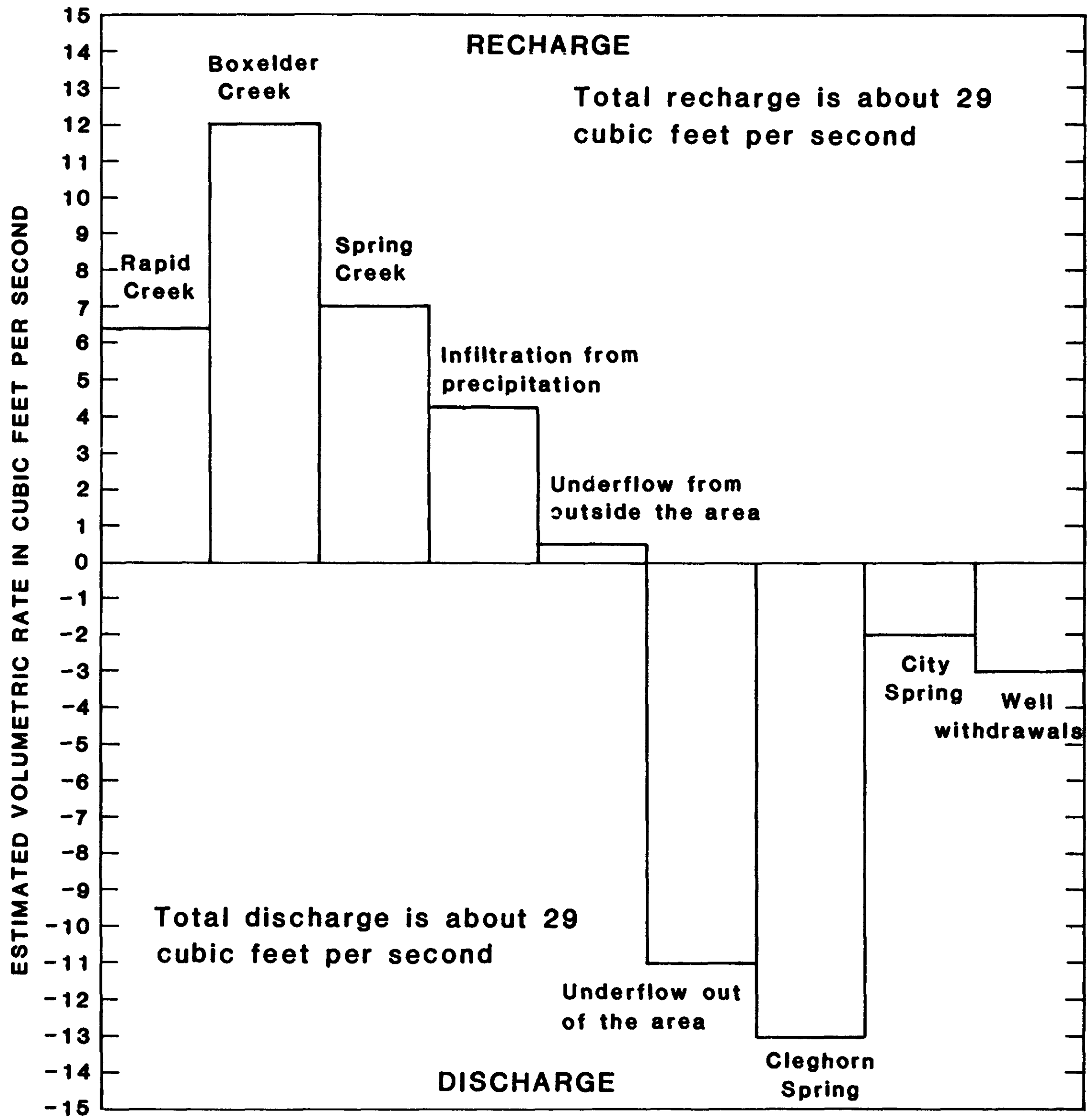


Figure 11.--Estimated hydrologic budget for the aquifer system comprising the Inyan Kara, Minnelusa, and Madison aquifers.

and Minnelusa outcrops was estimated for 35 years by using the mean average discharge at two Geological Survey stream gages. For 10,230 days, or 80 percent, of this 35-year period, there was less discharge at the downstream gage than at the upstream gage. For these days, the mean difference in flow at the two sites was 6.4 ft^3/s and the standard deviation was 7.4 ft^3/s. On 3,673 days, discharge at the upstream site was less than 16 ft^3/s and at the downstream site it was lesser still. On those days, the mean difference in the flow was 5.6 ft^3/s and the standard deviation was 2.8 ft^3/s. Using the greater of the two calculated mean differences, mean stream loss is estimated to be about 6.4 ft^3/s. Two ungaged perennial tributaries contribute less than 3 ft^3/s in the reach examined, so the estimates of mean stream loss may be low.

It was found that, other than during periods of low flow when all the streamflow is lost, losses from Rapid Creek to the aquifer are not proportional to streamflow. However, declines in the potentiometric surface of the Madison and the Minnelusa increase the quantity of stream loss in direct proportion to the increase in gradient between the creek and the aquifers.

Boxelder and Spring Creeks do not flow east of the outcrops of the Madison and Minnelusa aquifers except during periods of high flow. About 12 ft^3/s is lost from Boxelder Creek, mainly to the Madison aquifer, based on streamflow records for 4 years at a gaging station near Nemo, about 20 mi northwest of Rapid City, upstream from the area of stream loss. About 7 ft^3/s is lost from Spring Creek based on instantaneous measurements reported by Rahn and Gries (1973, p. 23-24). As on Rapid Creek, declines in the potentiometric surfaces may increase the volumetric rate of stream losses during high flows, possibly shortening the period when the creeks flow past the outcrops of the Madison and the Minnelusa.

Combined recharge from infiltration of precipitation on the outcrops of the three aquifers is estimated to be 4 ft^3/s. Rapid City is in a semiarid climate with mean annual rainfall ranging from 18 inches in the eastern part of the area to 20 inches in the western part of the area (U.S. Department of Commerce, 1980-83). Because the outcrops generally are covered by ponderosa pine and other vegetation and because evaporation is significant, it was assumed only 1 to 2 in/yr of precipitation recharges the aquifers. Rahn and Gries (1973, p. 17) estimated minimum recharge rates of 0.62 in/yr in the southern Black Hills, where mean annual precipitation is 17 in/yr, and 6.8 in/yr in the northwestern Black Hills, where mean annual precipitation is 22 in/yr. Ground-water modeling of the eastern Black Hills by the author indicates 1 to 2 in/yr is a reasonable estimate for the Rapid City area, though it may be more on parts of the Madison and Minnelusa outcrop, where altitude is higher and precipitation is about 20 in/yr. The annual rate was distributed over the aquifer outcrop in the study area to estimate the volumetric rate of recharge.

It is estimated that about 0.5 ft^3/s flows into the study area through the aquifers in the subsurface and about 11 ft^3/s flows out of the study area in the subsurface. Underflow was estimated using transmissivities from unpublished studies by the Geological Survey and the gradients calculated for the area boundaries from the potentiometric maps (fig. 3, 5, and 6). The value of transmissivity used for the Inyan Kara was 340 ft^2/d, for the Minnelusa it was 780 ft^2/d, and for the Madison it was 86 ft^2/d. Variations in transmissivity would affect the estimate of underflow proportionately, however, these values seem reasonable in the vicinity of the eastern boundary, based on regional aquifer models by Joe S. Downey (U.S. Geological Survey, written commun., 1982), H. Lee Case III (U.S. Geological Survey, written commun., 1982), and the author.

Cleghorn and City Springs are the principal discharge points from the aquifers (fig. 12). Cleghorn Spring discharges about 13 ft^3/s under the alluvium of Rapid Creek, based on instantaneous measurements by Rahn and Gries (1973, p. 45-46) and the Geological Survey. About 10 ft^3/s of the water enters Rapid Creek and about 3 ft^3/s is removed through a fish hatchery and two galleries. One gallery belongs to Rapid City and the other to homes in Cleghorn Canyon. Water from City Spring is not used. Based on instantaneous measurements by Rahn and Gries (1973, p. 46) and the Geological Survey, City Spring discharges about 2 ft^3/s to Lime Creek, a tributary of Rapid Creek.

There is inadequate information for total annual usage of ground water in the Rapid City area. As shown by table 3 and figure 12, there are numerous industrial and public supply wells in the vicinity of Rapid City. However, most of these wells yield less than 100 gal/min, or 0.2 ft^3/s, and are used intermittently. It was estimated, using reported pumpages, estimated pumpages, and estimated community populations, 3 ft^3/s is discharged from the aquifer system by well withdrawals. Although this estimate may be inaccurate, the well withdrawals are only about 10 percent of the total discharge and error of estimate would not significantly affect the total water-budget estimate.

The difference between estimated recharge, 30 ft^3/s, and discharge, 29 ft^3/s, for the aquifer system is less than 5 percent, which is less than the error expected from measurements of most of the components of the budget.

Table 3.--Public supply and industrial wells in the Rapid City area, June 1983

Local identifier[1/]	Owner	Depth (feet)	Date drilled	Reported yield (gallons per minute)
		Inyan Kara aquifer		
1N8E 9ADA	Rapid Valley	1,605	--	--
1N8E 9CABB	Rapid Valley	1,250	--	75
1N8E17CCAB	S.D. Concrete Company	983	1956	--
2N7E 2ACAD	Weston Heights	1,010	--	--
2N7E27DBDD	Singer Masonry	515	1978	50
2N8E 1DABB	Ellsworth Air Force Base	2,600	1952	200
2N8E17CDD	Vetsch's Country Village	1,735	--	--
2N8E20CCCD	Prairie Acres Estate	1,625	1974	--
2N8E23DBDA	Box Elder	2,222	1965	90
2N8E27CBAC	I-90 Skelly Truck Stop	1,798	1973	--
2N8E29CDCA	Berry Patch Campground	1,648	1962	75
2N9E 8CC	Bertelsen Water System	2,400	1960	--
2N9E17BDDB	Box Elder	2,500	1978	--
2N9E19DDD	Box Elder	2,346	1972	--

Table 3.--Public supply and industrial wells in the Rapid City area, June 1983--Continued

Local identifier[1]	Owner	Depth (feet)	Date drilled	Reported yield (gallons per minute)
	Spearfish Formation[2]			
2N7E28DD	Dakota Lime Company	300	1959	flowing
2N7E28DDD2	Black Hills Power Company	40	1956	--
	Minnekahta Limestone[2]			
2N7E21DAA	Henry Hackett Construction Co.	452	1979	--
2N7E27BCAA	Development Contractors	380	1979	12
2N7E34CBAA	Black Hills Power Company	236	1958	150, flowing
	Minnelusa aquifer			
1S7E 5BDCA	Spring Canyon Water Company	350	1977	--
1S7E 5CBAB	Spring Canyon Water Company	140	1966	--
1N7E 4DCB	Rapid City (Rapid City number 4)	1,075	1939	490
1N7E 5CDD	Dakota Wesleyn Church Camp	330	1958	14
1N7E 9BBCA	Rapid City (Rapid City number 3)	902	1937	210
1N7E15	Arrowhead Country Club	921	1955	--
1N7E15CCCB	Springbrook Acres	500	--	95
1N7E16CCCA	Carriage Hills	612	1977	50
1N7E17AABB	Chapel Lane	360	1972	72
1N7E22ABBD	Springbrook Acres	780	--	60
1N7E22BCAC	Springbrook Acres	445	1972	150
1N7E23BCB	Assembly of God Church	1,680	1976	75
1N7E23BDAD	Enchanted Hills	1,878	1973	100
1N7E27DABB	Henry Bachmier Campground	1,430	1973	40
1N7E29DDC	A. Croyle-Whispering Pines	715	1948	--
1N7E32DCA	M. Dunsmore-Colonial Village	300	1961	20
2N7E17BACA	Westwinds Mobile Village	650	1972	--
2N7E17DDBD	Ponderosa Mobile Homes	371	1957	--
2N7E 2	Weston Heights			
2N7E20CCCC	Hidden Valley	350	1961	50
2N7E20DD	Pines Drive-in	610	1954	28
2N7E27BB	Summit Construction Company	505	1961	--
2N7E27BBB	Harris Equipment Company	615	1961	--
2N7E33DAB1	Cement Plant			[3]150-300, flowing
2N7E33DAB2	Cement Plant			
2N7E33DAB3	Cement Plant			
2N7E33BCAD	Shrine Club	225	1978	flowing
2N7E34BDAD	Timberline Company	585	1960	150, flowing
2N7E34CBCD	Central Mix	371	1959	55, flowing

Table 3.--Public supply and industrial wells in the Rapid City area, June 1983--Continued

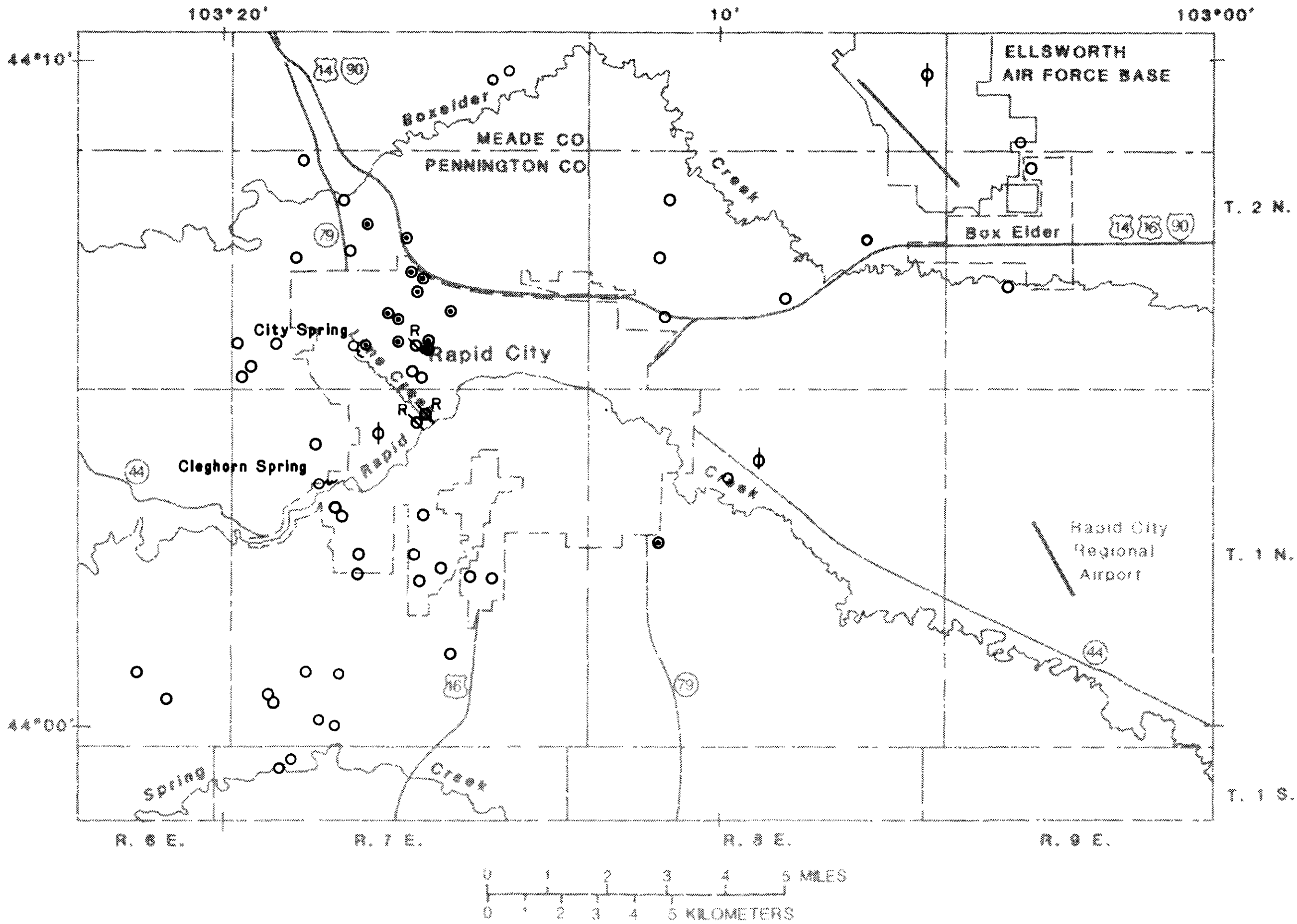
Local identifier[1/]	Owner	Depth (feet)	Date drilled	Reported yield (gallons per minute)
		Madison aquifer		
1N7E17AADD	Chapel Lane	820	1975	328
1N7E21BCAB	Carriage Hills	883	1977	—
2N6E26CAAD	South Canyon Estates	1,095	1978	100
2N6E35AABD	South Canyon Estates	740	—	22
2N7E21BDAB	Lien Quarry	1,200	1951	—
2N7E31BBAB	Ponderosa Ridge	580	1974	—
2N7E31CBAD	Westberry Trails	565	1972	90
2N7E31CCDA	Westberry Trails	680	1971	25
2N7E34BDCC	Black Hills Power Company	1,275	1959	4/ 520
2N9E29BBC	Box Elder (Box Elder city well number 4)	4,480	1983	105
		Deadwood aquifer		
1N7E29CDC	Countryside Estates	1,040	1980	—
1N7E31ABDB	Ponderosa Park	825	1957	—
1N6E36AAAD	Whispering Pines Association	650	1963	—
1N7E32CADB	M. Dunsmore-Colonial Village	1,170	1978	135
2N7E31ACAD	Ponderosa Ridge	1,040	1976	—

1/ Local identifier explained in text.

2/ The transmissivities of the Spearfish Formation and the Minnekahta Limestone are generally too small for the units to be described as aquifers. These wells are located in an area where wells in the Minnelusa and Madison aquifers flow. Probably water from the two deeper aquifers is leaking upward to the Minnekahta and Spearfish in the same area.

3/ Reported yield is combined yield of all three Cement Plant wells.

4/ Well flows about 180 gallons per minute. Well also penetrates the Deadwood aquifer. It is not known how much of the yield is attributable to the Deadwood.



EXPLANATION

WELLS

o Public supply

⊙ Industrial

ϕ Unused

ø^R Observation, equipped with record

Figure 12.--Location of selected wells, Cleghorn Spring, and City Spring.

SUMMARY AND CONCLUSIONS

The availability and quality of water from three bedrock aquifers, the Inyan Kara, the Minnelusa, and the Madison, in the Rapid City area was investigated in this study.

The Inyan Kara aquifer, though it is the shallowest aquifer in the eastern part of the study area, has the least potential for additional development. Small reported well yields (less than 200 gallons per minute), the proximity of the outcrop area to Rapid City, and the large concentration of radium-226 that exceed the U.S. Environmental Protection Agency's maximum permissible level limit the potential for additional development. Shallowest of the three aquifers, the Inyan Kara may not be able to sustain the large drawdowns required by large yields.

The Minnelusa aquifer may provide sufficient water for a Rapid City supply. In the western one-third of the study area, the concentration of sulfate in water from the Minnelusa is less than 250 milligrams per liter, the U.S. Environmental Protection Agency's maximum recommended level for community supply. If development reverses the hydraulic gradient in the Minnelusa, so that the direction of water movement is from east to west, water with sulfate concentration exceeding 250 milligrams per liter may move westward.

Based on estimated well and spring discharges, estimated transmissivities and storage coefficients, and water quality, the Madison aquifer has significant potential for additional development. Wells yielding more than 500 gallons per minute have been developed in the Madison in this area. Cleghorn Spring flows about 13 cubic feet per second and City Spring flows about 2 cubic feet per second; both springs are fed partly from the Madison. The Madison is the deepest of the major aquifers; therefore, sufficient drawdown is available to allow large well yields. The permeability of the Madison is the result of fracturing and solution and is therefore erratically distributed. The Madison may be the most permeable near structures in the western one-half of the study area. Water quality probably is satisfactory, though hardness may exceed 300 milligrams per liter as calcium carbonate. The Madison aquifer is known to have the greatest recharge rate of the three aquifers. About 25 cubic feet per second of flow is lost from the three creeks in the area; most of this flow recharges the Madison. The Madison aquifer has the greatest potential to increase recharge by capturing additional streamflow.

It is estimated, based on approximations of transmissivity and storage coefficient and reported well yields, that 5 to 10 cubic feet per second of water could be supplied by less than 5 wells completed in the Madison, if they were constructed similarly to the existing wells, which yield more than 500 gallons per minute or 1 cubic foot per second. An optimal well-field design requires a more specific evaluation of the effect of known boundary conditions, transmissivities, storage coefficient, and estimates of pumping rates.

Further data collection and investigation of the hydrology of the Rapid City area would be beneficial to an improved understanding of the aquifers. More information on ground-water and surface-water relationships would be beneficial to more accurate assessments of recharge from streamflow. About 85 percent of recharge to the ground-water system comes from losses of flow on Spring, Rapid, and Boxelder Creeks. The relationship of flow in these creeks to precipitation and the effect of aquifer head fluctuations on stream losses are not known quantitatively. Furthermore, baseflow of Rapid Creek in Rapid City is from springs and it is unknown how much the flow from these springs would decrease if development of ground-water increases.

Additional data collection would improve estimates of how the ground-water system will adjust to development or drought by capturing recharge and discharge. For example, ground-water development and the resultant drawdowns may increase stream losses, decrease spring flow, and increase underflow into the area by an unknown quantity. Drought would decrease recharge from precipitation and streamflow. The ground-water system may compensate for decreased recharge by decreasing discharge from the area or increasing underflow into the area.

Further studies would be useful for revaluating the effects of different stresses on the system. Possible studies that would be helpful are in the following three areas:

1. Monitoring streamflow: Additional gaging stations would provide data for better estimating stream losses and for developing equations describing the relationship of streamflow to precipitation and aquifer head. Currently, 1984, there are gaging stations on Spring Creek downstream from the reach where losses occur, on Rapid Creek upstream and downstream from the reach where losses occur, and on Boxelder Creek upstream and downstream from the reach where losses occur. Gages on Spring Creek upstream of the Madison outcrop and on Rapid Creek downstream from the two perennial tributaries would be beneficial. All the gages would need to be maintained for a period sufficient to evaluate rainfall-runoff relationships and the relationship of hydraulic head to streamflow infiltration.

2. Measuring precipitation: Continuous-record precipitation measurements from the basins of the three creeks made concurrently with discharge measurements would be needed in the development of equations describing rainfall-runoff relationships.

3. Drilling and aquifer testing: Drawdowns from production wells in the Rapid City area may be affected by proximity of recharge or discharge boundaries, such as stream-loss reaches or springs. Carefully designed aquifer tests would provide information about the effects of boundary conditions. The hypothesis that the secondary permeability of the Madison aquifer and lower Minnelusa Formation is greater along geologic structures could be tested.

4. Modeling: A digital model using the results of the rainfall-runoff evaluations and aquifer tests could be used to evaluate the effects of the alternative proposals for ground-water development.

5. Water quality: Modeling the transport of sulfate that may result from ground-water development would be useful in evaluating the potential for water-quality degradation as a result of changes in the natural gradients.

Five to ten years of streamflow and precipitation records generally are needed to adequately define their relationship. Therefore, even though ground-water development may not be anticipated in the near future, measurements of streamflow and precipitation could begin sooner so the evaluation will be available when needed.

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