

Prepared in cooperation with the
CITY OF RAPID CITY

Flow-System Analysis of the Madison and Minnelusa Aquifers in the Rapid City Area, South Dakota—Conceptual Model

Water-Resources Investigations Report 02-4185



U.S. Department of the Interior
U.S. Geological Survey

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By Andrew J. Long and Larry D. Putnam

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CONVERSION FACTORS AND VERTICAL DATUM

	Multiply	By	To obtain
cubic foot per second (ft ³ /s)		0.02832	cubic meter per second
foot (ft)		0.3048	meter
foot per day (ft/d)		0.3048	meter per day
foot per mile (ft/mi)		0.1894	meter per kilometer
foot squared per day (ft ² /d)		0.09290	meter squared per day
gallon per day (gal/d)		0.003785	cubic meter per day
gallon per minute (gal/min)		0.06309	liter per second
million gallons per day (Mgal/d)		0.04381	cubic meter per second
inch		2.54	centimeter
inch		25.4	millimeter
inch per year (in/yr)		25.4	millimeter per year
mile (mi)		1.609	kilometer
square mile (mi ²)		259.0	hectare
square mile (mi ²)		2.590	square kilometer

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

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$$

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

Water year (WY): Water year is the 12-month period, October 1 through September 30, and is designated by the calendar year in which it ends. Thus, the water year ending September 30, 1999, is called “WY99.”

SYMBOL DEFINITIONS AND DIMENSIONS

Symbol	Dimensions	Description
K	L/T	Horizontal hydraulic conductivity
K_v	L/T	Vertical hydraulic conductivity
S	dimensionless	Storage coefficient
S_y	dimensionless	Specific yield (unconfined aquifer)
T	L^2/T	Transmissivity
Q	V/T	Discharge rate
A	A	Area
ΔH	L	Hydraulic head potential
ΔL	L	Length over which ΔH applies
ET	L	Evapotranspiration

L = length

T = time

A = area

V = volume

OTHER DEFINITIONS

Aquifer analysis area - Includes the outcrops and aquifer areas of the Madison and Minnelusa hydrogeologic units (fig. 1).

Areal recharge - Infiltration from precipitation falling directly on the outcrop recharge areas.

Basin yield - The rate of streamflow leaving a basin divided by the area of the basin, usually expressed in inches per year.

Unsaturated area - The area of a formation that does not contain a water table because the bottom of the dipping formation is at a higher altitude than the elevation of the water table.

High-flow area - The near-outcrop area that includes Rapid City and extends 2 to 3 mi north of Boxelder Creek where extensive tectonic activity, carbonate and sulfate dissolution, brecciation, ground-water recharge, and ground-water circulation has taken or is taking place.

Paired wells - Two wells in the same location or very close proximity that are each open in a different aquifer.

Streamflow recharge - Recharge from streamflow that loses water to the outcrop recharge areas.

Summer period - April through September (S-88 = summer 1988 = April 1988 to September 1988).

Winter period - October through March (W-88 = winter 1988 = October 1987 to March 1988).

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ABSTRACT

The conceptual model of the Madison and Minnelusa aquifers in the Rapid City area synthesizes the physical geography, hydraulic properties, and ground-water flow components of these important aquifers. The Madison hydrogeologic unit includes the karstic Madison aquifer, which is defined as the upper, more permeable 100 to 200 ft of the Madison Limestone, and the Madison confining unit, which consists of the lower, less permeable part of the Madison Limestone and the Englewood Formation. Overlying the Madison hydrogeologic unit is the Minnelusa hydrogeologic unit, which includes the Minnelusa aquifer in the upper, more permeable 200 to 300 ft and the Minnelusa confining unit in the lower, less permeable part. The Madison and Minnelusa hydrogeologic units outcrop in the study area on the eastern flank of the Black Hills where recharge occurs from streamflow losses and areal recharge. The conceptual model describes streamflow recharge, areal recharge, ground-water flow, storage in aquifers and confining units, unsaturated areas, leakage between aquifers, discharge from artesian springs, and regional outflow.

Effective transmissivities estimated for the Madison aquifer range from 500 to 20,000 ft²/d and for the Minnelusa aquifer from 500 to 10,000 ft²/d. Localized anisotropic transmissivity in the Madison aquifer has tensor ratios as high as 45:1. Vertical hydraulic conductivities for the Min-

nelusa confining unit determined from aquifer tests range from 1.3×10^{-3} to 3.0×10^{-1} ft/d. The confined storage coefficient of the Madison and Minnelusa hydrogeologic units was estimated as 3×10^{-4} ft/d. Specific yield was estimated as 0.09 for the Madison and Minnelusa aquifers and 0.03 for the Madison and Minnelusa confining units. Potentiometric surfaces for the Madison and Minnelusa aquifers have a general easterly gradient of about 70 ft/mi with local variations. Temporal change in hydraulic head in the Madison and Minnelusa aquifers ranged from about 5 to 95 ft in water years 1988-97. The unconfined areas were estimated at about 53 and 36 mi² for the Madison and Minnelusa hydrogeologic units, respectively, in contrast to an aquifer analysis area of 629 mi².

Dye-tracer tests, stable isotopes, and hydrogeologic features were analyzed conjunctively to estimate generalized ground-water flowpaths in the Madison aquifer and their influences on the Minnelusa aquifer. The western Rapid City area between Boxelder Creek and Spring Creek was characterized as having undergone extensive tectonic activity, greater brecciation in the Minnelusa Formation, large transmissivities, generally upward hydraulic gradients from the Madison aquifer to the Minnelusa aquifer, many karst springs, and converging flowpaths.

Water-budget analysis included: (1) a dry-period budget for declining water levels; October 1, 1987, to March 31, 1993; (2) a wet-period budget for rising water levels, April 1,

1993, to September 30, 1997; and (3) a full 10-year period budget for water years 1988-97. By simultaneously balancing these water budgets, initial estimates of recharge, discharge, change in storage, and hydraulic properties were refined. Inflow rates for the 10-year budget included streamflow recharge of about 45 ft³/s or 61 percent of the total budget and areal recharge of 22 ft³/s or 30 percent. Streamflow recharge to the Madison hydrogeologic unit was about 86 percent of the total streamflow recharge. Outflow for the 10-year budget included springflow of 31 ft³/s or 42 percent of the total budget, water use of about 10 ft³/s or 14 percent, and regional outflow of 22 ft³/s or 30 percent. Ground-water storage increased 9 ft³/s during the 10-year period, and net ground-water movement from the Madison to Minnelusa hydrogeologic unit was about 8 ft³/s.

INTRODUCTION

The Madison and Minnelusa aquifers are the main source of ground water in the Black Hills area (Driscoll and Carter, 2001). The city of Rapid City obtains more than one-half of its municipal water supply from these two bedrock aquifers via deep wells and springs. Numerous additional users in the Rapid City area obtain water from the Madison or Minnelusa aquifers for domestic, industrial, and irrigation usage. Ground-water flow within the Madison and Minnelusa aquifers is complex. Extensive fracturing, solution enhancement, and brecciation contribute to heterogeneity, anisotropic transmissivity, and spatially variable ground-water seepage between the two aquifers. A long-term cooperative study between the U.S. Geological Survey and the city of Rapid City has provided hydrogeologic data and interpretation for planning and management of the Madison and Minnelusa aquifers.

Purpose and Scope

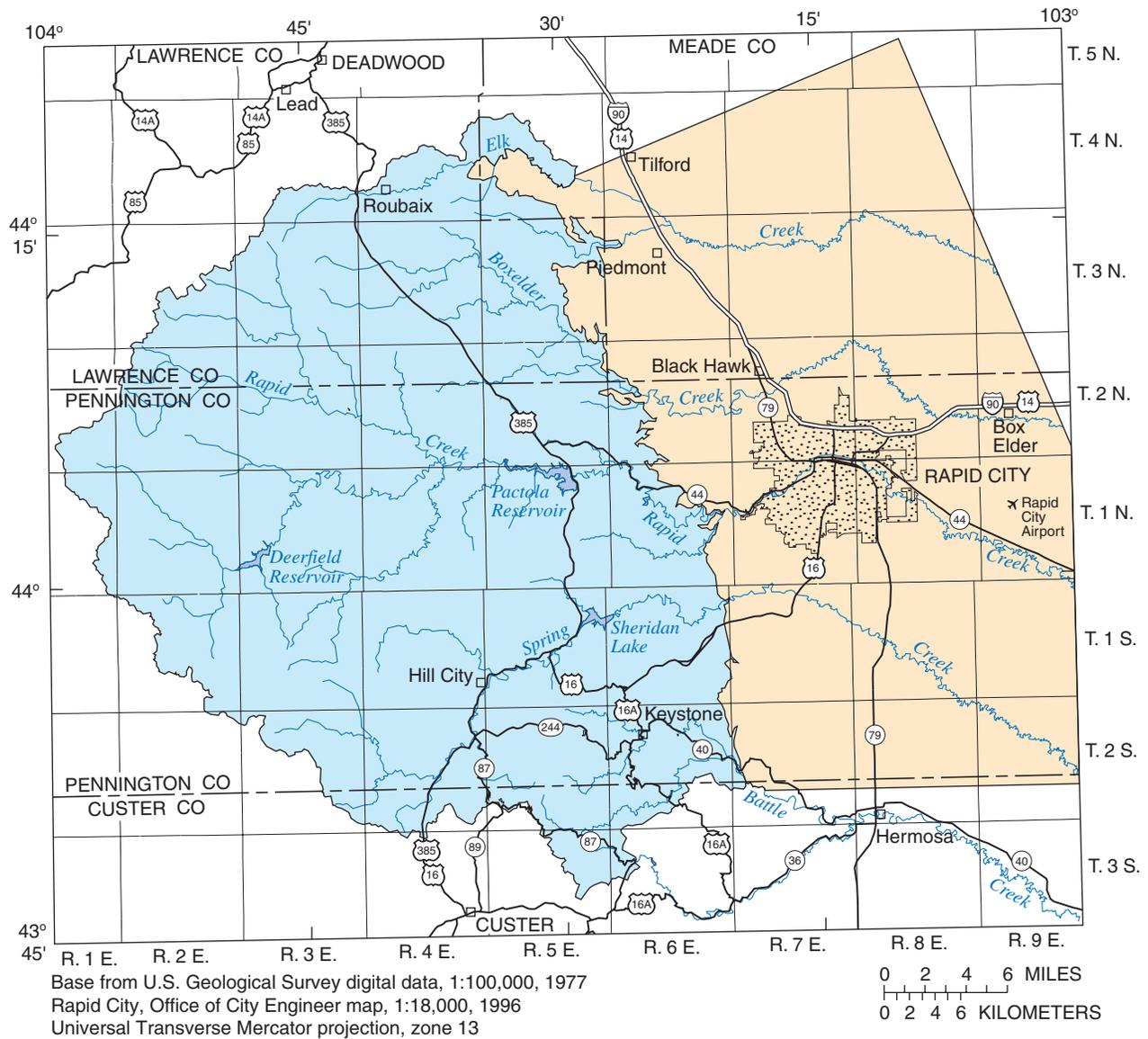
The primary purpose of this report is to present a conceptual model of ground-water flow in the Madison and Minnelusa aquifers in the Rapid City area leading to a better understanding of the unique concepts involved. The conceptual model consists of discussions of hydraulic properties, hydraulic head, and ground-

water flow. A detailed water-budget analysis encompassing WY88-97 characterizes and quantifies recharge and discharge for the study area and is used to refine estimates of hydraulic properties. An additional purpose of the conceptual model was to compile data for numerical modeling and other research efforts in the future.

Description of Study Area

The study area, which includes Rapid City and the surrounding area, extends north of Elk Creek, to the south near Battle Creek, east of the city of Boxelder, and west into the central Black Hills (fig. 1). Streams flowing from the central Black Hills contribute to streamflow losses that recharge the Madison and Minnelusa aquifers. The western extent of the study area comprises these stream basins, which include Elk, Boxelder, Rapid, Spring, and Battle Creeks. This western area is included in the study area for analysis of streamflow recharge and evapotranspiration. The eastern part of the study area, where the Madison and Minnelusa hydrogeologic units exist, is referred to as the aquifer analysis area (figs. 1 and 2). These hydrogeologic units are described in subsequent sections of the report.

Land-surface altitudes range from more than 7,000 ft in the western highlands of the study area to about 3,000 ft in the eastern lowlands. The western extent of the study area is characterized by high relief with predominantly pine and spruce forests. The eastern lowlands comprise approximately the eastern one-half of the aquifer analysis area and are characterized by rolling prairies with bottom lands along stream channels. The outcrops of the Madison and Minnelusa hydrogeologic units are located in the western part of the aquifer analysis area (fig. 2) along the eastern flank of the Black Hills uplift. These outcrops are characterized by high-relief forested areas cut by deep canyons with entrenched meanders and steep cliffs formed by resistant limestone and sandstone. Average precipitation rates range from about 27 in/yr in the northwest to 17 in/yr in the eastern lowlands with most precipitation occurring in March, April, May, and June (Driscoll, Hamade, and Kenner, 2000). Summer temperatures in the western highlands generally are cooler and have less variation during the winter (table 1). As of 1999, about 88,000 people lived in the Rapid City metropolitan area (U.S. Census Bureau, 2000), whereas population is much sparser in other parts of the study area.



- EXPLANATION**
- DRAINAGE AREAS USED IN CALCULATION OF STREAMFLOW LOSSES
 - AQUIFER ANALYSIS AREA

Figure 1. Location of study area.

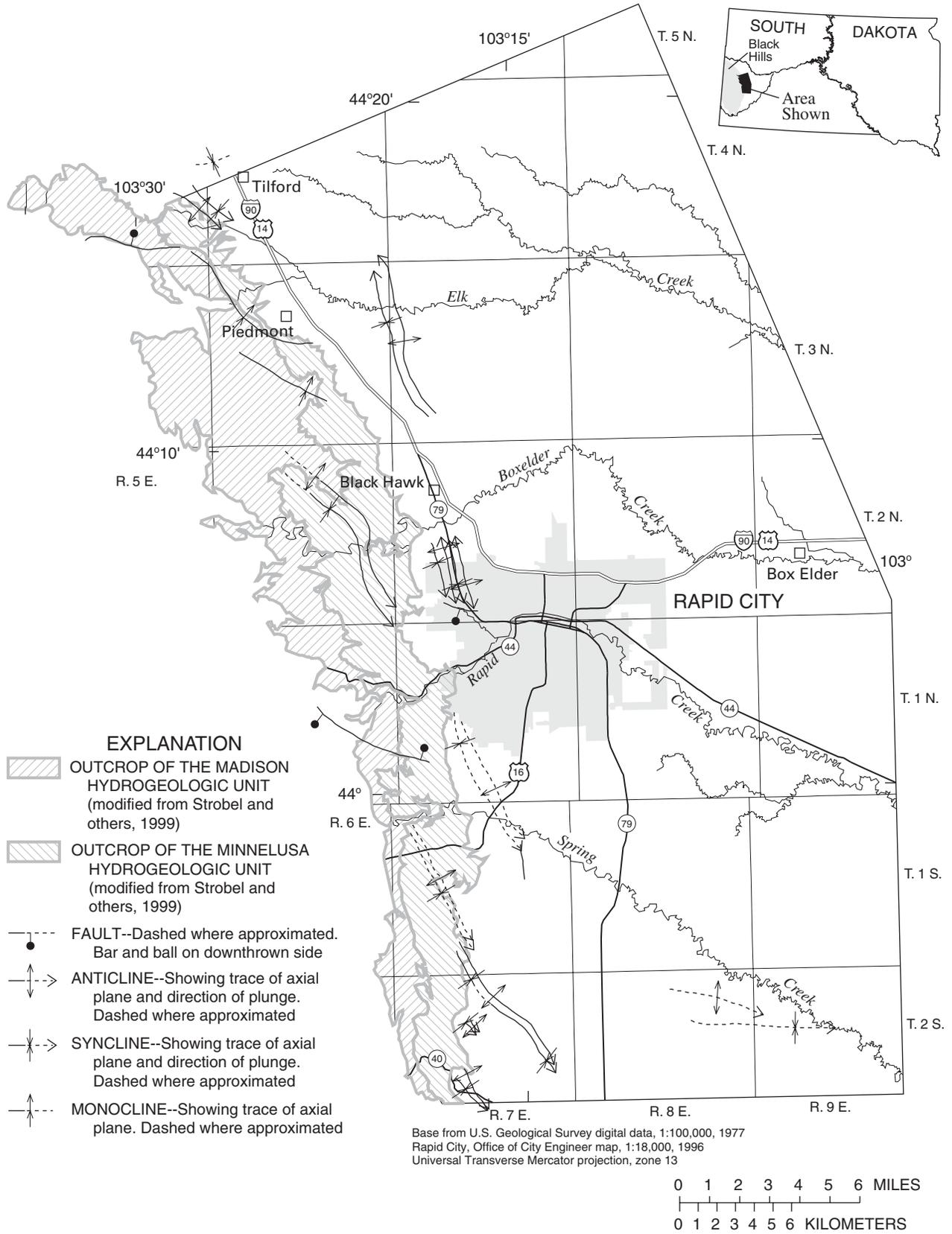


Figure 2. Detail of aquifer analysis area shown in figure 1.

Table 1. Long-term average temperatures in the study area for months of January and July

[Data averaged from 1961 to 1990 (National Oceanic and Atmospheric Administration, 1996)]

	January	July
	(degrees Fahrenheit)	
Pactola Dam ¹ (western highlands)	21.2	64.4
Rapid City Airport ¹ (eastern lowlands)	22.1	72.2
Difference	.9	7.8

¹Shown in figure 1.

Previous Investigations

Greene (1993) analyzed aquifer tests and geophysical well logs to determine aquifer properties for the Madison and Minnelusa aquifers in the Rapid City area. Greene and Rahn (1995) presented evidence based on cave-passageway orientations, dye tests, aquifer tests, and well-bore geophysics that the directional orientation of anisotropic transmissivity is localized. Long and Derickson (1999) analyzed hydraulic response to recharge in the Madison aquifer using a linear-systems approach. Long (2000) modeled flow in the Madison aquifer in the Rapid City area by incorporating localized anisotropy. Carter, Driscoll, Hamade, and Jarrell (2001) presented a water budget for the Madison and Minnelusa aquifers for the Black Hills area.

The Madison aquifer has been characterized as both a dual-porosity aquifer (Greene and others, 1998) and a leaky aquifer (Greene, 1993). In the northern Black Hills, Greene and others (1998) adapted a method similar to the Theis (1935) method to determine aquifer properties for dual porosity from an aquifer test. In the eastern Black Hills, Greene (1993) used the method of Neuman and Witherspoon (1969a, 1969b) to determine aquifer properties from an aquifer test for a leaky, two-aquifer system. Long (2000) used numerical modeling to show that dual porosity and leakage might be simultaneously affecting the hydraulics. Rahn (1992) characterized the permeability of the Madison aquifer and summarized published data related to the Madison aquifer in the Black Hills area.

Studies of Madison and Minnelusa springs include Rahn and Gries (1973), Klemp (1995), Wenker (1997), and Anderson and others (1999). Dye-tracer tests in the Madison aquifer include Rahn (1971), Rahn

and Gries (1973), and Greene (1999). Studies of Madison Limestone cave development in the Black Hills include Howard (1964) and Ford (1989). Geochemical studies on the Madison and Minnelusa aquifers include Busby and others (1991, 1995) and Naus and others (2001). Regional studies include Downey (1984, 1986), Cooley and others (1986), Downey and Dinwiddie (1988), Kyllonen and Peter (1987), and Plummer and others (1990).

Acknowledgments

The authors thank the city of Rapid City for providing extensive assistance with data collection associated with this study. The Water Rights Program of the South Dakota Department of the Environment and Natural Resources (DENR) provided monitoring wells and assisted in the collection and compilation of water-level data. The South Dakota DENR also provided water-use data. Other assistance with data collection was provided by Chapel Lane Water Company, Carriage Hills Water User's Association, Hart Ranch, and Black Hills Power and Light Company.

HYDROGEOLOGIC SETTING

Uplift at the end of the Cretaceous period followed by erosion has created the dome-like structure and geomorphology of the Black Hills. Metamorphic and igneous rocks of Precambrian age are exposed in the Black Hills' central core, whereas stratigraphic layers of Paleozoic age and younger are exposed on its flanks. The outcrops of Paleozoic units form concentric rings surrounding the Precambrian core and dip radially outward.

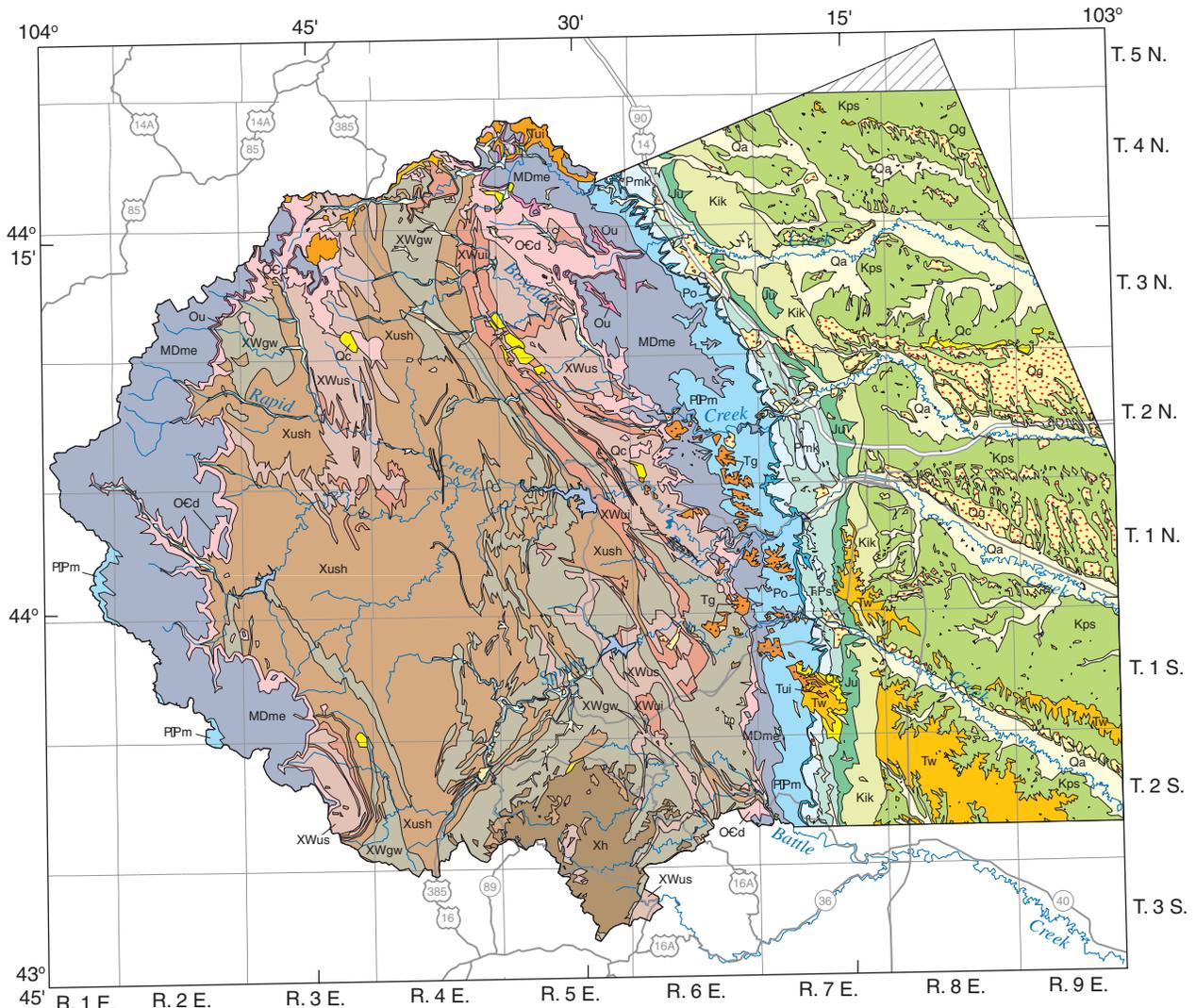
The Madison and Minnelusa aquifers are contained within the Madison and Minnelusa hydrogeologic units, which are exposed in the western part of the aquifer analysis area (fig. 2). These units coincide with stratigraphic units shown in figures 3 and 4 by the symbols MDme and PIPm. In the aquifer analysis area, stratigraphic units dip in an easterly direction away from the Precambrian core (fig. 5). Water-table conditions generally exist in outcrop areas; however, the updip parts of the outcrops (western extent) may not have a water table because of their higher altitudes. East of the water-table areas, hydraulic head is above the tops of the units due to their easterly dip causing artesian (confined) conditions to exist (fig. 5).

ERATHEM	SYSTEM	ABBREVIATION FOR STRATIGRAPHIC INTERVAL	STRATIGRAPHIC UNIT	THICKNESS IN FEET	DESCRIPTION		
CENOZOIC	QUATERNARY & TERTIARY (?)	QTu	UNDIFFERENTIATED SANDS AND GRAVELS	0-50	Sand, gravel, and boulders		
	TERTIARY	Tw	WHITE RIVER GROUP	0-600	Light colored clays with sandstone channel fillings and local limestone lenses. Includes flyville, latte, trachyte, and phondite.		
		Tui	INTRUSIVE IGNEOUS ROCKS	--	Principal horizon of limestone lenses giving teepee buttes.		
MESOZOIC	CRETACEOUS	Kps	PIERRE SHALE	1,200-2,000	Dark-gray shale containing scattered concretions. Widely scattered limestone masses, giving small teepee buttes. Black fissile shale with concretions.		
			NOBARRA FORMATION	100-225	Impure chalk and calcareous shale.		
			CARLILE FORMATION	400-750	Light-gray shale with numerous large concretions and sandy layers. Dark-gray shale.		
			GREENHORN FORMATION	25-380	Impure slabby limestone. Weathers buff. Dark-gray calcareous shale, with thin Orman Lake limestone at base.		
				300-550	Gray shale with scattered limestone concretions. Clay spur bentonite at base.		
			BELLE FOURCHE SHALE	150-250	Light-gray siliceous shale. Fish scales and thin layers of bentonite.		
				20-60	Brown to light-yellow and white sandstone.		
				170-270	Dark-gray to black siliceous shale.		
				10-200	Massive to slabby sandstone.		
			LAKOTA FORMATION	35-700	Coarse gray to buff cross-bedded conglomeratic sandstone. Interbedded with buff, red, and gray clay, especially toward top. Local fine-grained limestone.		
				0-220	Green to maroon shale. Thin sandstone.		
			JURASSIC	Ju	MORRISON FORMATION	0-225	Massive fine-grained sandstone.
					UNKPAPA SS	250-450	Greenish-gray shale, thin limestone lenses.
					SUNDANCE FORMATION		Glauconitic sandstone; red sandstone near middle.
GYPSUM SPRING FORMATION	0-45	Red siltstone, gypsum, and limestone.					
SPEARFISH FORMATION	250-700	Red sandy shale, soft red sandstone and siltstone with gypsum and thin limestone layers. Gypsum locally near the base.					
TRIASSIC	TRFs	MINNEKAHTA LIMESTONE	125-65	Thin to medium-bedded finely-crystalline, purplish-gray laminated limestone.			
		OPECHE SHALE	50-135	Red shale and sandstone.			
PERMIAN	Pm	MINNELUSA FORMATION	1,2-375-800	Yellow to red cross-bedded sandstone, limestone, and anhydrite locally at top. Interbedded sandstone, limestone, dolomite, shale, and anhydrite.			
			Red shale with interbedded limestone and sandstone at base.				
PALEOZOIC	PENNSYLVANIAN	MDme	MADISON (PAHASAPA) LIMESTONE	2250-550	Massive light-colored limestone. Dolomite in part. Cavemous in upper part.		
			ENGLEWOOD FORMATION	30-60	Pink to buff limestone. Shale locally at base.		
			WHITEWOOD (RED RIVER) FORMATION	0-60	Buff dolomite and limestone.		
			WINNIPEG FORMATION	0-100	Green shale with siltstone.		
			DEADWOOD FORMATION	275-400	Massive to thin-bedded buff to purple sandstone. Greenish glauconitic shale, laggy dolomite, and flatpebble limestone conglomerate. Sandstone, with conglomerate locally at the base.		
MISSISSIPPIAN	Ou	DEADWOOD FORMATION		Schist, slate, quartzite, and arkosic grit. Intruded by diorite, metamorphosed to amphibolite, and by granite and pegmatite.			
			UNDIFFERENTIATED METAMORPHIC AND IGNEOUS ROCKS				
CAMBRIAN	OCd	DEADWOOD FORMATION					
			UNDIFFERENTIATED METAMORPHIC AND IGNEOUS ROCKS				
PRECAMBRIAN	pCu	UNDIFFERENTIATED METAMORPHIC AND IGNEOUS ROCKS					

Modified from information furnished by the Department of Geology and Geological Engineering, South Dakota School of Mines and Technology (written commun., January 1994)

1 Modified based on drill-hole data.
 2 Thickness based on structure contours of Minnelusa Formation, Madison Limestone, and Deadwood Formation tops (Carter and Redden, 1999a, 1999b, 1999c).
 3 Based on Carter and others, 2001.

Figure 3. Stratigraphic section for the study area.



Base from U.S. Geological Survey digital data, 1:100,000, 1977
 Rapid City, Office of City Engineer map, 1:18,000, 1996
 Universal Transverse Mercator projection, zone 13

Geology from Strobel and others, 1999



EXPLANATION

QUATERNARY UNITS		PALEOZOIC UNITS	
Qa	Alluvium	Pmk	Minnekahta Limestone
Qc	Colluvium	Po	Opeche Shale
Qg	Gravel deposits	PPm	Minnelusa Formation
TERTIARY UNITS		MDme	Madison (Pahasapa) Limestone and Englewood Formation
Tg	Gravel deposits	Ou	Whitewood Formation and Winnipeg Formation
Tw	White River Group	OEd	Deadwood Formation
Tui	Undifferentiated shallow intrusive igneous rocks	PRECAMBRIAN UNITS	
MESOZOIC UNITS		Xh	Harney Peak Granite
Kps	Pierre Shale to Skull Creek Shale, undifferentiated	Xush	Undifferentiated metamorphosed phyllite and schist
Kik	Inyan Kara Group	XWui	Undifferentiated igneous rocks
Ju	Morrison Formation to Sundance Formation, undifferentiated	XWgw	Metamorphosed graywacke
TPs	Spearfish Formation (Triassic and Permian)	XWus	Undifferentiated metamorphosed sedimentary deposits
		Hatched	AREA NOT COVERED BY STROBEL AND OTHERS, 1999

Figure 4. Geologic map of study area.

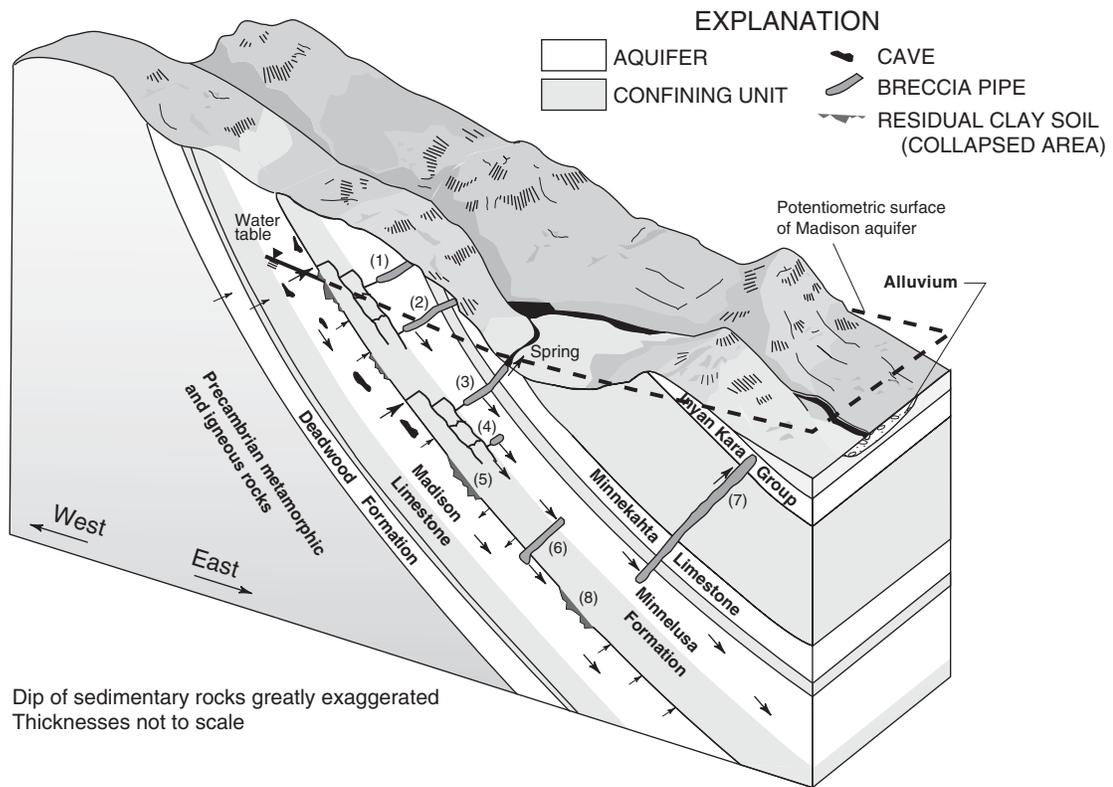


Figure 5. Schematic showing conceptual hydrogeologic section of the study area (modified from Hayes, 1999). Each aquifer shown is separated from other aquifers by confining units. Hydraulic connection between aquifers is increased by vertical breccia pipes and fractures. The schematic shows: (1) exposed breccia pipe above hydraulic head in Madison aquifer; (2) exposed breccia pipe with hydraulic head below land surface; (3) breccia pipe at active spring-discharge point; (4) developing breccia pipe; (5) fractures in confining unit; (6) breccia pipe originating in the Madison Limestone; (7) breccia pipe extending from Minnelusa Formation to the Inyan Kara Group; and (8) discontinuous residual clay soil. Arrows show general areal leakage, focused leakage at breccia pipes, or ground-water flow directions.

Figure 5 also illustrates potential ground-water flow-paths and features that influence flow in the Madison and Minnelusa aquifers. Breccia pipes, which have the potential to enhance hydraulic connection between aquifers, are discussed in greater detail in the “Vertical Hydraulic Conductivity” section. Hydrogeologic units that may hydraulically affect the Madison and Minnelusa aquifers are composed of rocks of Precambrian age through Early Cretaceous age (Inyan Kara Group) and also Quaternary surficial deposits, which include alluvial aquifers (saturated sand and gravel along streams).

Madison Hydrogeologic Unit

The Mississippian-age Madison Limestone is composed of limestone and dolomite. In the study area to the east of its outcrop, the formation is 250 to 550 ft thick (fig. 3). The Madison hydrogeologic unit is defined in this report as the Madison aquifer and underlying confining unit, which includes the lower Madison Limestone and Englewood Formation. The Madison aquifer is defined as the upper 100 to 200 ft of the Madison hydrogeologic unit where secondary permeability generally is high because of solution openings

and fractures (Greene, 1993). The upper surface of the formation is a weathered karst surface, unconformable with the overlying Minnelusa Formation (Cattermole, 1969). The aquifer is considered karstic because of the extensive solution enlargement of fractures that have resulted in a predominance of conduit flow.

Secondary permeability in the lower part of the Madison Limestone (Madison confining unit) generally is much smaller than in the upper part (Greene, 1993); however, the confining unit can have greater permeability near outcrop areas, especially along stream channels. The Englewood Formation, which underlies the Madison Limestone and is less than 60 ft thick, is considered part of the confining unit. The Englewood Formation is composed of argillaceous, dolomitic limestone and probably could logically be considered a member of the Madison Limestone because of its lithology (Gries and Martin, 1985). Strobel and others (1999) combined the Madison Limestone and Englewood Formation as a single hydrogeologic unit. For simplicity, the outcrop of the Madison hydrogeologic unit is referred to as the Madison outcrop in this report.

Wells completed in the Madison aquifer in the study area are capable of producing 5 to 2,500 gal/min. About 64 percent of the wells yield 5 to 50 gal/min, 11 percent yield 50 to 200 gal/min, and 25 percent yield 200 to 2,500 gal/min. The depth of wells ranges from 20 to 4,600 ft with 78 percent of the wells less than 1,000 ft and 41 percent less than 500 ft.

Minnelusa Hydrogeologic Unit

In the study area to the east of its outcrop, the Pennsylvanian- and Permian-age Minnelusa Formation is 375 to 800 ft thick (fig. 3). Bowles and Braddock (1963) describe the upper part as thick sandstone with thin limestone, dolomite, and mudstone, and the lower part as having less sandstone and more shale, limestone, and dolomite. Siltstone, gypsum, and anhydrite also can be present. At the base of the Minnelusa Formation is a red clay shale that varies between 0 and 50 ft thick (Cattermole, 1969; Greene, 1993). This shale, which is discontinuous in the aquifer analysis area, is an ancient residual soil developed on the surface of the Madison Limestone (Gries, 1996).

The Minnelusa hydrogeologic unit is defined in this report as the Minnelusa aquifer and underlying confining unit. The Minnelusa aquifer is defined as the upper, more permeable 200 to 300 ft of the Minnelusa Formation because of the coarser sandstone, solution openings, breccias, and other collapse features (Peter and others, 1988; Greene, 1993). The aquifer is confined by the overlying Opeche Shale. The lower part of the formation, which is less permeable and generally impedes flow between the Minnelusa and Madison aquifers (Kyllonen and Peter, 1987; Peter and others, 1988; Greene, 1993) is defined as the Minnelusa confining unit. Near outcrop areas, however, the lower part can have greater permeability due to weathering. For simplicity, the outcrop of the Minnelusa hydrogeologic unit is referred to as the Minnelusa outcrop in this report.

Wells completed in the Minnelusa aquifer in the study area are capable of producing 5 to 700 gal/min. About 66 percent yield from 5 to 50 gal/min, 28 percent yield 50 to 200 gal/min, and 6 percent yield 200 to 700 gal/min. The depth of wells ranges from 80 to 3,000 ft with 90 percent of the wells less than 1,000 ft and 60 percent less than 500 ft.

CONCEPTS OF THE GROUND-WATER-FLOW SYSTEM

Pertinent concepts of the ground-water-flow system include general concepts such as basic hydraulics, recharge, spring discharge, and aquifer interaction. Hydraulic properties described in this section, such as transmissivity, anisotropy, vertical hydraulic conductivity, and storage properties, influence hydraulic head and ground-water flow. Estimated potentiometric surfaces give valuable insight into the spatial distribution of these hydraulic properties. Long-term observation wells provide essential data for the analysis of hydraulic response to stress. The areal extent and location of unconfined areas is important because of the large changes in ground-water storage occurring there. All of the items mentioned above influence ground-water flowpaths, which can be analyzed using natural and artificial tracers.

General Concepts

Figure 6 conceptually illustrates an artesian aquifer with hydrogeology similar to that of the Madison and Minnelusa aquifers. Infiltrating precipitation or streamflow losses may have an easterly flow component rather than a strictly vertical one because of the greater hydraulic conductivity parallel to bedding planes dipping easterly. The hydraulic head at the recharge area fluctuates with the changing recharge rate and causes a pressure wave to propagate through the confined part of the aquifer. This wave decreases in amplitude with distance traveled because of head losses in the aquifer. For this reason, hydraulic head fluctuations in downgradient locations east of the recharge area are less than at the recharge area unless other stresses such as pumping are introduced.

In a setting such as that shown in figure 6, the unconfined area occurs on the downdip side of the outcrop area. The western updip part of the outcrop not containing a water table is defined as the “unsaturated area” in this report. The unsaturated area may contain infiltrating or perched water, but should not be confused with the space directly above the water table often called the “vadose zone” or “unsaturated zone.”

Movement of ground water between the Madison and Minnelusa aquifers is influenced by vertical hydraulic gradients, hydraulic properties of the intervening confining unit, and recharge rates (fig. 7). Recharge water may be stored under perched conditions before percolating downward to the regional water table. Pools of perched water can be found in Madison Limestone caves, and water perched on discontinuous layers of low permeability material may exist in the Minnelusa Formation.

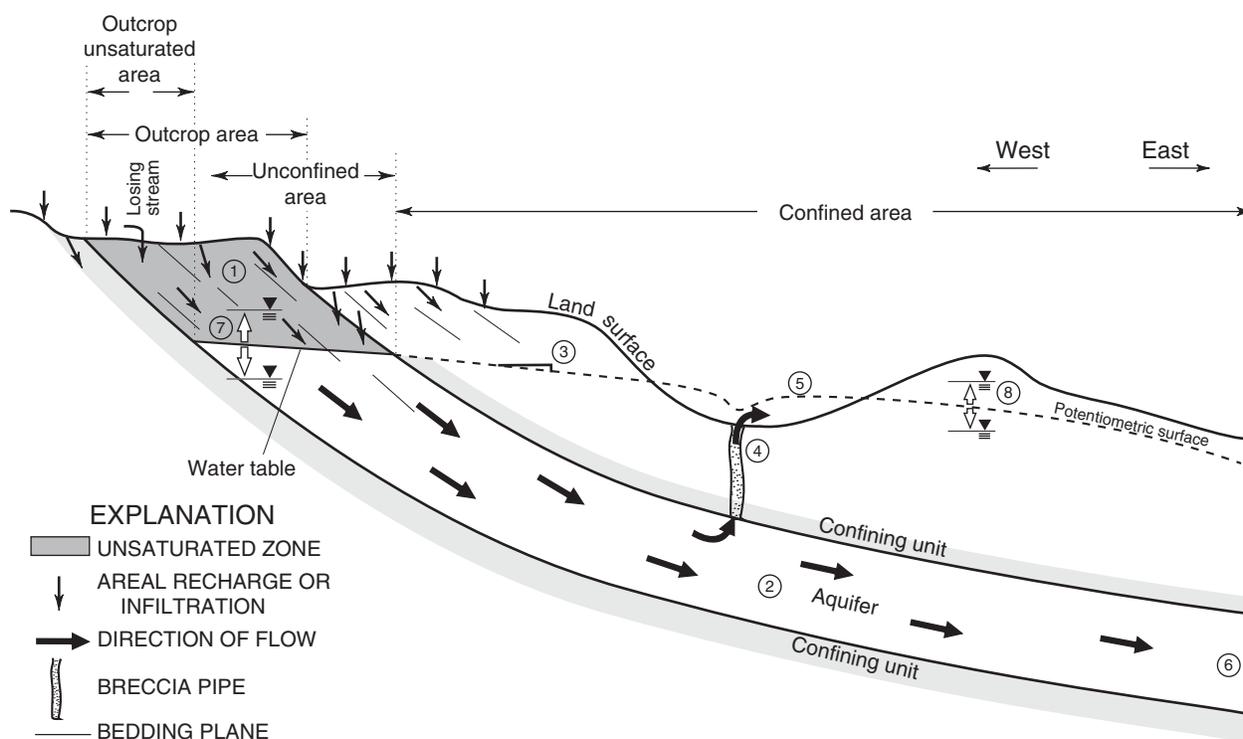


Figure 6. Generalized diagram with vertical exaggeration of an artesian aquifer recharged at the updip end. The diagram shows: (1) recharge infiltrates and moves downward vertically or diagonally parallel to bedding planes; (2) near horizontal flow with head losses resulting from resistance from aquifer material; (3) sloping potentiometric surface results from head losses; (4) artesian spring discharges through high-conductivity breccia pipe or fracture because hydraulic head is above the land surface; (5) spring causes depression in the potentiometric surface; (6) outflow rate is controlled by hydraulic gradient and transmissivity; (7) hydraulic head fluctuation at recharge area is controlled by changes in recharge rate; and (8) smaller hydraulic head fluctuation downgradient is in response to larger fluctuation at recharge area.

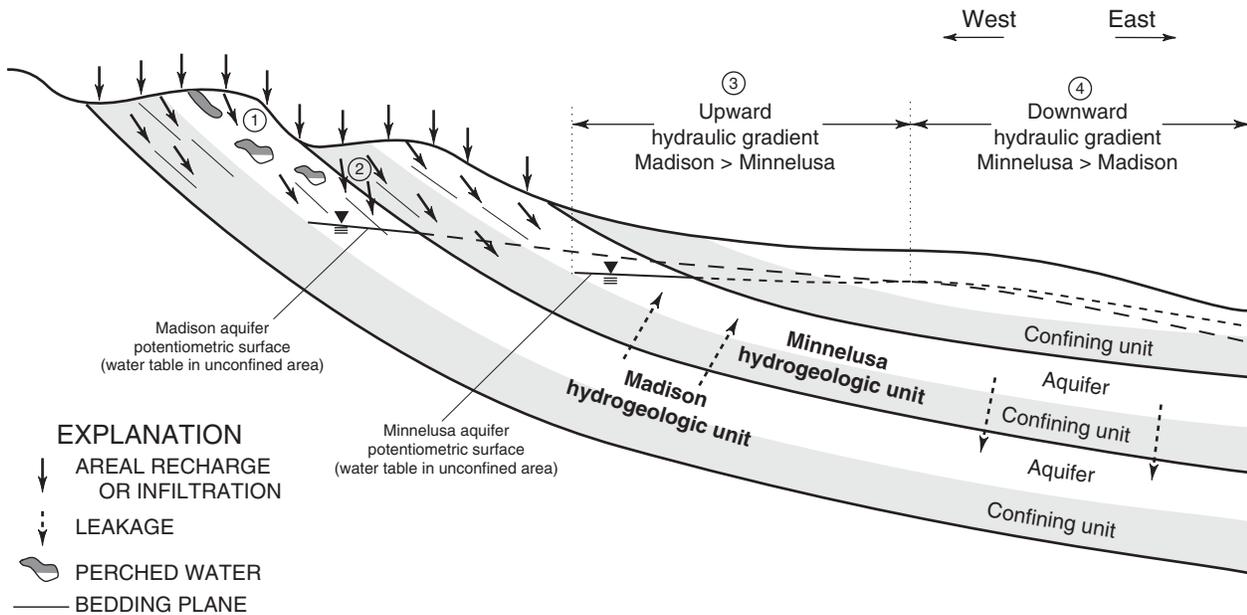


Figure 7. Recharge conditions and vertical gradients in the Madison and Minnelusa hydrogeologic units. The diagram shows: (1) perched water; (2) part of the recharge on the Minnelusa outcrop infiltrates to the Madison aquifer; (3) hydraulic head in Madison aquifer greater than in Minnelusa aquifer creating upward hydraulic gradient; and (4) hydraulic head greater in Minnelusa aquifer than in Madison aquifer creating downward hydraulic gradient.

Although the confining units generally do not transmit water at a high rate, their capacity to store water could have significant effects on the hydraulics of the ground-water-flow system. Water that leaks between the Madison and Minnelusa aquifers must pass through a confining unit as much as 500 ft thick that is composed of material of variable porosity where a substantial amount of water can be held in storage. The confining units also can affect solute transport and hydraulic response to recharge because ground water can move into and out of these layers in response to changes in hydraulic head.

Discharge from artesian springs is an important consideration in the analysis of the Madison and Minnelusa aquifers. There can be difficulty determining whether an artesian spring originates in the Madison aquifer, the Minnelusa aquifer, or both. An example of the hydraulics of ground-water flow from a

hypothetical artesian spring includes a vertical conduit of high permeability, such as a breccia pipe, beginning in the Madison aquifer and ending in an alluvial aquifer (fig. 8). In this example, hydraulic head in the Madison aquifer is higher than in the Minnelusa aquifer, and the permeability of the Madison aquifer, breccia pipe, and alluvium is greater than the Minnelusa aquifer. Based on these assumptions, ground water would flow from the Madison aquifer up through the breccia pipe, discharging partly into the Minnelusa aquifer and partly into the alluvium where it may emerge as seepage to the stream. This discharge would create a depression in the Madison aquifer potentiometric surface. Minnelusa aquifer water also may flow into the alluvium, mixing with Madison aquifer water, thus ultimately discharging as a mixture of the two waters.

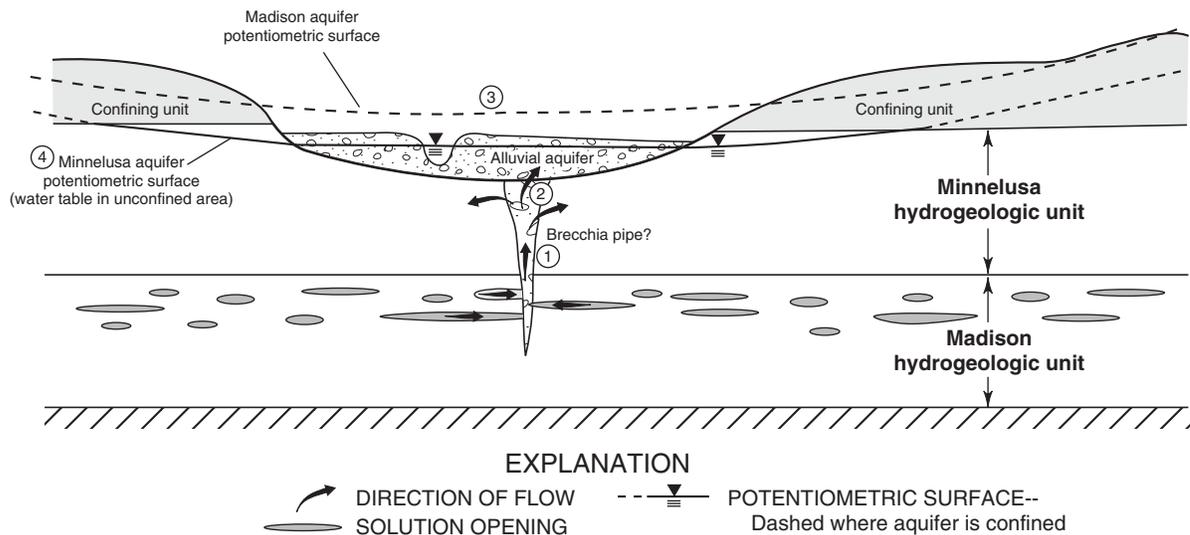


Figure 8. Generalized diagram of an artesian spring. The diagram shows: (1) the Madison aquifer hydraulic head is higher than that of the Minnelusa aquifer causing an upward hydraulic gradient inducing flow through a natural pipe; (2) the spring discharges into the alluvial aquifer; (3) spring discharge causes a depression in the Madison aquifer potentiometric surface surrounding the spring; and (4) Minnelusa aquifer hydraulic head is influenced by the stream and water table in the alluvial aquifer.

Hydraulic Properties

Hydraulic properties, including transmissivity, anisotropic transmissivity, vertical hydraulic conductivity, storage coefficient, and specific yield, were estimated based on (1) previously published work, (2) a water-budget analysis presented later in this report, and (3) an aquifer test at well RC-9 (appendix A). In areas where little or no data were available, aquifer properties were estimated based on a combination of factors. Well locations and average potentiometric surfaces included in this discussion are shown on plates 1 and 2 and are discussed in more detail in the “Hydraulic Head and Ground-Water Flow” section. Preliminary investigations (Long, 2000) also were helpful in estimating aquifer properties, and water-budget analysis served to refine estimates because these properties needed to be adjusted to achieve a balance between inflow and outflow.

Transmissivity

An aquifer test in the Madison aquifer at well RC-9 is described in appendix A, and results are summarized in table 2 along with the results of two previously published aquifer tests in the aquifer analysis area. Locations of pumped wells and observation wells are shown in figures 9 and 10, which also show the estimated transmissivity (T) distributions for the Madison and Minnelusa aquifers. These distributions are generally in agreement with table 2; however, anisotropy and heterogeneity could account for variations. For example, an aquifer test measures the directional T between a pumped well and observation well. A general or “effective” T can be estimated based on multiple observation wells in an aquifer test (see “Anisotropic Transmissivity” section). Estimates of this effective T (figs. 9 and 10) are based on aquifer tests, well yields, potentiometric surfaces, water budgets, and other hydrogeologic information. Table 3

lists aquifer properties reported for the Madison and Minnelusa aquifers in the general region but not necessarily within the study area. Additional data compiled for the Black Hills area by Rahn (1992) show a similar range in Madison aquifer transmissivity.

Well production rates in comparison to draw-down and potentiometric surfaces are also indicative of relative T values. The production rates and drawdowns shown in table 4 are in general agreement with the effective T distributions shown in figures 9 and 10. The low production rate and large drawdown in well RC-7 (fig. 9) indicate that T decreases to the east of Rapid City. In addition, a water sample from well RC-7 in 1991 (Feb. 7, 1991) had a specific conductance of 3,490 microsiemens per centimeter at 25 degrees Celsius indicating a high concentration of dissolved solids in contrast to water from many other Madison aquifer wells. The high specific conductance is interpreted to be a result of limited ground-water flow in that area. Inferences in some local areas can be made from the potentiometric surfaces (pls. 1 and 2) by assuming that T is generally larger in areas where the hydraulic gradient is small. Potentiometric surfaces for

both aquifers have low gradients in the west-central part of the aquifer analysis area. Although this is only a general indication of T because recharge rates affect hydraulic gradients, aquifer tests also indicate high T values in that area.

A zone of relatively large T for the Madison aquifer in the eastern part of the area (fig. 9) is based in part on a trough in the potentiometric surface at that location. This type of potentiometric feature would most likely be related to highly transmissive rocks. The production rate of 350 gal/min and relatively low dissolved solids concentration (Vince Finkhouse, City of Boxelder Public Works, oral commun., 2001) from a Madison aquifer production well in the city of Boxelder (pl. 2, site 30) is consistent with large T within this zone. In addition, a regional analysis of the Madison aquifer by Downey (1986, p. E54) shows a similar spatial T distribution. The lower T values in the northeast and southeast parts of the area for the Madison aquifer were estimated by balancing the water budget (see “Water Budget” section) and are consistent with those estimated by Downey (1986, p. E54).

Table 2. Hydraulic properties reported for the Madison and Minnelusa hydrogeologic units determined from aquifer tests in the aquifer analysis area

[T , transmissivity; K_v , vertical hydraulic conductivity; S , storage coefficient; ft, feet; ft^2/d , feet squared per day; ft/d , feet per day; NA, not applicable; --, no data available]

Pumped well and date of test	Layer	Observation well and site number (pls. 1 and 2)	Distance from pumped well (ft)	T (ft^2/d)	K_v of the Minnelusa confining unit (ft/d)	S (dimensionless)	Source
RC-5 ¹ Spring 1990 (site 79)	Madison aquifer	LC (43)	685	1,600	6.8×10^{-3}	1.0×10^{-4}	Greene (1993)
		SP-2 (46)	1,700	2,600	1.6×10^{-2}	1.0×10^{-4}	
		BHPL (36)	3,950	5,200	1.1×10^{-2}	1.0×10^{-4}	
		CL-2 (50)	8,900	40,000	9.1×10^{-3}	3.0×10^{-4}	
		CHLN-2 (56)	11,700	40,000	5.3×10^{-3}	3.0×10^{-4}	
RC-6 Spring 1990 (site 35)	Minnelusa aquifer	CQ-1 (200)	2,930	12,000	NA	3.0×10^{-3}	Greene (1993)
	Minnelusa confining unit	CQ-1 (200)	2,930	--	3.0×10^{-1}	2×10^{-7}	
		CQ-2 (33)	2,919				
	Madison aquifer	CQ-2 (33)	2,919	17,000	NA	2×10^{-3}	
RC-9 Fall 1995 (site 49)	Madison aquifer	CL-2 (50)	6,290	14,700	1.7	2.1×10^{-5}	Appendix A
		RC-11 (62)	8,603	11,500	2.7	2.7×10^{-4}	
		CHLN-2 (56)	7,562	14,100	0.9	1.4×10^{-5}	
		SP-2 (46)	4,564	13,900	0.3	6.8×10^{-5}	

¹Anisotropic transmissivity of $56,000 \text{ ft}^2/\text{d}$ was determined with the major axis at an angle of 42 degrees east of north. The minor axis of transmissivity was $1,300 \text{ ft}^2/\text{d}$ at an angle of 48 degrees west of north.

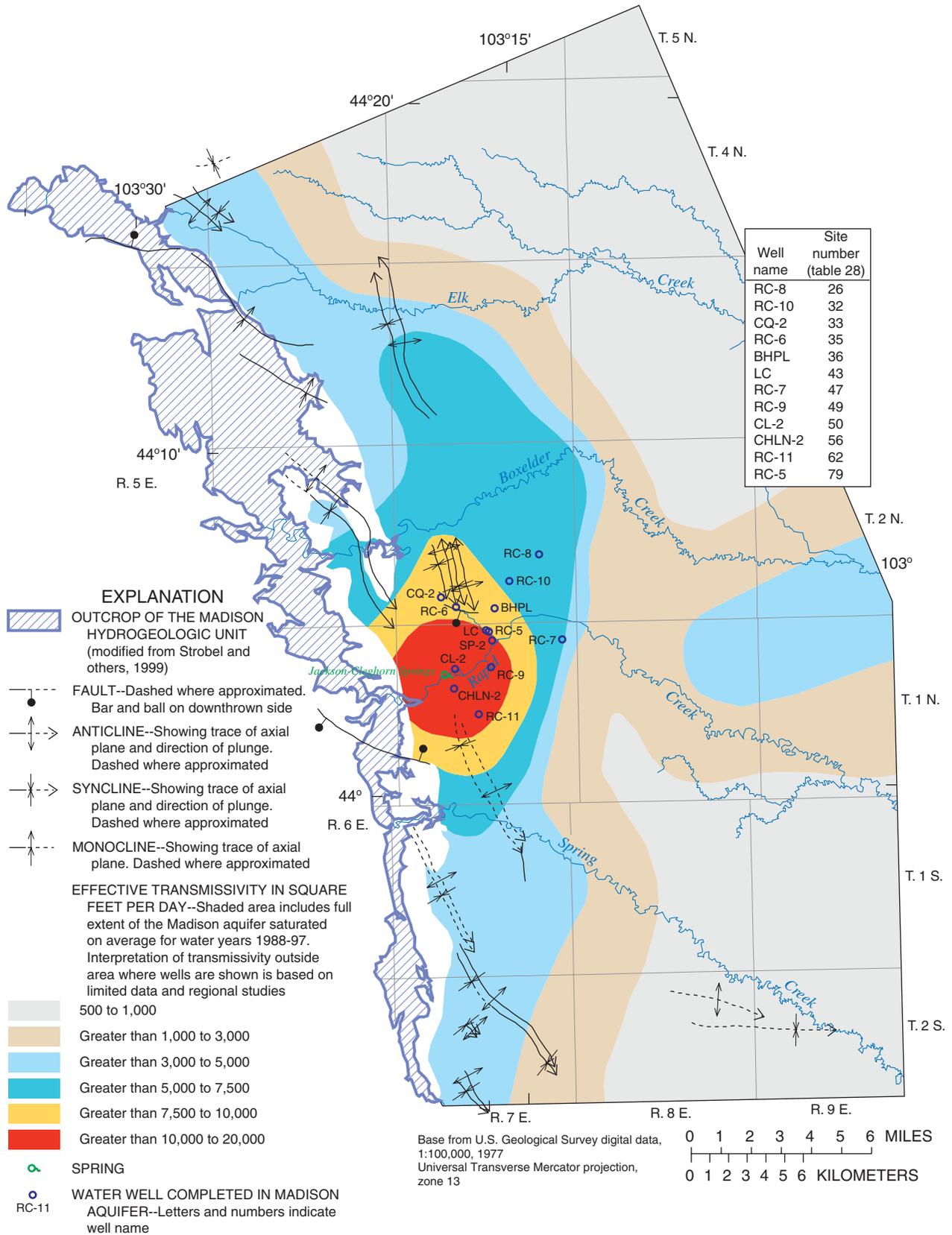


Figure 9. Effective transmissivity distribution estimates for the Madison aquifer. Transmissivity estimates are provided for areas where the Madison aquifer exists as shown on plate 1 and do not extend into areas where only the Madison confining unit exists.

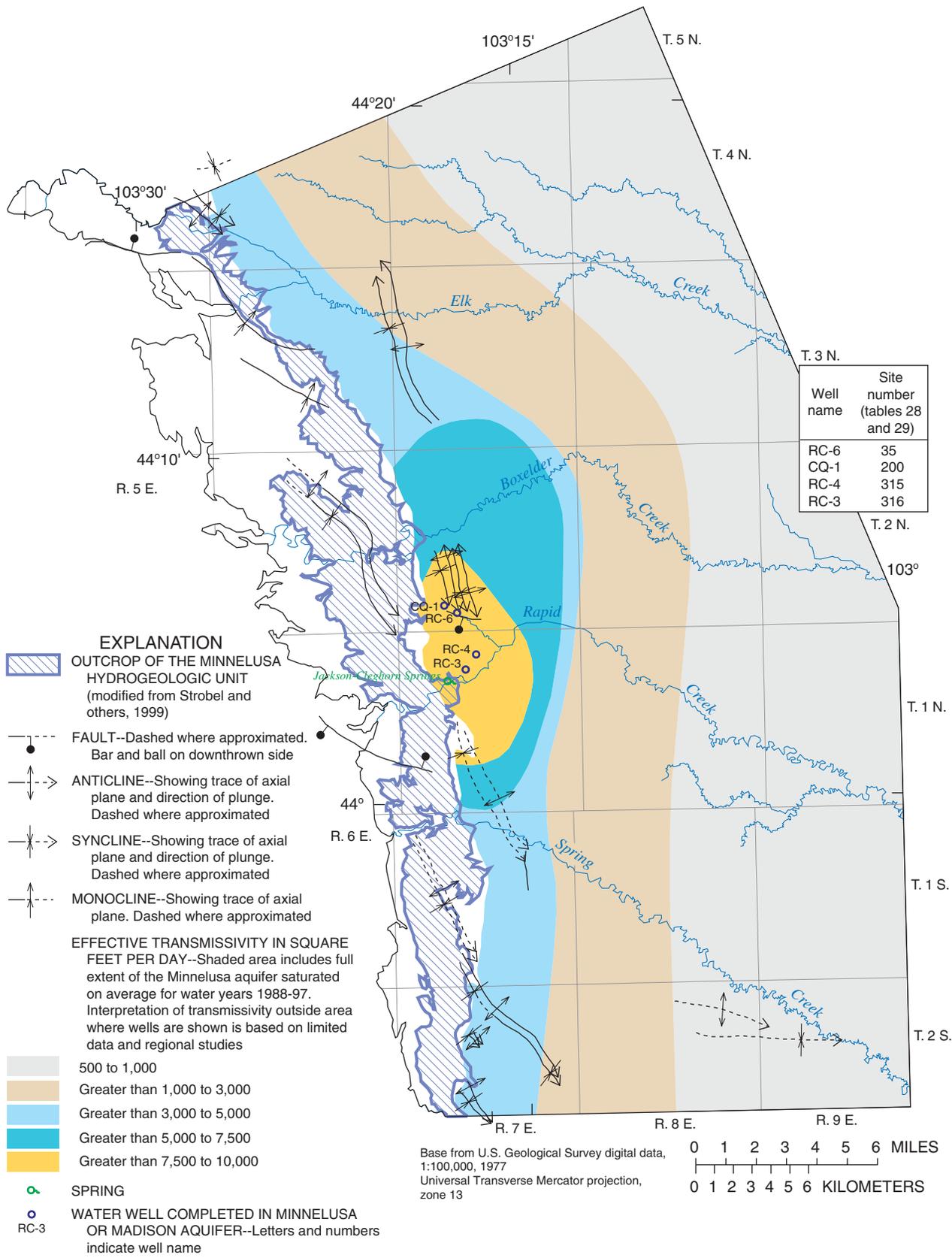


Figure 10. Effective transmissivity distribution estimates for the Minnelusa aquifer. Transmissivity estimates are provided for areas where the Minnelusa aquifer exists as shown on plate 2 and do not extend into areas where only the Minnelusa confining unit exists.

Table 3. Estimates of regional values of hydraulic conductivity, transmissivity, vertical hydraulic conductivity, and storage coefficient

[Modified from Kyllonen and Peter, 1987, p. 20-21. ft/d, feet per day; ft²/d, feet squared per day; --, no data available]

Original source	Hydraulic conductivity (ft/d)	Transmissivity (ft ² /d)	Vertical hydraulic conductivity (ft/d)	Storage coefficient (dimensionless)	Data source or method
Madison Aquifer					
Konikow (1976, p. 41)	--	860 - 2,200	--	--	Flow net analysis and model, includes correction for temperature variation.
Miller (1976, p. 25)	--	0.01 - 5,400	--	--	Drill-stem tests in southeastern Montana.
Blankennagel and others (1977, p. 52-53)	2.4x10 ⁻⁵ - 1.9	--	--	--	Permeability test core.
Woodward-Clyde Consultants (1980, p. 4-13)	--	3,000	--	2x10 ⁻⁴ - 3x10 ⁻⁴	Aquifer test, long-term response of aquifer to pumping in western Black Hills region, and model.
Blankennagel and others (1981, p. 50)	--	5,090	--	2x10 ⁻⁵	Step-drawdown tests.
Downey (1984, p. 45)	--	250 - 1,500	--	--	The range given is for Black Hills part of Downey's model.
Kyllonen and Peter (1987, p. 21)	--	4.3 - 8,600	--	--	Model calibrated values.
Downey (1986, p. E54)	--	less than 250 to 3,000	--	--	Model calibrated values.
Carter, Driscoll, Hamade, and Jarrel (2001)	--	100 - 7,400	--	--	Water-budget analysis.
Greene and others (1998)	--	41,700	--	3x10 ⁻⁴	Interference test.
Minnelusa Aquifer					
Blankennagel and others (1977, p. 50)	less than 2.4x10 ⁻⁵ to 1.4	--	--	--	Permeability test of core.
Pakkong (1979, p. 41)	--	880	--	--	Aquifer test.
Woodward-Clyde Consultants (1980, p. 4-12)	--	30 - 300	--	6.6x10 ⁻⁵ - 2.0x10 ⁻⁴	Aquifer test, flow and specific capacity data, permeability data, and lithologic considerations.
J.S. Downey, U.S. Geological Survey, Denver, Colo., written commun., 1982)	--	700 - 1,000	--	--	Model calibrated values.
Kyllonen and Peter (1987, p. 21)	--	0.86 - 8,600	--	--	Model calibrated values.
Downey (1986, p. E55)	--	less than 250 to 1,000	--	--	Model calibrated values.
Greene and others (1998)	--	9,600	--	7x10 ⁻⁵	Interference test.
Minnelusa Confining Unit					
Blankennagel and others (1977, p. 50-51)	--	--	less than 2.4x10 ⁻⁵ to 0.01	--	Permeability test of core.
Downey (1982, p. 74)	--	--	5.0x10 ⁻⁷ - 7.0x10 ⁻⁷	--	Model calibrated values.
Kyllonen and Peter (1987, p. 21)	--	--	3.4x10 ⁻⁶ - 3.4x10 ⁻⁴	--	Model calibrated values.

Table 4. Selected information for Rapid City production wells

[From Anderson and others, 1999. --, no data available]

Well	Site number (pls. 1 and 2)	Year drilled	Major aquifer	Depth of hole (feet below land surface)	Approximate static water level (feet below or above (-) land surface)	Approximate pumping water level (feet below land surface)	Drawdown (pumping level minus static level)	Approximate well yield (gallons per minute)
RC-1	317	1935	Minnelusa ¹	1,460	-32	--	--	640
RC-3	316	1936	Minnelusa ²	957	30	--	--	670
RC-4	315	1939	Minnelusa	1,070	-5	--	--	700
RC-5	79	1989	Madison	1,292	-102	210	312	1,700
RC-6	35	1990	Madison ³	1,300	8	426	418	770
RC-7	47	1991	Madison	3,280	250	773	523	150
RC-8	26	1991	Madison	2,680	125	440	315	545
RC-9	49	1991	Madison	1,050	-85	--	--	2,580
RC-10	32	1991	Madison	1,790	-73	277	350	1,790
RC-11	62	1991	Madison	1,280	64	374	310	820

¹Also may produce from Madison and Deadwood aquifers.²Also may produce from Madison aquifer.³Also may produce from Minnelusa aquifer.

Transmissivity in the Madison aquifer is primarily influenced by fractures and solution openings. Geophysical well logs indicate that in the Rapid City area, the relative volume of solution openings is generally largest near the outcrop areas (Greene, 1993), which is a result of fracturing caused by the Black Hills uplift. The potential for enlargement of fracture openings by dissolution is greatest near recharge areas where carbon dioxide is readily available and the dissolved solids concentration is low. Carbon dioxide in recharge water, which increases in concentration within the soil zone, combines with water to form carbonic acid causing the dissolution of calcite. As carbonate rock is dissolved and water becomes more saturated along the flowpath, dissolution potential decreases and secondary porosity is less developed.

Fracturing was assumed to coincide with areas where there is curvature in strata indicated by a change of dip. Areas where changes in dip for the Madison and Minnelusa hydrogeologic units are greater than 2 percent where determined from contour maps of altitude of tops (Carter and Redden, 1999a, 1999b) and are

concentrated near the outcrops (figs. 11 and 12). Curvature also could be the result of an erosional surface of the top of the Madison Limestone; however, formation thickness in the area showing curvature is relatively uniform. Areas where change in dip is greater than 2 percent generally extend about 3 mi to the east of the outcrop and about 5 mi in the area east of the Boxelder and Rapid Creek streamflow-loss zones. This wider area could indicate more extensive tectonic activity and help explain the higher *T* values. Because of this tectonic activity and other reasons to be discussed later, this area is referred to as the high-flow area. Near the center of the high-flow area is a syncline-anticline set (a, figs. 11 and 12) with a fault at the southern end. Jackson-Cleghorn Springs are also located in the central part of the high-flow area, and another syncline-anticline set (b, figs. 11 and 12) crosses the Boxelder Creek loss zone and extends to the southeast toward Jackson-Cleghorn Springs. A third syncline-anticline set (c, figs. 11 and 12) is located south of Jackson-Cleghorn Springs extending toward Spring Creek.

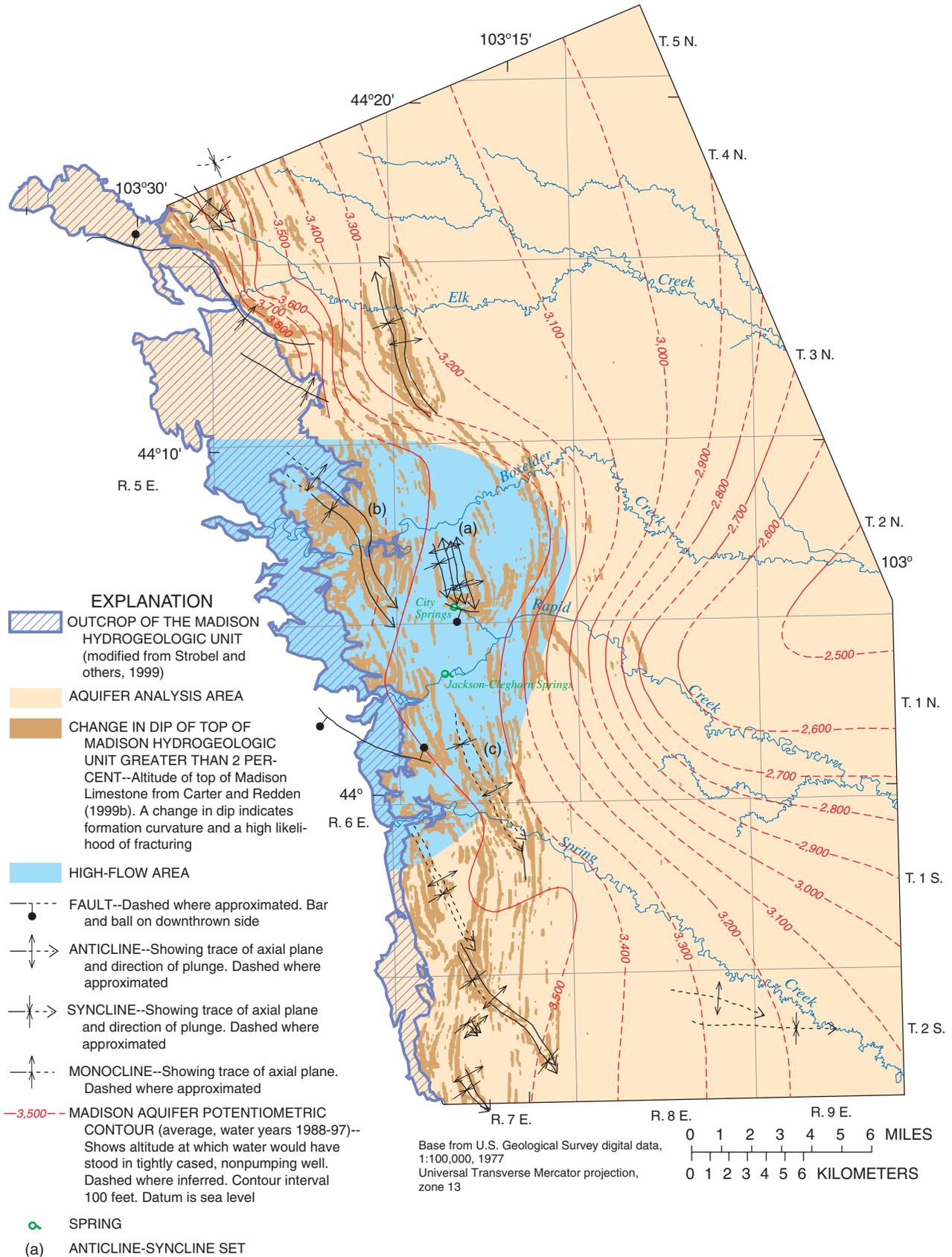


Figure 11. Hydrogeologic features indicating transmissivity distribution in the Madison aquifer. A change in dip indicates formation curvature and a likelihood of fracturing.

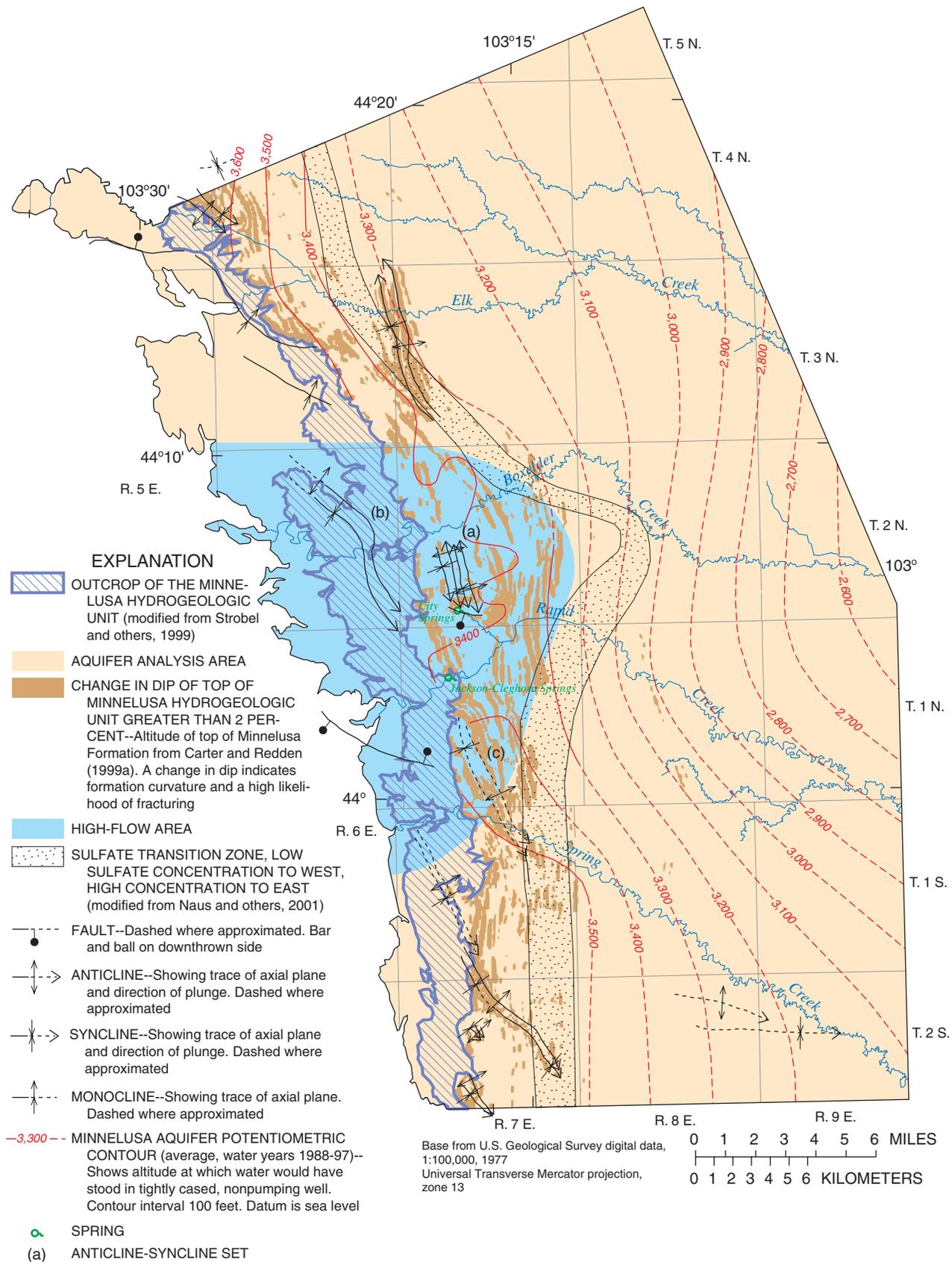


Figure 12. Hydrogeologic features indicating transmissivity distribution in the Minnelusa aquifer. A change in dip indicates formation curvature and a likelihood of fracturing.

Estimated T values greater than 7,500 ft²/d in the high-flow area (figs. 11 and 12) are consistent with aquifer test results in the Madison aquifer (table 2). Also, aggressive dissolution of carbonate rocks in the Jackson-Cleghorn Springs area is likely to have occurred because of the convergence of large volumes of recharge water moving toward the springs, which probably flow primarily from the Madison aquifer (Rahn and Gries, 1973; Back and others, 1983; Anderson and others, 1999). Karst solution enlargement of fractures often is initiated at a spring and proceeds radially outward from the spring (Clemens and others, 1997), which can create large T values in areas surrounding a spring. Jackson-Cleghorn Springs are likely to be similar to the generalized diagram of an artesian spring shown in figure 8.

A large part of the transmissivity of the Minnelusa aquifer (fig. 10) is due to the primary porosity of the sandstone layers; secondary porosity results from brecciation and from fracturing due to faulting, folding, and separation of bedding planes. Dissolution of interbedded carbonate rock layers and carbonate cements also can increase secondary porosity. Although there are very little T data for the Minnelusa aquifer in the study area, a similarity to the spatial distribution of T in the Madison aquifer is likely because the same tectonic forces have led to increased secondary porosity in both aquifers.

A process that probably has increased T in the Minnelusa aquifer in the near-outcrop area is the collapse resulting from the dissolution of gypsum and anhydrite, which are calcium sulfate minerals. Greater dissolution is more likely to occur closer to the outcrops because of smaller concentrations of dissolved solids in recharge waters. Brobst and Epstein (1963) discuss the removal of up to 200 to 300 ft of gypsum and anhydrite layers in the southwestern Black Hills due to this process, which could result in significant collapse and fracturing. The downdip advancement of evaporite removal beginning near the outcrop was documented by Naus and others (2001) by an analysis of sulfate concentrations in Minnelusa aquifer water. The zone of transition for sulfate concentrations (fig. 12) separates concentrations less than 250 mg/L (milligrams per liter) to the west, which indicates removal of gypsum and anhydrite, from concentrations greater than 1,000 mg/L to the east. The transition zone generally ranges from 2 to 3 mi downdip from the Minnelusa outcrop and about 7 mi downdip from the outcrop congruent with the high-flow area (fig. 12). The wider

area probably results from increased ground-water circulation due to a combination of factors within the high-flow area.

Anisotropic Transmissivity

In well-developed karst aquifers, solution-enhanced fractures and bedding planes provide secondary porosity that dominates ground-water flow and results in anisotropic transmissivity. Anisotropic transmissivity can be represented by an ellipse with perpendicular axes that define the magnitude and direction of the maximum and minimum transmissivity tensors (T_{max} and T_{min}) (Freeze and Cherry, 1979). Effective transmissivity (T_e), as defined by Hantush (1966a), is $\sqrt{(T_{max} \times T_{min})}$, or the geometric mean of T_{max} and T_{min} . Greene (1993) reported a ratio of T_{max} to T_{min} of 45:1 from an aquifer test at RC-5 (site 79, table 3) in the Madison aquifer.

The distribution of T shown in figures 9 and 10 refer to effective transmissivity. For the aquifer test at RC-5 (table 2), the large discrepancy in T calculated for each of the five observation wells was interpreted as resulting from anisotropy with the major axis of transmissivity (T_{max}) trending northeast-southwest (Greene, 1993). To determine this anisotropy, Greene (1993) applied the method of Hantush (1966a, 1966b), which assumes the aquifer is homogeneous and anisotropic. However, the results of the aquifer test at RC-5 also could be interpreted as resulting, at least in part, from heterogeneity. In addition to this, Greene and Rahn (1995) and Long (2000) indicated that anisotropy in the Madison could be localized in its horizontal orientation.

Anisotropic transmissivity not only can affect flow direction but also hydraulic head and hydraulic gradients as well. Long (2000) used a numerical model to show how the potentiometric surface changes when comparing isotropic to anisotropic conditions. A ratio of 40:1 can cause flow direction to deflect as much as 70 degrees from perpendicular to equipotential lines (Long, 2000). There is much evidence in support of the presence of anisotropy in the Madison aquifer but very little data to approximate its spatial distribution.

Some formations have been found to contain two mutually perpendicular fracture sets. McQuillan (1973) described the fractured-limestone Asmari Formation of southwestern Iran, which has such fracture sets. Stearns and Friedman (1972) described a major class of fracture systems called "regional orthogonal fractures."

Also, according to Price (1959), uplift can create fractures in one orientation, and further uplift can create a new set of fractures orthogonal to the first.

Greene and Rahn (1995) determined that anisotropic transmissivity in the Madison aquifer near the Black Hills had predominantly one of two mutually perpendicular orientations, depending on the local area, and called this “localized anisotropic transmissivity.” The orientation was found to be mainly either northeast or northwest. Those authors presented evidence based on analysis of cave orientations, fracture traces, aquifer tests, tracer tests, and geophysical methods. Within the study area for this report, seven out of the eight diagrams of the orientations of cave passageways from Greene and Rahn (1995) generally display a predominant orientation that ranges from about 40 to 70 degrees east of north. Interpretation of an aquifer test at RC-5 resulted in an anisotropic orientation of 42 degrees east of north (Greene, 1993). Interpretation of bedding plane solution openings from an acoustic televiwer log at RC-6 showed a predominant orientation approximately perpendicular to anisotropy determined from the RC-5 aquifer test (Greene and Rahn, 1995). Synclines and anticlines in the aquifer analysis area (fig. 2) are generally oriented about 20 to 25 degrees west of north. Downey (1984) inferred a lineament pattern from satellite imagery in the northern Great Plains, where in the Black Hills area, the predominant lineament pattern appears to be either 45 degrees west of north or 45 degrees east of north. Using localized anisotropy in these two general orientations was effective in calibrating a numerical model of the Madison aquifer for the Rapid City area (Long, 2000).

This localized anisotropy may have occurred when one set of orthogonal fractures was selectively enhanced by dissolution in comparison to the other fracture set. Many researchers have studied the conditions that influence conduit network patterns (Howard and Groves, 1995; Clemens and others, 1997; Kaufman and Braun, 1999, 2000; Gabrovsek and Dreybrodt, 2000). Tectonic movements can contribute to the hydraulic conditions that allow fracture permeability to be enhanced in a particular direction in a particular area. Local hydraulic gradients can cause the enhancement of one set of fractures over another because the fracture set that is aligned most closely with the groundwater flow direction will capture the largest flows and become preferentially enlarged. As the increasingly dominant fracture set captures progressively more of the flow, the gradient and the direction of the resultant

flow vector also would change. Another factor that may have influenced the present conduit network is development of cave and solution openings prior to the Black Hills uplift. Because the Madison Limestone was being eroded at the land surface after the Mississippian sea retreated (Gries, 1996), the surface topography and drainage would have been a factor in the development of these paleo-cave networks.

Vertical Hydraulic Conductivity

Vertical hydraulic conductivities (K_v) of the Minnelusa confining unit estimated from aquifer tests in the aquifer analysis area range from 5.3×10^{-3} to 2.7 ft/d (table 2), which indicates potential for large spatial variability in leakage between the Madison and Minnelusa aquifers. These K_v values are notably larger than regional values reported by various investigators (table 3). Because the aquifer tests reported in table 2 represent only a small sample of the aquifer analysis area, K_v values calculated do not necessarily represent the entire area. Indeed, these K_v values could be some of the largest in the study area because the aquifer tests were conducted in the high-flow area (figs. 11 and 12) where extensive structural deformation has occurred as previously discussed in the “Transmissivity” section. However, because of the variable distribution of structural features, this high-flow area probably has some of the largest variability of K_v values in the study area as well.

Part of the variability of K_v in the Minnelusa confining unit determined from aquifer tests (table 2) could be due to the selection of the analytical model and associated assumptions. Three different models were used for the RC-5, RC-6, and RC-9 aquifer tests, which included Hantush and Jacob (1955), Neuman and Witherspoon (1969a), and Hantush (1960), respectively. An important difference in the assumptions made by these models relates to the storage properties of the confining units. The models selected for RC-6 and RC-9 take into account storage in the confining units, whereas the model used for RC-5 assumes no storage in the confining units. The lower K_v values determined for RC-5 as compared to RC-6 and RC-9 (table 2) could be partly due to the different assumptions related to storage in confining units.

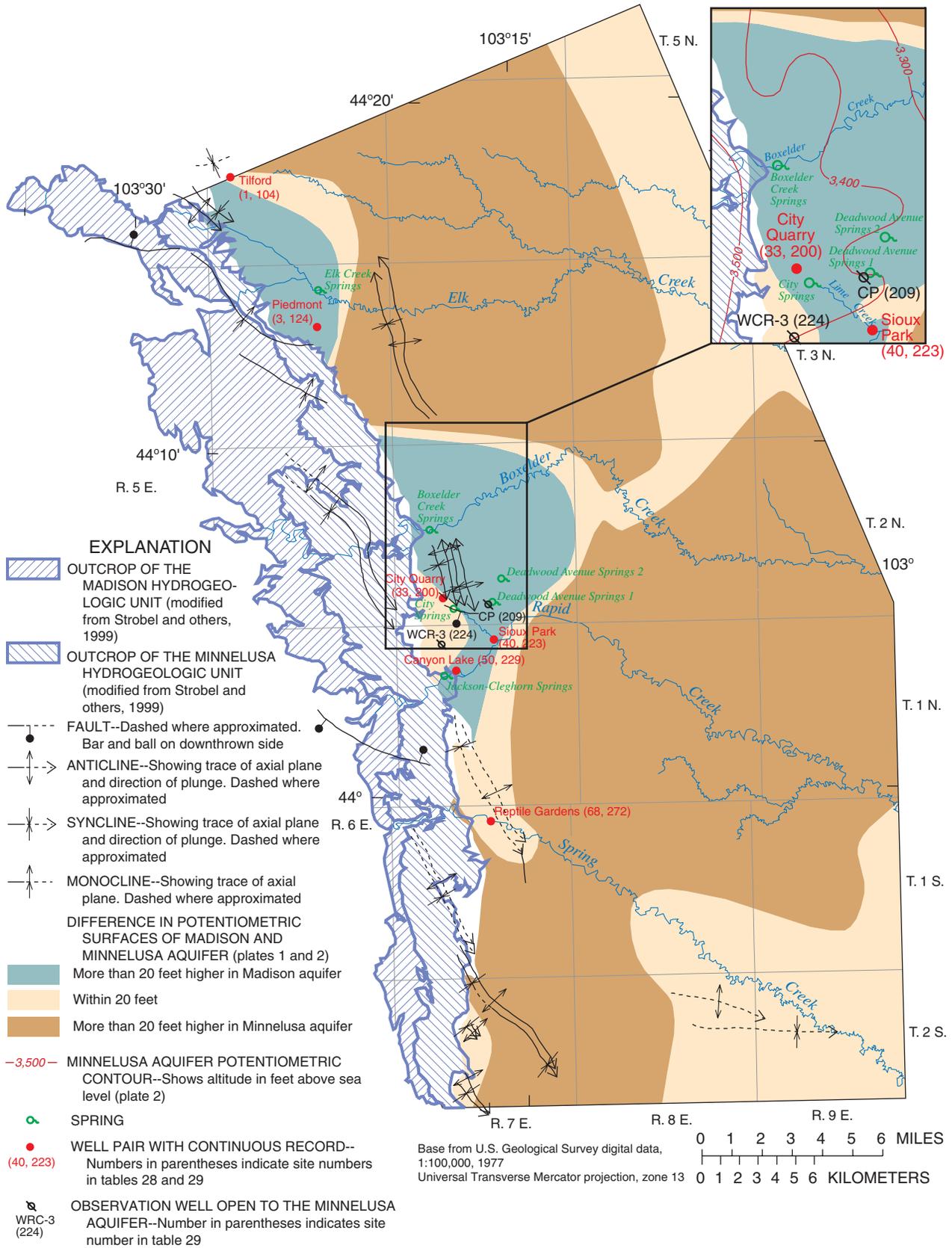


Figure 13. Comparison of hydraulic head in Madison and Minnelusa aquifers.

The uneven distribution of a residual clay soil on top of the Madison Limestone after weathering and reworking during the Mississippian and Pennsylvanian Periods (Gries, 1996) could cause heterogeneities in hydraulic connection. Greater leakage rates might occur where the residual clay is not present. Cattermole (1969) and Greene (1993) described this residual deposit as 0 to 50 ft of red, clayey shale at the base of the Minnelusa aquifer.

Other possible features influencing variability of hydraulic connection are faults, fractures, or breccia pipes. Hayes (1999) concluded that collapse brecciation within the Minnelusa Formation was the cause of episodic sediment discharge at Cascade Springs, which is located in the southern Black Hills. Hayes (1999) also used geochemical modeling to conclude that dissolution of anhydrite within the Minnelusa Formation by upward leakage from the Madison aquifer was the mechanism for development of the breccia pipes, which are the spring throats at Cascade Springs. Hayes (1999) further concluded that collapse brecciation resulting from upward leakage of water from the Madison aquifer is a probable mechanism that has contributed to development of numerous other artesian springs around the Black Hills area. Dye-tracer tests and geochemical analysis of artesian springs in the Black Hills area that flow from outcrops of geologic units overlying the Madison Limestone often indicate a source from the Madison aquifer (Klemp, 1995; Anderson and others, 1999, p. 37; Greene, 1999). Many breccia pipes that are visible in outcrop sections of the Minnelusa Formation probably are throats of previous artesian springs that have been abandoned over geologic time (Hayes, 1999). Breccia pipes that connect the Madison and Minnelusa aquifers but do not presently extend to the land surface could allow highly localized leakage between aquifers.

Breccia pipes can form when ground water dissolves gypsum and anhydrite in the Minnelusa Formation, thus, creating voids that initiate collapse brecciation, which may propagate upward to form vertical breccia pipes (fig. 14). Many breccia pipes probably formed along fractures, especially the intersection of fractures (fig. 14), where increased vertical groundwater flow could occur (Brobst and Epstein, 1963). Breccia pipes also can be initiated by collapse of the lower Minnelusa Formation into Madison Limestone caves (figs. 14 and 15) and propagate upward through the Minnelusa aquifer (Bowles and Braddock, 1963; Brobst and Epstein, 1963; Gott and others, 1974). These localized breccia pipes are in addition to the

areally extensive brecciation in the Minnelusa Formation documented by Brobst and Epstein (1963).

Comparisons of hydrographs for paired observation wells indicate possible hydraulic connection between the Madison and Minnelusa aquifers at some locations but not at others. There are six paired wells within the aquifer analysis area (fig. 16). Three of these pairs (Tilford, City Quarry, Reptile Gardens) have similar hydrographs indicating a possible hydraulic connection between aquifers. The City Quarry wells, which have nearly identical hydrographs (fig. 16c), are located about one-half mile from City Springs and RC-6, where an aquifer test (Greene, 1993) and dye-tracer test (Greene, 1999) have indicated nearly certain hydraulic connection.

If recharge rates for the Madison and Minnelusa aquifers were similar, this could explain similarities in hydrographs; however, streamflow recharge rates, which are generally larger than areal recharge within the study area, are very different for the Madison and Minnelusa aquifers as discussed later. This is especially true in the southern part of the aquifer analysis area near the Reptile Gardens wells where the outcrop area is very small and streamflow losses are much larger than areal recharge, yet the paired wells have similar hydrographs (fig. 16f). This indicates that at least part of the hydrograph similarity could be the result of hydraulic connection. For example, the rise in hydraulic head in both aquifers in the summer of 1995 was about 20 ft. However, the estimated streamflow recharge rate from Spring Creek into the Madison aquifer was about 18 ft³/s, whereas the estimated recharge rate to the Minnelusa aquifer was about 2 ft³/s (see "Recharge from Streamflow Loss" section).

Conversely, dissimilarity of hydrographs does not necessarily indicate the absence of hydraulic connection. The Canyon Lake paired wells (fig. 16e) are located about 0.5 mi from Jackson-Cleghorn Springs where Madison aquifer water passes through the Minnelusa aquifer before discharging at the surface. Hydraulic head in the Minnelusa aquifer is generally more than 50 ft lower than in the Madison aquifer and shows no resemblance to the Madison hydrograph at Canyon Lake. Hydraulic head in the Minnelusa aquifer is apparently influenced by the level of Canyon Lake, as evidenced by a sharp water-level decline when the lake was drained near the end of 1995.

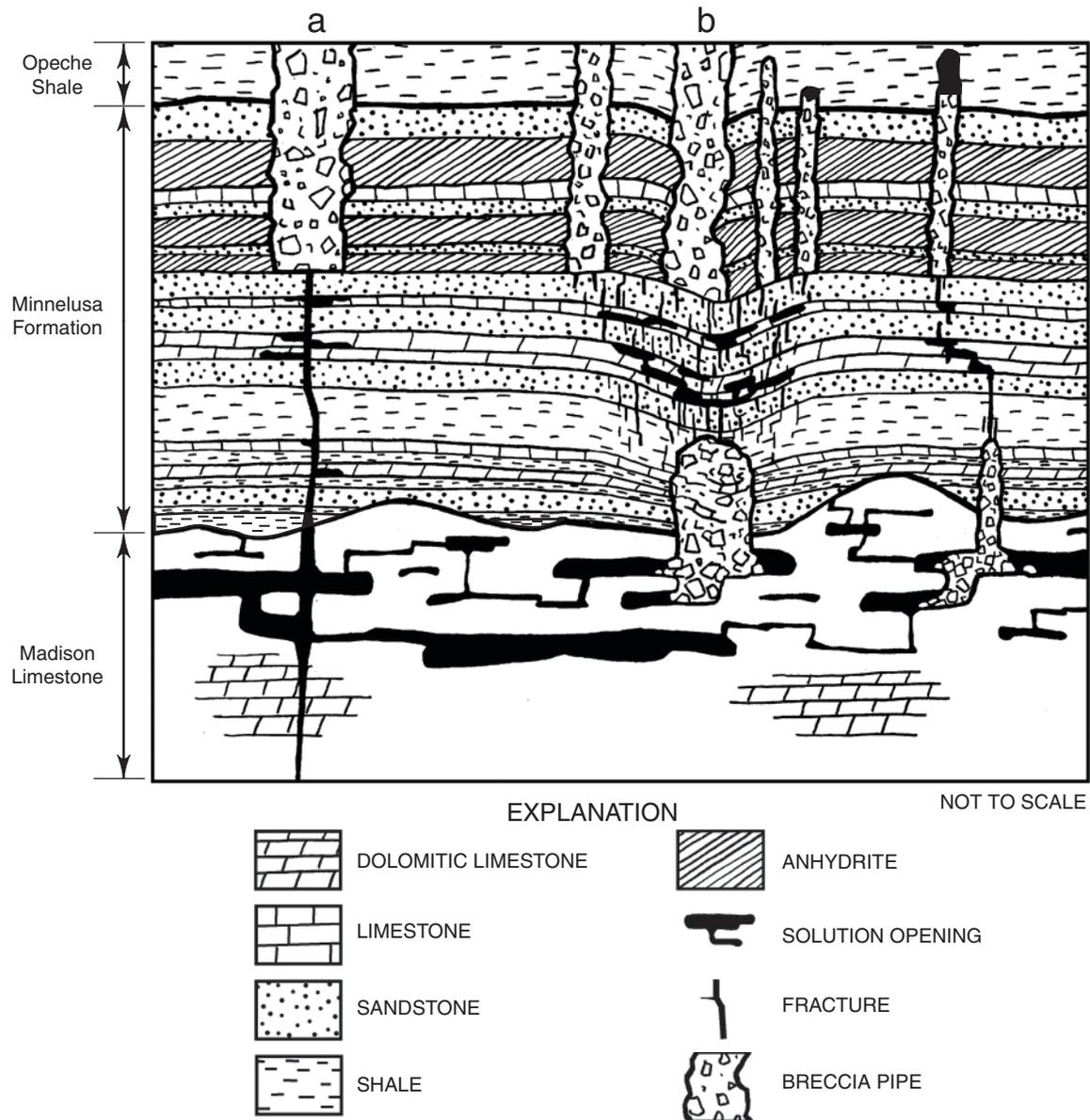


Figure 14. Geologic features that could enhance vertical hydraulic conductivity including (a) breccia pipe that formed along a fracture and (b) breccia pipe initiated by collapse of Minnelusa Formation into Madison Limestone cave.

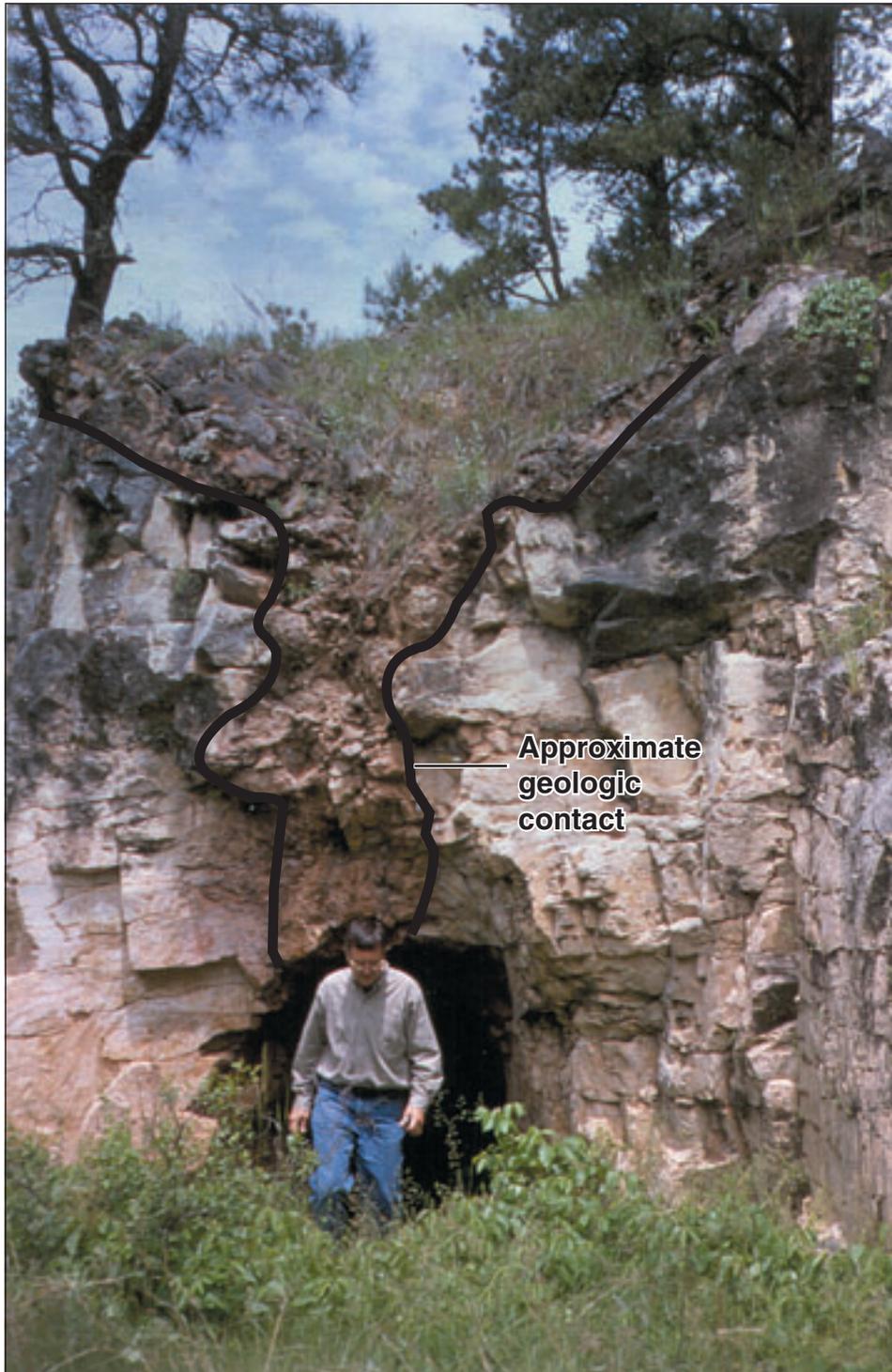


Figure 15. Entrance to Onyx Cave in the Madison Limestone in Wildcat Canyon of the southern Black Hills. Just above the cave opening are brecciated rocks of the Minnelusa Formation that have collapsed.

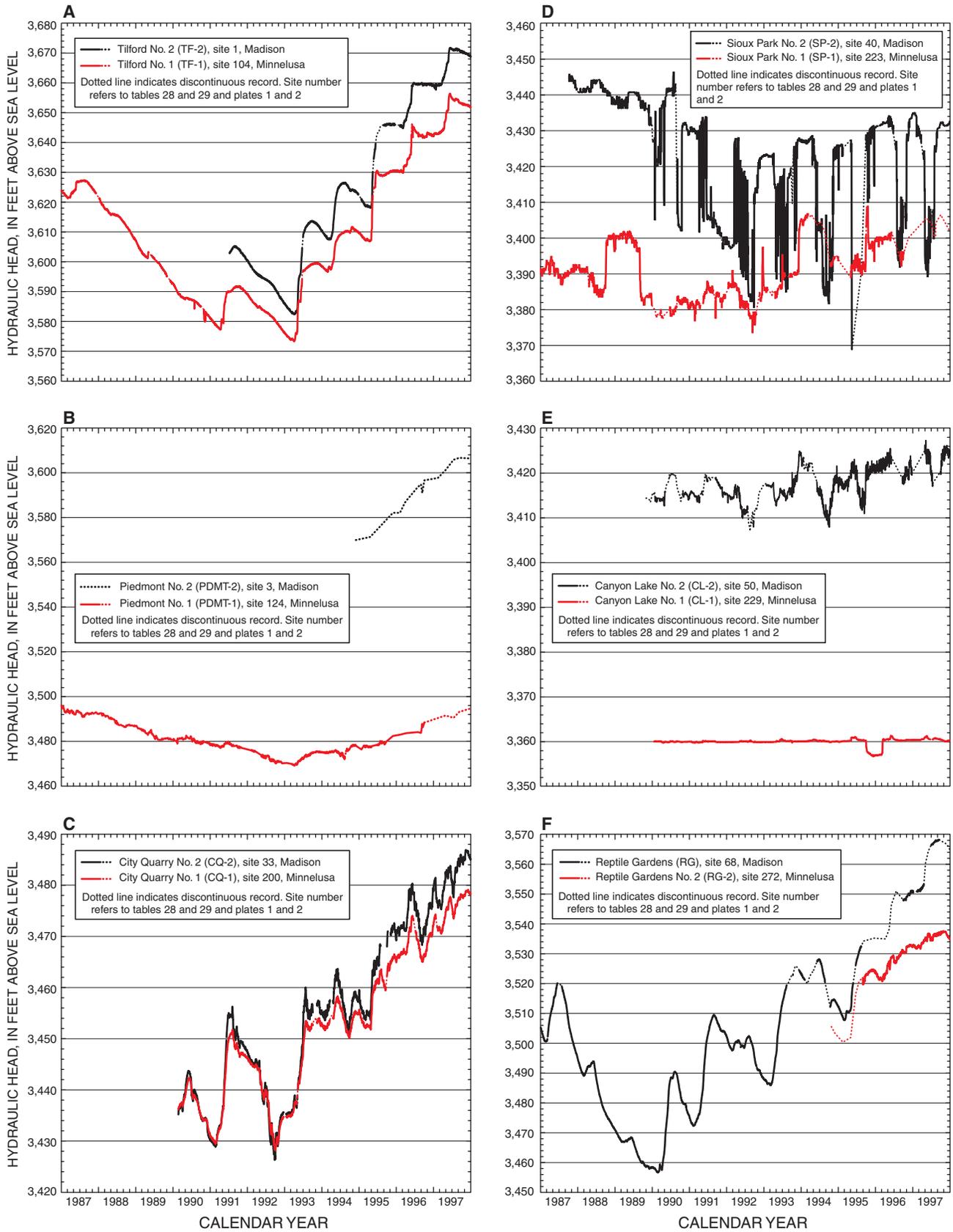


Figure 16. Hydrographs for paired wells.

Additional evidence of hydraulic connection between the aquifers is observed in the hydrograph of the Minnelusa observation well WCR-3 (figs. 13 and 17), which is located about 2 mi south of the City Quarry paired observation wells. Well WCR-3 shows declines in hydraulic head that are coincident with pumping from the Madison aquifer during September and October 1995. In October, an aquifer test (appendix A) was conducted in the Madison aquifer using production well RC-9 (fig. 9). Except for a short period of pumping from well RC-10, municipal withdrawals from the Madison and Minnelusa aquifers were terminated in that area from September 25 through October 16. On September 25, the WCR-3 hydrograph shows an upward deflection in hydraulic head (fig. 17) presumably due to the termination of pumping. When RC-10 began pumping on September 29, hydraulic head in WCR-3 declined until pumping ceased less than 2 days later. When RC-9 began pumping for the aquifer test beginning October 4, there was a sharp decline in hydraulic head. Hydraulic head began to increase on

October 6 before pumping from RC-9 was terminated, which may have resulted because the aquifer was in a general recovery period and drawdown due to pumping RC-9 was beginning to flatten. The Black Hills Power and Light well (BHPL) was either not pumping or pumping intermittently because of plant maintenance until October 12 when the pumping rate increased, which is coincident with a decline at WCR-3. When Chapel Lane Water Company began using its production well (CHLN-2) on October 16, a similar decline was noted. These observations also indicate that hydraulic connection between the two aquifers is spatially variable, because noticeable responses did not occur in the Sioux Park Minnelusa well (fig. 13), which is located closer to the pumping wells than is WCR-3. Also, the Sioux Park paired wells have dissimilar hydrographs (fig. 16d).

Irregularities in the potentiometric surface of the Minnelusa aquifer near the 3,400-ft contour (fig. 13 inset) could be the result of localized upward leakage from the Madison aquifer. The central area of

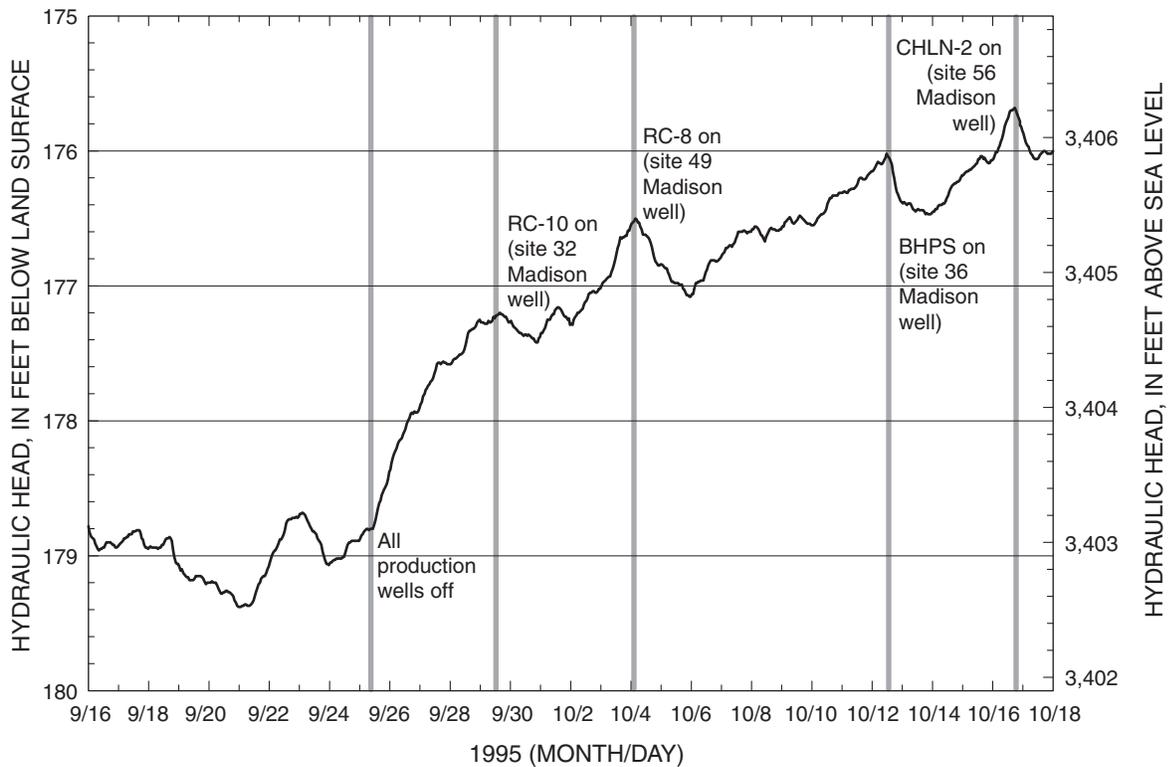


Figure 17. Possible response of hydraulic head at West Camp Rapid Minnelusa well (WCR-3) to pumping from Madison aquifer.

upward hydraulic gradient coincides with the high-flow area (figs. 11 and 12) and contains several artesian springs that are assumed or known to originate from the Madison aquifer. These upward hydraulic gradients could result in movement of Madison aquifer water into the Minnelusa aquifer through vertical breccia pipes to produce an irregular potentiometric surface in the Minnelusa aquifer.

Specific Yield

Specific yield (S_y) is the storage term used to describe and make calculations for storage in unconfined areas described in this report. Lohman and others (1972) defined S_y and related properties, which include total porosity, effective porosity, and specific retention. S_y of a rock or soil is defined as the ratio of (1) the volume of water that the rock or soil, after being saturated, will yield by gravity to (2) the volume of the rock or soil. S_y is equal to total porosity minus specific retention. The specific retention of a rock or soil is the ratio of (1) the volume of water that the rock or soil, after being saturated, will retain against the pull of gravity to (2) the volume of the rock or soil. Specific retention increases with decreasing grain size or pore size. Total porosity is the ratio of the total volume of pore space in a material to the total volume of the material. Effective porosity, which is an upper limit for S_y , is the ratio of interconnected pore space available for the transmission of water to the total volume of the material.

Due to heterogeneity, a wide range of porosity values for the Madison hydrogeologic unit have been reported (table 5). Although direct measurements of S_y were not available for the study area, estimates were made based on porosities and other hydrogeologic information. The average S_y was estimated as 0.09 for the Madison and Minnelusa aquifers and 0.03 for the Madison and Minnelusa confining units.

The definitions of S_y and specific retention imply sufficient time for gravity drainage to complete, which often is not the case in natural environments (Lohman and others, 1972). Therefore, the effective value of S_y is generally lower than that based strictly on the definition depending on factors such as particle or pore size, rate of water-table change, and time. Perching of water also can decrease the effective value of S_y because water is retained in these perched spaces as the water table declines. Other than in solution openings and fractures, the permeability of the Madison hydrogeologic

unit is generally low, and water collects in poorly drained depressions on the floors of solution openings above the water table. These depressions often form on the floors of enlarged bedding planes, which have irregular surfaces and are nearly horizontal. The Minnelusa hydrogeologic unit also has a high potential to retain perched water because of low-permeability shale layers.

Estimates of S_y for the Madison and Minnelusa confining units are lower than for the aquifer units because of differences in lithology. S_y of the Madison confining unit is less than that of the aquifer because of smaller effective porosity and larger specific retention, which results from porosity dominated by small fractures rather than solution openings. The lower Minnelusa Formation generally contains less sandstone and more limestone, dolomite, and shale than the upper part (Bowles and Braddock, 1963). Therefore, smaller effective porosity and greater specific retention in the Minnelusa confining unit results in smaller S_y than in the aquifer.

Storage Coefficient

Storage coefficient, S , is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head (Lohman and others, 1972). In a confined aquifer, storage coefficient can be orders of magnitude smaller than in an unconfined aquifer. This is because in an unconfined aquifer, large changes in storage can occur due to the rise and fall of the water table; in a confined aquifer, smaller changes in storage occur as a result of the slight expansion or contraction of the aquifer material and water due to hydraulic-head changes. For an unconfined aquifer, storage coefficient is virtually equal to the specific yield (Lohman and others, 1972). Aquifer tests in the aquifer analysis area indicate that S varies between 1×10^{-4} and 2×10^{-3} for confined conditions of the Madison aquifer (table 2). The only value for the Minnelusa aquifer from these aquifer tests is 3×10^{-3} . However, table 3 shows that S as low as 7×10^{-5} has been estimated for the Minnelusa aquifer outside of the study area. Because there doesn't appear to be a definitive pattern, S for all confined areas of the Madison and Minnelusa aquifers is taken at a middle value of 3×10^{-4} for this report.

Table 5. Estimates of porosity and specific yield (S_y) for the Madison and Minnelusa hydrogeologic units from previous investigations and this study

[--, no data available]

Total porosity (as a fraction of 1)	Effective porosity (as a fraction of 1)	Specific yield (dimensionless)	Data source or method	Source
Madison Limestone				
0.11	0.05	--	Oil tests	Rahn (1985)
Madison Aquifer				
--	0.35 (average)	--	Well RC-6 resistivity log	Greene (1993)
--	0.35 (average)	--	Well LC resistivity log	Greene (1993)
--	--	0.09	Water budget ¹	This report
Madison Confining Unit				
--	--	0.03	Water budget ¹	This report
Minnelusa Formation				
0.10	0.05	--	Oil tests	Rahn (1985)
Minnelusa Aquifer				
--	0.10 - 0.15	--	Well RC-6 neutron porosity log	Greene (1993)
--	0.05 - 0.10	--	Well RC-5 neutron porosity log	Greene (1993)
--	--	0.09	Water budget ¹	This report
Minnelusa Confining Unit				
--	0.05 (average)	--	Well RC-6 neutron porosity log	Greene (1993)
--	0.05 (average)	--	Well RC-5 neutron porosity log	Greene (1993)
--	--	0.03	Water budget ¹	This report

¹See "Water-Budget Analysis" section.

Hydraulic Head and Ground-Water Flow

Potentiometric surfaces, hydraulic response to stress, the extent of unconfined areas in relation to confined areas, and flowpaths are important considerations in understanding the dynamics of the ground-water-flow system. Analysis of hydraulic response to stress can be used to characterize the aquifers and estimate properties such as storage and transmissivity. Hydraulic gradients can be useful for estimating transmissivities, recharge areas, discharge areas, and flow directions. The areal extent of unconfined areas is important for analysis of storage and ground-water flow near recharge areas. Flowpaths are important when considering sources of springs and wells.

Potentiometric Surfaces

Potentiometric maps of the Madison and Minnelusa aquifers (pls. 1 and 2; figs. 11 and 12) were interpreted based on available hydraulic heads in observation wells, public-supply wells, and private wells. The potentiometric surfaces for both aquifers show a general easterly gradient of about 1,000 ft in 15 mi. Detailed information for the wells used in interpreting potentiometric maps is listed in tables 28 and 29 (appendix B). Where data are sparse in the eastern part of the aquifer analysis area, contours were based on Downey (1986).

Because the hydraulic heads were measured at various times, a potentiometric surface could not be interpreted for a particular date; therefore, the potentiometric maps represent an average potentiometric

surface for WY88-97. To achieve this, each hydraulic-head measurement was either adjusted up if the measurement was made during a period of low water levels or adjusted down if made during a period of high water levels. Adjustment to each hydraulic head measurement was based on the WY88-97 hydrograph of the nearest continuous-record well (figs. 18 and 19). Hydrographs of longer periods of record are available for some wells (Driscoll, Bradford, and Moran, 2000). WY88-97 included a range of climatic conditions from dry during the late 1980's through wet conditions in the middle to late 1990's. Periods of continuous records that included the influence of pumping were eliminated from the analysis. Water levels for many wells have been obtained from drillers' reports, which generally are fairly accurate; however, locations can be inaccurate. In areas of large topographic relief, accurate locations are essential to determine land-surface altitudes. However, because it was infeasible to visit all of the wells to check or verify locations, hydraulic head measurements not considered reliable were not used (tables 28 and 29).

In a few cases, unusually high hydraulic heads were measured in wells located on or near the outcrop areas and are likely to represent perched water, which is known to exist near the Madison outcrop area. Wind Cave in the southern Black Hills contains a 300-ft-long body of water (Phantom Lake) that is perched considerably above the water table (Marc Ohms, Wind Cave National Park, oral commun., 2001). Hydraulic head measurements thought to be from perched water were omitted from the potentiometric-surface analysis.

The trough in the potentiometric surface in the eastern part of the Madison aquifer, where data are sparse, is based on the regional potentiometric surface of the Madison aquifer shown in Downey (1986, p. E39). The few hydraulic heads measurements available for the eastern part of the Madison aquifer (pl. 1) are in agreement with Downey's (1986) interpretation. Downey and Dinwiddie (1988, p. A47) show a narrow path of high easterly ground-water velocity in the Madison aquifer along the axis of this area, and Downey (1986, p. E54) shows a zone of anomalously high transmissivity in this area. If there is a high-transmissivity pathway in this area of the Madison aquifer that draws down the hydraulic head, it is likely to draw down hydraulic head in the Minnelusa aquifer as well, especially if there is enhanced vertical hydraulic conductivity in the Minnelusa confining unit. Therefore, the Minnelusa aquifer was interpreted as having a lowered potentiometric surface in this area (pl. 2).

Hydraulic Response to Recharge

Hydraulic-head changes in the Madison and Minnelusa aquifers in the study area are highly variable (figs. 18 and 19). The difference of the maximum and minimum hydraulic head in continuous-record observation wells during WY88-97 ranged from about 5 to 120 ft (fig. 20). With the effects of pumping from RC-5 removed from the LC and SP-2 hydrographs, a pattern emerges whereby hydraulic-head change is small in the Jackson-Cleghorn Springs area and increases with distance from the springs (fig. 20). The transmissivity distribution probably is part of the reason for this pattern because higher transmissivity tends to damp hydraulic head fluctuations in response to stresses such as recharge or pumping. Based on aquifer tests and the hydraulic gradients shown on plates 1 and 2, transmissivity near the Jackson-Cleghorn Springs area is high and generally decreases with distance from the springs.

Hydraulic head fluctuates in response to changing recharge rates at the outcrop areas. In the Spring Creek area where areal recharge is small compared to streamflow recharge, a direct correlation of streamflow loss to hydraulic head in the Madison aquifer was described by Long and Derickson (1999) by invoking a time-invariant transfer function (fig. 21). Hydraulic head can be predicted based on this transfer function applied to the streamflow-loss rate. Based on data from the Reptile Gardens Madison well (RG) about 3 mi from the recharge area, the transfer function showed that (1) the peak response is less than one month, (2) the system has memory of about 4 years, and (3) ground-water recession follows a logarithmic curve. The very long memory (elapsed time before all effects of a stress have diminished) in contrast to the short response time of the system probably results from dual porosity. A long-term system memory can result from delayed storage within the aquifer's matrix of tiny fractures and small pore spaces in contrast to the very fast flowpaths of large solution openings. This also can result from leakage to and from overlying or underlying confining units, which can store water in a similar way to that of a dual-porosity system. Numerical modeling has shown that hydraulic head fluctuation in the Madison aquifer can be damped by leakage into and out of vertically adjacent layers and also by dual-porosity effects (Long, 2000). Storage properties and/or the hydraulic response of dual-porosity reservoirs are described in Barenblatt and others (1960), Warren and Root (1963), Streltsova (1988), and Bai and others (1993). Streltsova (1988) also describes these properties for leaky aquifers.

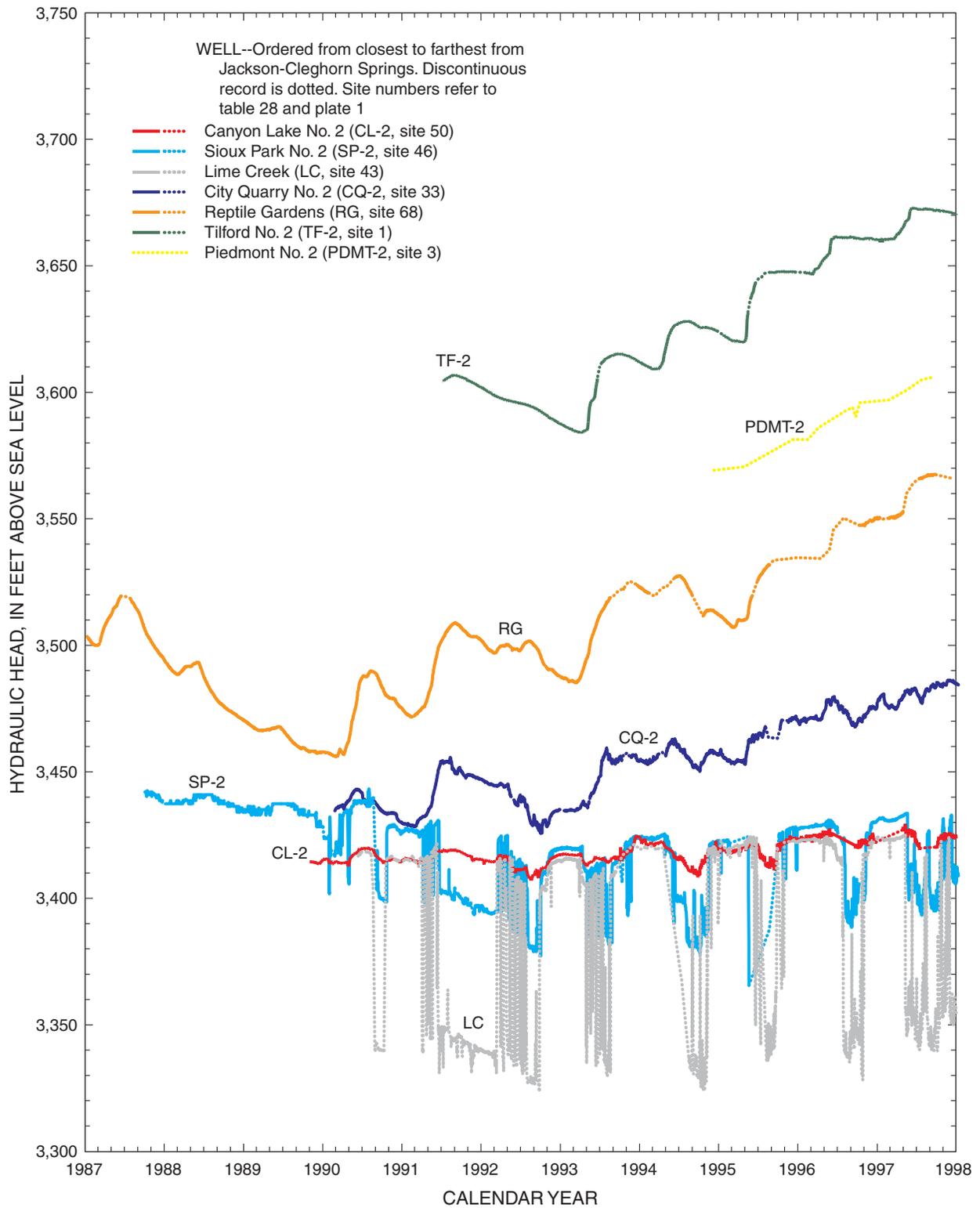


Figure 18. Hydrographs of continuous-record observation wells in the Madison aquifer.

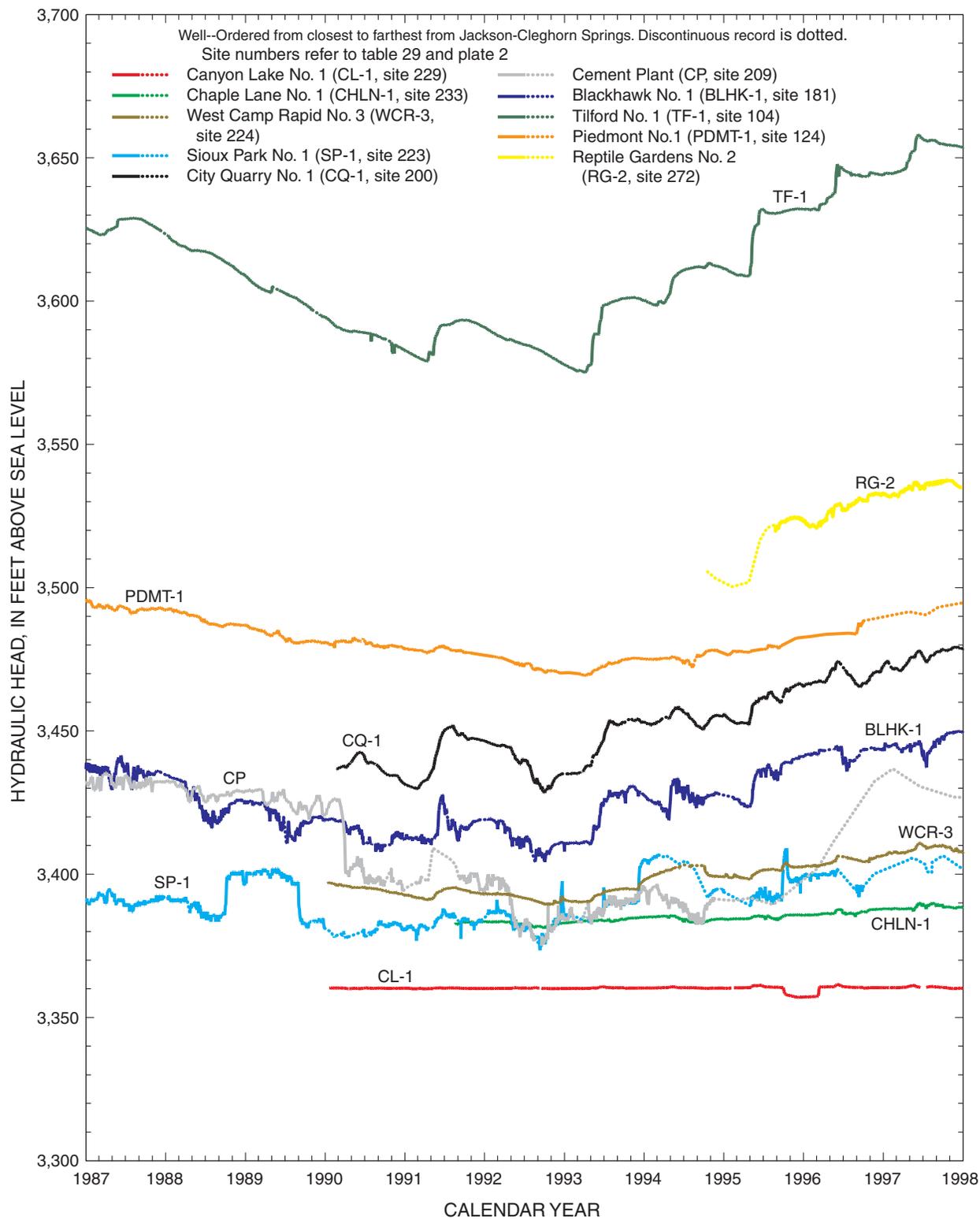


Figure 19. Hydrographs of continuous-record observation wells in the Minnelusa aquifer.

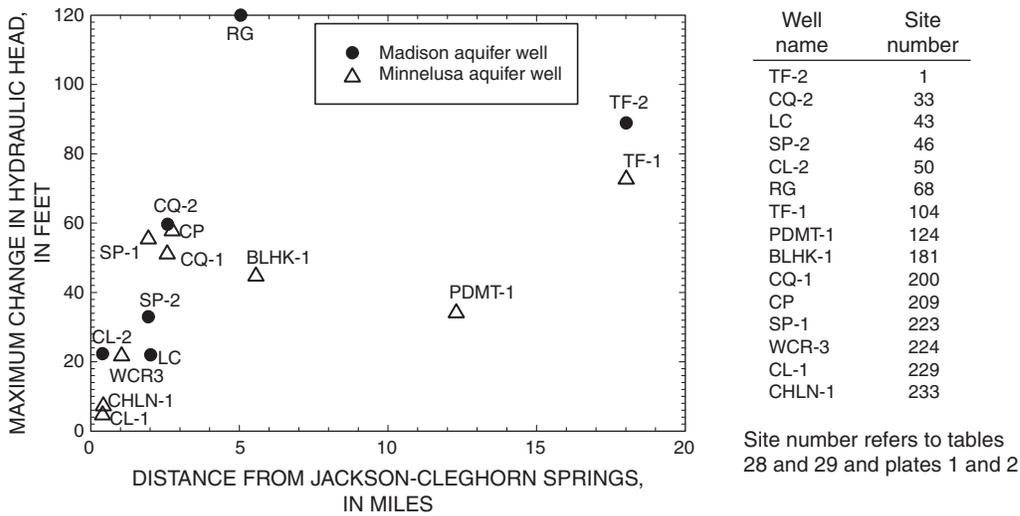


Figure 20. Maximum hydraulic head change in selected continuous-record observation wells during WY88-97 versus distance from Jackson-Cleghorn Springs. In general, maximum hydraulic head change increases with distance from Jackson-Cleghorn Springs. Maximum hydraulic head change in wells with shorter periods of record was estimated. Hydrographs are plotted in figures 18 and 19.

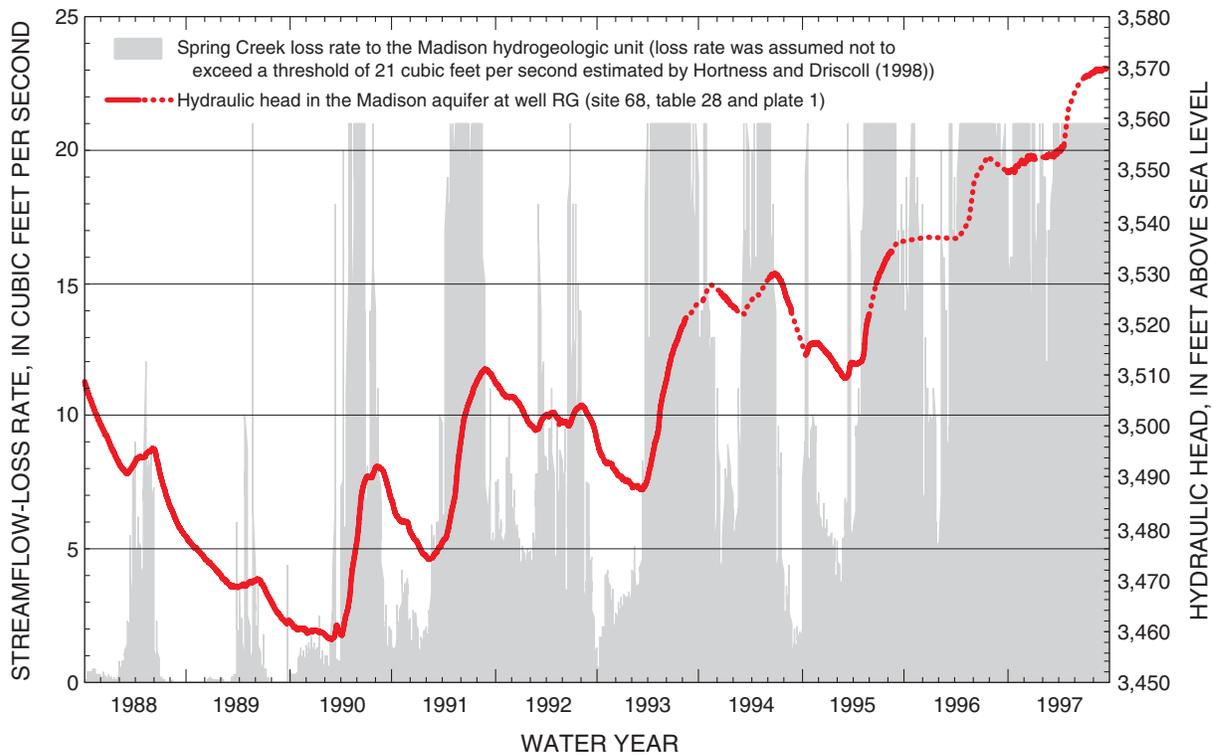


Figure 21. Relation between Spring Creek streamflow loss and hydraulic head in Madison aquifer.

Unconfined Areas

The boundaries of unconfined areas (pls. 1 and 2) are determined by the locations where the average potentiometric surfaces (WY88-97) contact the tops and bottoms of the Madison and Minnelusa aquifers and associated confining units. Altitudes for top and bottom of the Madison and Minnelusa hydrogeologic units were taken from maps of the structural tops of the Minnelusa Formation, Madison Limestone, and Deadwood Formation from Carter and Redden (1999a, 1999b, 1999c). The top of the Minnelusa Formation was taken as the top of the Minnelusa hydrogeologic unit. The top of the Madison Limestone was taken as the top of the Madison hydrogeologic unit and the bottom of the Minnelusa hydrogeologic unit. The top of the Deadwood Formation was taken as the bottom of the Madison hydrogeologic unit. A uniform thickness of 150 ft (assumed thickness of the Madison aquifer) was subtracted from the top of the Madison hydrogeologic unit to estimate the altitude of the surface between the aquifer and confining unit. The same was done for the Minnelusa hydrogeologic unit, with a uniform thickness of 250 ft assumed for the aquifer thickness. These aquifer thicknesses are the midpoints of ranges given by Greene (1993).

Because potentiometric surfaces are generally some distance below the land surface in the outcrop areas, and the aquifers and confining units dip to the east (fig. 6), unconfined areas are present eastward of outcrop areas. The western part of outcrop areas generally are not saturated but may contain infiltrating or perched water.

Boundaries of the unconfined areas of the Madison and Minnelusa aquifers shift to the east or west as hydraulic head fluctuates. During WY88-97, the maximum fluctuation in measured hydraulic head was about 100 ft, which would cause these boundaries to shift a distance of 600 to 2,000 ft or about 1 to 2 percent of the total east-west dimension of the aquifer analysis area. Although unconfined areas shift horizontally, the total areal coverage changes negligibly. Because of these comparatively small changes in position and area, the unconfined zones shown on plates 1 and 2 were assumed to be spatially constant in time for water-budget purposes. Saturated thickness and transmissivity of the unconfined zones were assumed constant in time, which is justifiable if the dip of the beds are relatively constant within areas where the unconfined areas shift from east to west. It follows that even

if unconfined areas change position vertically and horizontally as hydraulic heads rise and fall, saturated thicknesses also would be assumed constant.

The location and extent of the unconfined areas are significant in analyzing aquifer storage because most of the change in storage occurs in these areas. Estimates of specific yield (unconfined storage term) for the Madison and Minnelusa aquifers are three or more orders of magnitude larger than estimates of storage coefficient for confined conditions (tables 2, 3, and 5). Estimates of unconfined area coverages for the Madison and Minnelusa hydrogeologic units are 52.9 mi² and 36.3 mi², respectively. Although the unconfined areas represent a small percentage of the aquifer analysis area (629.4 mi²), the amount of water these areas are capable of releasing from storage with a given change in head is orders of magnitude larger than that released in the confined part of the aquifer.

Eight hydrogeologic sections (fig. 22), A-A' through H-H', (pls. 1 and 2), show differences in unconfined areas. Section A-A' shows how the steep dip of a monocline results in a small unconfined area in the Madison aquifer relative to that of the Minnelusa aquifer. Section B-B' illustrates an area where the Madison outcrop is large, but most of the outcrop area is unsaturated with a small unconfined area near the eastern edge of the outcrop. Although most of the outcrop is not saturated at this location, the areal extent of the outcrop makes it a large source of areal recharge. The "unsaturated area" in section B-B' consists mainly of the lower part of the Madison hydrogeologic unit, which is generally considered a confining unit; however, weathering and dissolution of fractures has probably increased its permeability in outcrop areas allowing recharge water to quickly infiltrate and flow laterally toward water-table areas. This flow might consist of water cascading through a series of subsurface pools or non-Darcian channel flow, and could have very high velocities in some areas. For example, dye testing (Rahn and Gries, 1973; Greene, 1999) indicated ground-water flow velocities on the order of miles per hour along a flowpath starting in a swallow hole in Boxelder Creek, located in the Madison confining unit outcrop, and emerging from Gravel and Doty Springs (see cover photo).

Sections C-C' and D-D' illustrate how an anticline-syncline structural feature with a southeasterly plunge influences ground-water flow and the areal extent of the unconfined area near Boxelder Creek (pl. 1). Section C-C' shows that saturated areas

of the Madison hydrogeologic unit are separated by an anticline. Section D-D' shows how an anticline blocks much easterly flow in the Madison aquifer, thus, diverting flow to the southeast along the syncline axis (pl. 1). Therefore, a large part of the streamflow recharge from Boxelder Creek probably is directed toward Rapid City. Some easterly flow within the Madison confining unit also is plausible but probably is minor compared to southeasterly flow in the aquifer.

Section E-E' shows the uniform dip of the hydrogeologic strata in the Rapid Creek and Jackson-Cleghorn Springs area. A fault separates section E-E' from section F-F' on the upthrown side (pl. 1) where strata have been lifted higher than on the downthrown side in relation to the potentiometric surfaces. In addition, gently dipping beds and structural features have resulted in large unconfined areas or unsaturated areas along section F-F'.

Section G-G' shows how variations in dip create a wide Madison outcrop area in comparison to that of the Minnelusa outcrop. Section H-H' illustrates the reason that the unconfined area of the Madison hydrogeologic unit is farther to the east of the outcrop than at section G-G'.

Flowpaths

Dye-tracer tests, stable isotopes, and hydrogeologic features were analyzed conjunctively to estimate generalized ground-water flowpaths in the Madison aquifer and analyze the influences of flowpaths in the Minnelusa aquifer. A dye-tracer test (Greene, 1999) showed that ground water moved rapidly from the Boxelder Creek loss zone to five ground-water sampling sites in the Madison aquifer. Natural tracers in the form of stable isotopes provided more generalized evidence but were available for a larger part of the study area. The spatial configuration of saturated areas in relation to unsaturated areas indicated probable flowpaths at some locations.

As discussed in the previous section, the anticline-syncline set that crosses Boxelder Creek

(fig. 23) has the potential to impede easterly ground water recharged near Boxelder Creek. Section D-D' (fig. 22,) shows that easterly ground-water flow across the anticline, if any, would be within the Madison confining unit. The more likely flowpath, however, is to the southeast along the axis of the syncline where the Madison aquifer is fully saturated.

The dye-tracer test (Greene, 1993) indicates a focused flowpath, which probably follows the syncline southeasterly before turning to the east (fig. 23). The dye-tracer test consisted of injection of Rhodamine WT dye at the Boxelder Creek loss zone, which was detected at City Springs, RC-6, RC-10, BHPL, WT-2, and CQ-2 but was not detected at Jackson-Cleghorn Springs, RC-5, RC-8, or RC-9 (fig. 23). Except for observation well CQ-2, all these wells are production wells that were being pumped. The sites where dye was detected are grouped in a semi-linear pattern oriented downgradient, bounded by RC-8 on the north and RC-5 on the south. Greene (1993) measured breakthrough curves for all sites where dye was detected except for CQ-2. Dye detection at City Springs began 30 days after injection and continued until the 261st day with a peak concentration at 48 days. Dye detection at RC-10 and BHPL began less than 50 days after injection and continued until the 198th and 159th day respectively with peak concentrations less than 10 days after that of City Springs. If the flowpath was dispersive rather than focused, dye may have been detected at RC-5 and RC-8, especially considering the duration of breakthrough curves at the other sites. In addition, the mass recovery of 36 percent of the injected dye reported by Greene (1993) probably would not be possible without a focused flowpath.

Stable isotopes of oxygen and hydrogen (¹⁸O and ²H) in recharge water can be used as natural tracers to determine source areas and flowpaths for ground water. Isotope values are reported as a ratio of ¹⁸O/¹⁶O or ²H/¹H of a sample water compared to a standard. The equation for oxygen given in parts per thousand (per mil) is as follows:

$$\delta^{18}\text{O}_{\text{sample}} = \frac{(\text{}^{18}\text{O}/\text{}^{16}\text{O})_{\text{sample}} - (\text{}^{18}\text{O}/\text{}^{16}\text{O})_{\text{standard}}}{(\text{}^{18}\text{O}/\text{}^{16}\text{O})_{\text{standard}}} \times 1,000. \quad (1)$$

A smaller delta (δ) value is referred to as being isotopically lighter, while a larger value is considered heavier. For further discussion on stable isotope analysis in natural waters and distribution in the Black Hills area, see Naus and others (2001).

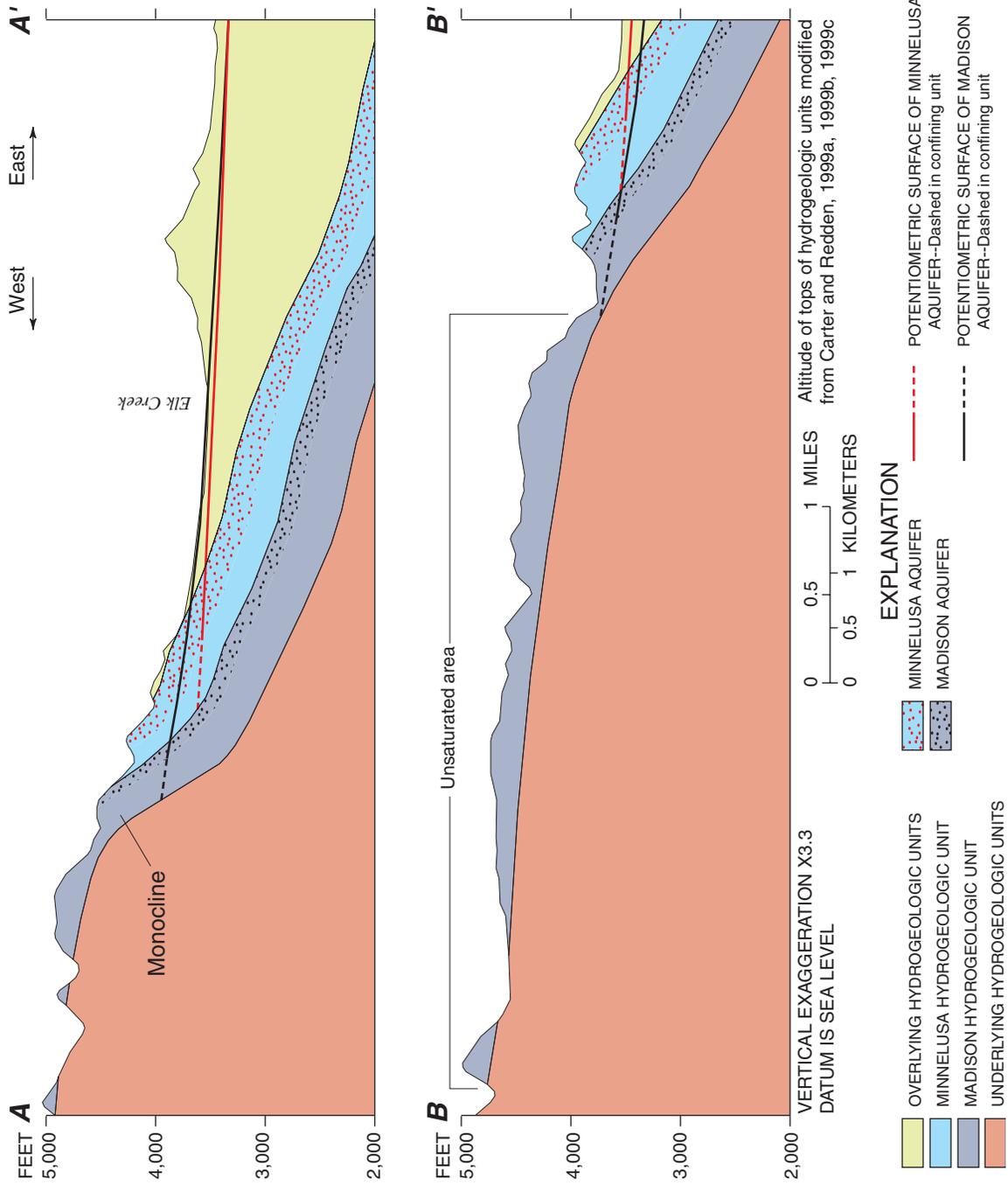


Figure 22. Hydrogeologic section showing average potentiometric surfaces of the Madison and Minnelusa aquifers (plates 1 and 2) in relation to hydrogeologic strata (location of sections shown on plates 1 and 2).

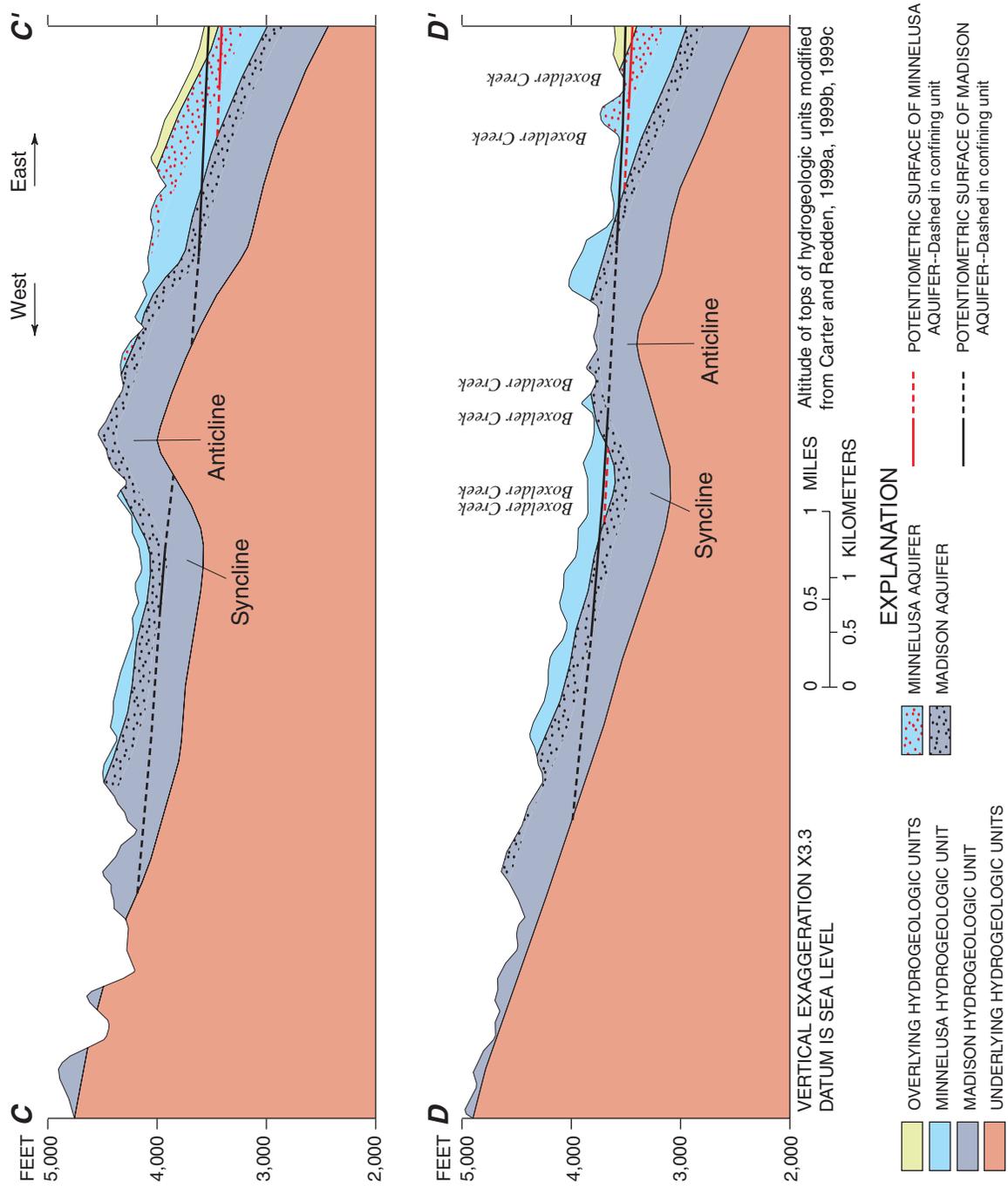


Figure 22. Hydrogeologic section showing average potentiometric surfaces of the Madison and Minnelusa aquifers (plates 1 and 2) in relation to hydrogeologic strata (location of sections shown on plates 1 and 2).—Continued

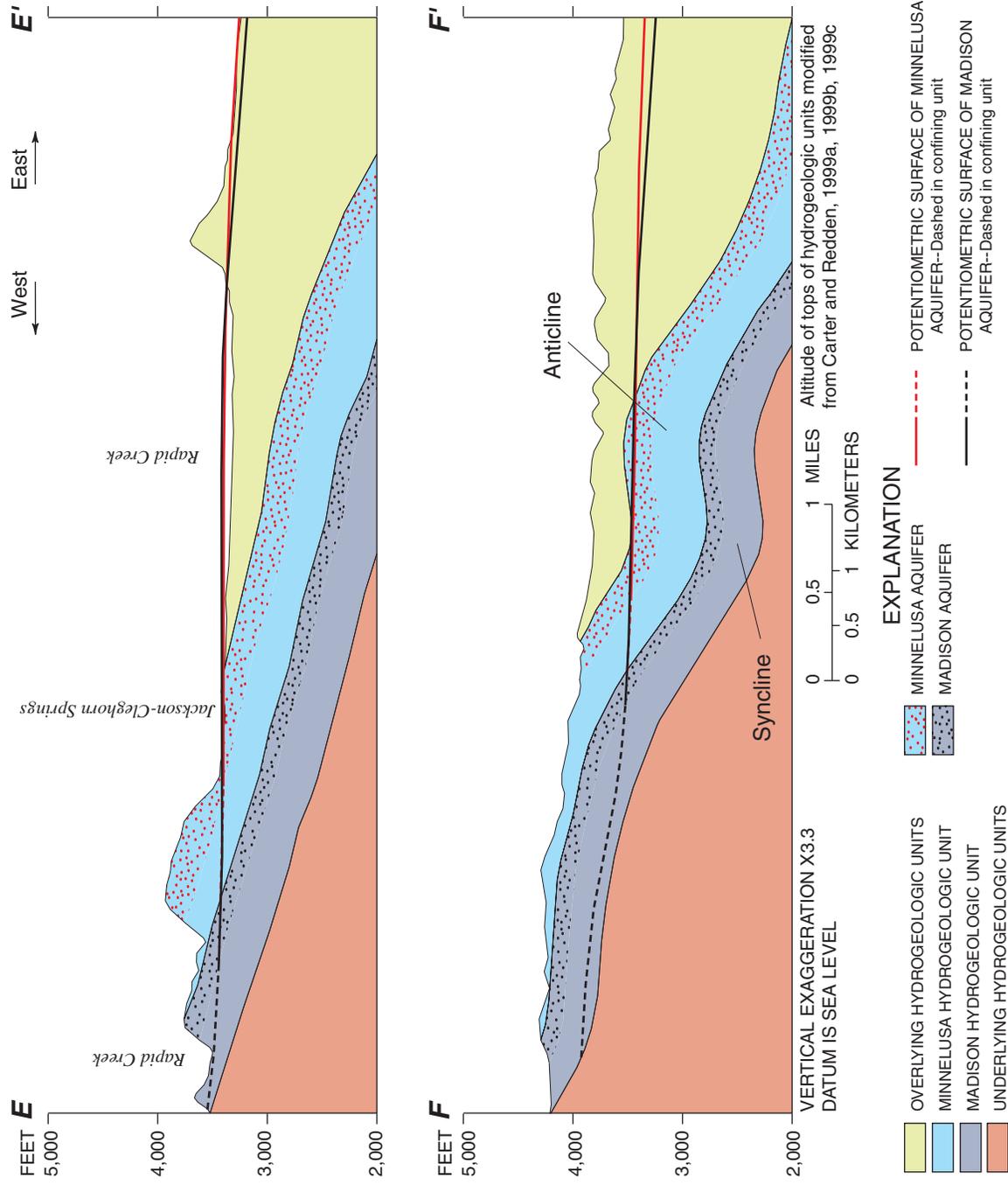


Figure 22. Hydrogeologic section showing average potentiometric surfaces of the Madison and Minnelusa aquifers (plates 1 and 2) in relation to hydrogeologic strata (location of sections shown on plates 1 and 2).—Continued

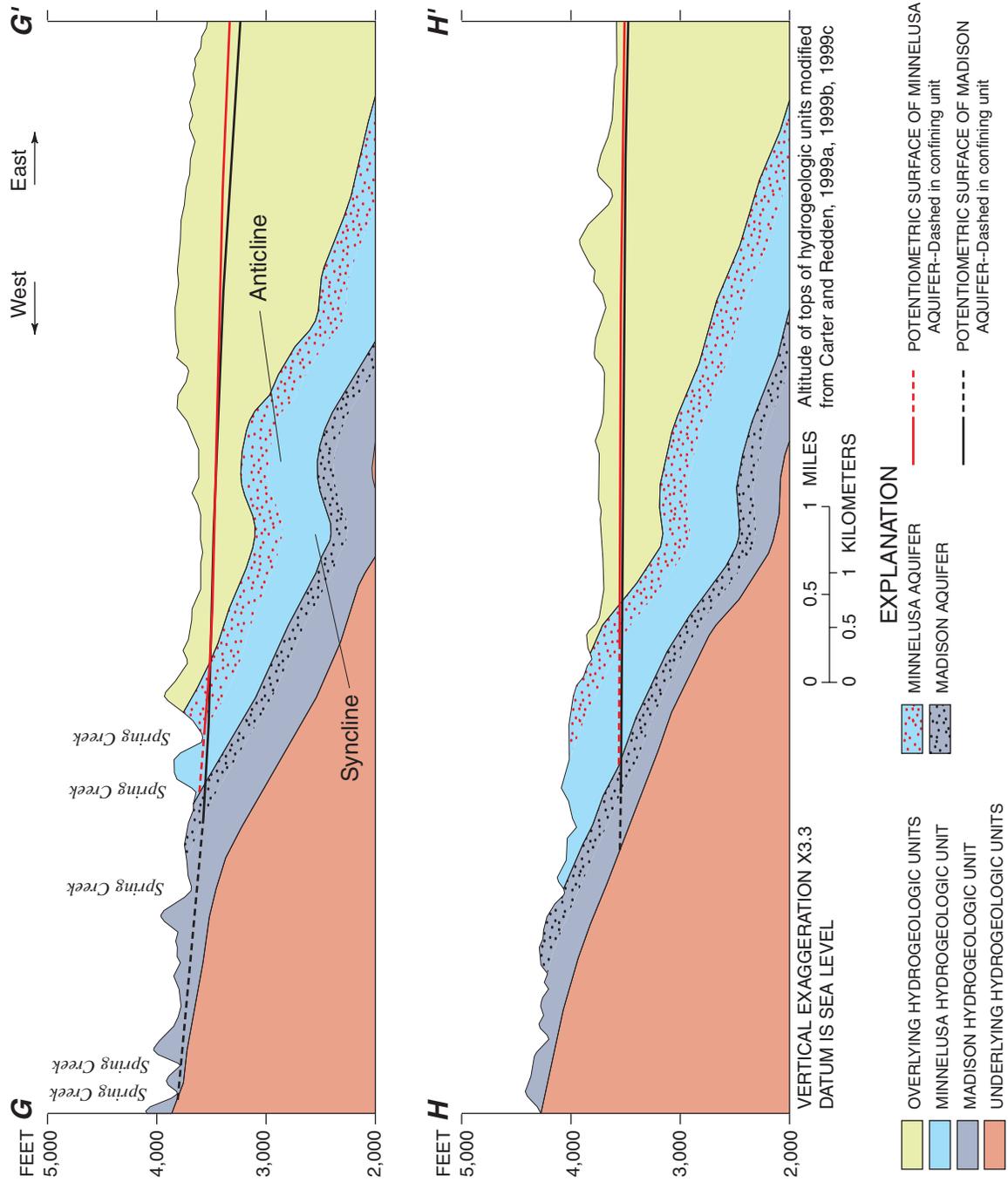


Figure 22. Hydrogeologic section showing average potentiometric surfaces of the Madison and Minnelusa aquifers (plates 1 and 2) in relation to hydrogeologic strata (location of sections shown on plates 1 and 2).—Continued

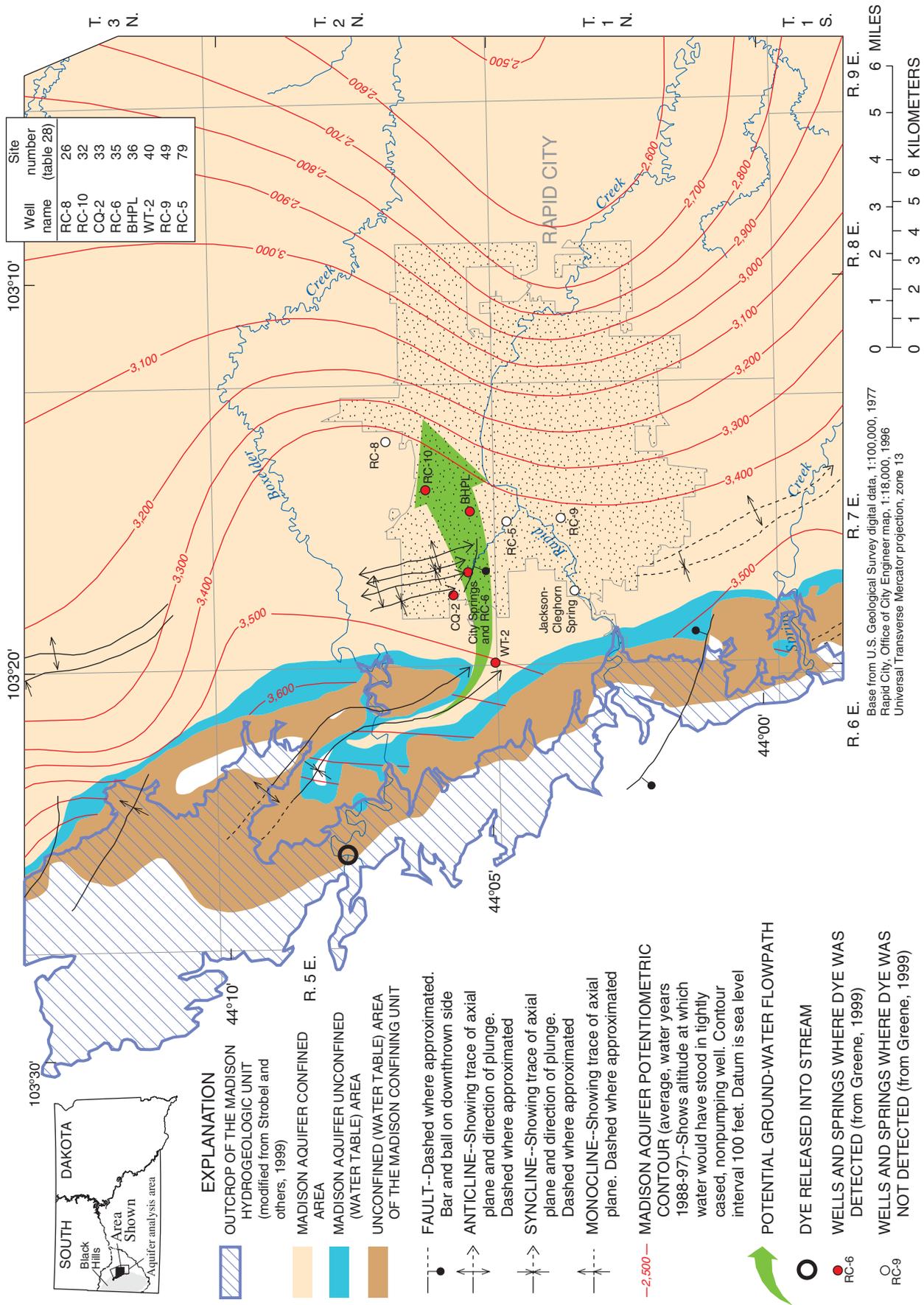


Figure 23. Generalized ground-water flowpath in the Madison aquifer determined from Boxelder Creek dye test.

Boxelder Creek, Rapid Creek, and Spring Creek have unique isotopic signatures in recharge water, which makes estimation of flowpaths possible in some locations. With respect to $\delta^{18}\text{O}$, Spring Creek is the isotopically heaviest of the three streams, Boxelder Creek is lightest, and Rapid Creek is between the two (table 6, fig. 24). Precipitation is isotopically lightest in the northwestern part of the study area and becomes heavier to the southeast. Figure 25 presents a generalized distribution of $\delta^{18}\text{O}$ in surface water and ground water near recharge areas (Naus and others, 2001).

Figure 26 shows flowpaths interpreted from isotope analysis and other information previously described. The flowpaths originate from streamflow-loss zones in the central and southern areas and from areal outcrop recharge in the northern area where the Madison outcrop is large. $\delta^{18}\text{O}$ values in the Madison aquifer in the Rapid City area (Naus and others, 2001) were grouped into three ranges: a heavy range (greater than -13 per mil) indicating Spring Creek origin, a medium range (-13 to -14 per mil) indicating Rapid Creek origin, and a light range (less than -14 per mil) indicating Boxelder Creek origin. The -13 to -14 per mil range also is representative of areal recharge to the north of Boxelder Creek (fig. 25) where the influence of areal recharge is relatively large because of the large outcrop area. Ranges indicating recharge from Rapid Creek and Boxelder Creek are heavier than the values shown in table 6 because of mixing with areal recharge from the outcrop, which is isotopically heavier. Figure 25 shows that stream basins collect water from isotopically lighter areas and recharge the aquifers in areas where areal recharge is isotopically heavier. The exception to this is Spring Creek, where the basin centroid is isotopically similar to the outcrop area near its loss zone.

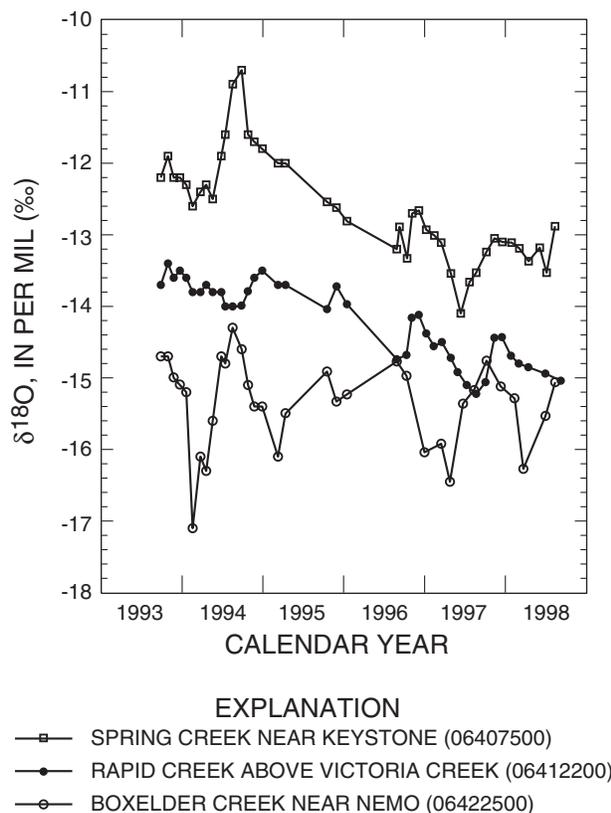
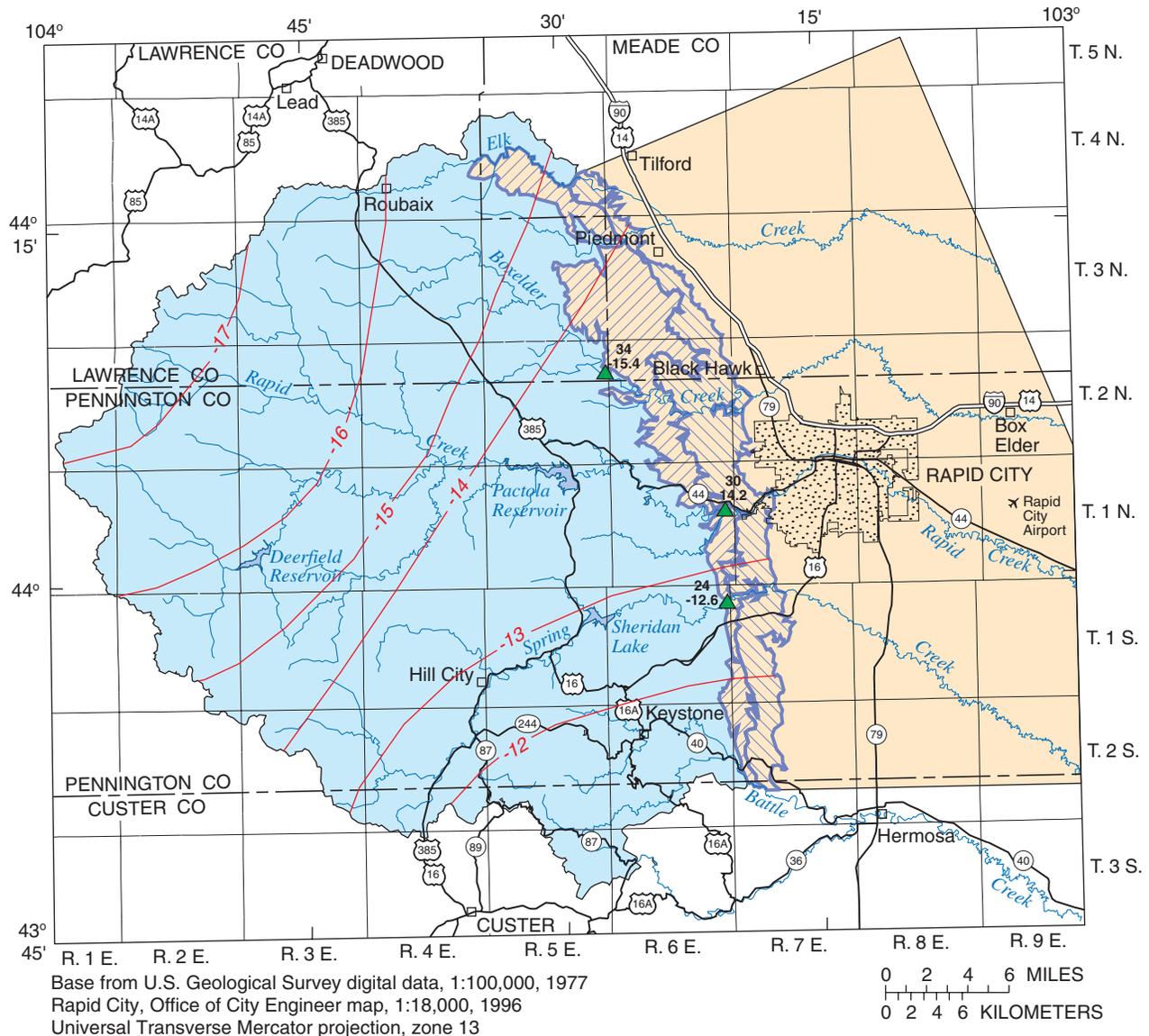


Figure 24. Temporal variation of $\delta^{18}\text{O}$ in Spring Creek, Rapid Creek, and Boxelder Creek (modified from Naus and others, 2001).

Table 6. Summary of $\delta^{18}\text{O}$ for Spring Creek, Rapid Creek, and Boxelder Creek

[Values reported by Naus and others (2001) for sampling locations upstream from loss zones]

Site number (fig. 25)	Gaging station name and number	Number of samples	$\delta^{18}\text{O}$ value (per mil)		
			Average	Maximum	Minimum
24	Spring Creek near Keystone (06407500)	41	-12.6	-10.7	-14.1
30	Rapid Creek above Victoria Creek (06412200)	39	-14.2	-13.4	-15.2
34	Boxelder Creek near Nemo (06422500)	33	-15.4	-14.3	-17.1



- EXPLANATION**
- OUTCROP OF THE MADISON HYDROGEOLOGIC UNIT (modified from Strobel and others, 1999)
 - OUTCROP OF THE MINNELUSA HYDROGEOLOGIC UNIT (modified from Strobel and others, 1999)
 - DRAINAGE AREAS CONTRIBUTING TO STREAMFLOW LOSS
 - AQUIFER ANALYSIS AREA
 - 15-- LINE OF EQUAL AVERAGE $\delta^{18}\text{O}$ VALUE--Contour interval 1 per mil (modified from Naus and others, 2001)
 - ▲ STREAMFLOW-GAGING STATION--Numbers indicate gage-site table and average $\delta^{18}\text{O}$ value in per mil

Figure 25. Generalized distribution of $\delta^{18}\text{O}$ in surface water and groundwater near recharge areas. Contours indicate $\delta^{18}\text{O}$ values of areal-recharge water, whereas $\delta^{18}\text{O}$ values of streamflow-gaging stations indicate that of streamflow recharge.

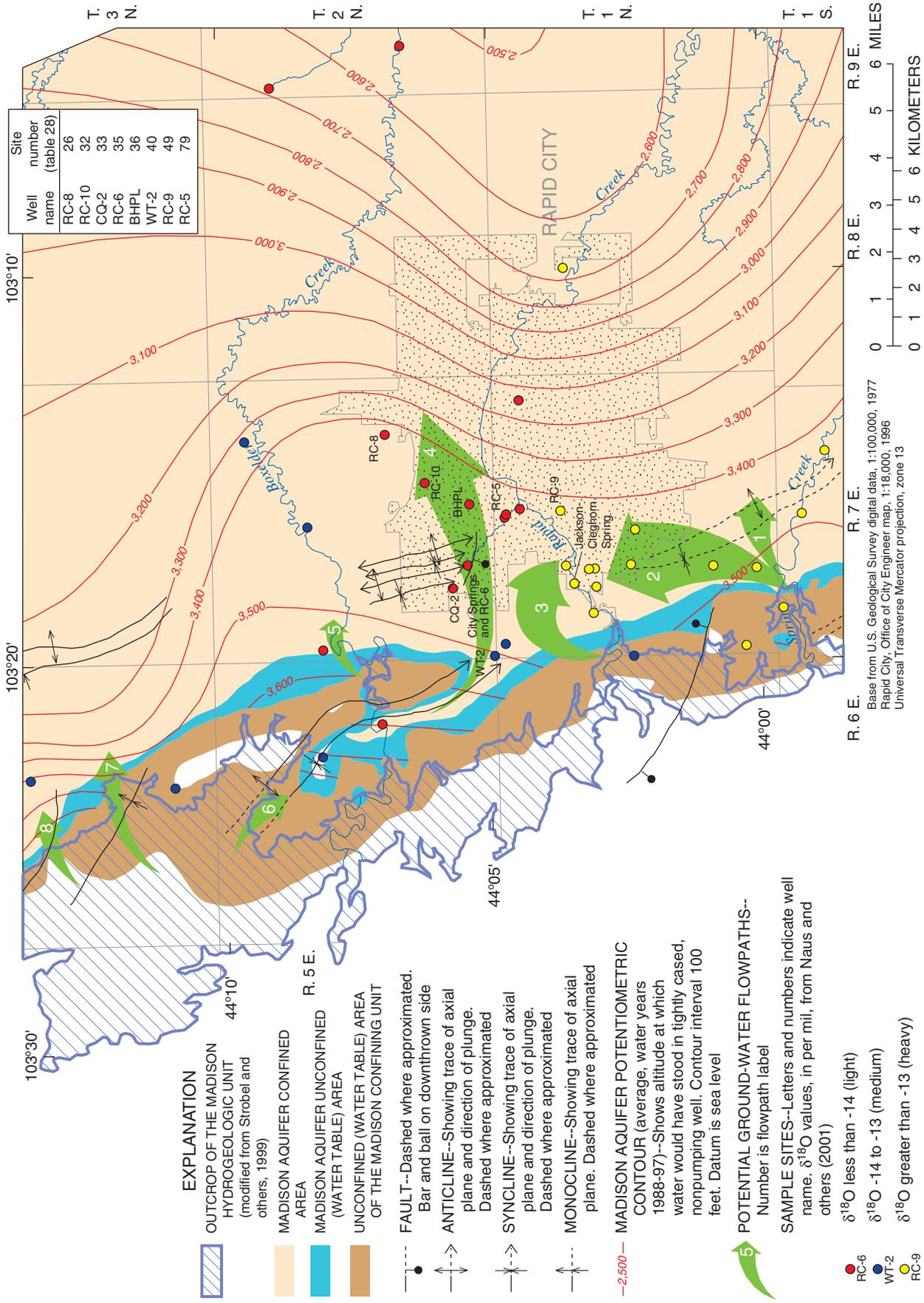


Figure 26. Generalized ground-water flowpaths in the Madison aquifer based on $\delta^{18}\text{O}$.

Ground-water flowpaths in the Madison aquifer probably are influenced by the large and stable discharge (about 22 ft³/s) of Jackson-Cleghorn Springs (Anderson and others, 1999). Naus and others (2001) reported a $\delta^{18}\text{O}$ value of -12.92 per mil (average from 1986 to 1998) for Jackson-Cleghorn Springs, which indicates a large, and probably dominant, contribution from the south (table 6). Numerous other sites in the heavy range (greater than -13 per mil) indicate a northward flowpath (fig. 26, flowpath 2) from Spring Creek as well. This interpretation is consistent with conclusions of Anderson and others (1999) and Greene (1997). Streamflow recharge from Spring Creek combined with outcrop recharge between Spring Creek and Rapid Creek is estimated at about 12 ft³/s on average (see "Water Budget" section). The steady streamflow-loss rate from Rapid Creek of about 10 ft³/s to the Madison and Minnelusa outcrops (Hortness and Driscoll, 1998) is the maximum that Rapid Creek could supply to Jackson-Cleghorn Springs. Based on these recharge rates and discharge at the spring complex, all of the streamflow recharge from Spring Creek probably moves northward during periods of lower streamflows; some of this recharge probably moves easterly during higher streamflow periods (flowpath 1). Because of these temporal variations in flow direction, ground water surrounding the Spring Creek loss zone could be a mixture of Spring Creek water and water from farther south.

Because of the sites east of the Rapid Creek loss zone indicating water from the south, Rapid Creek streamflow recharge probably moves initially northward, then eastward in the Madison aquifer (fig. 26, flowpath 3). Anderson and others (1999) drew similar conclusions based on isotope analysis. Probably, some of the water recharged from Rapid Creek discharges from Jackson-Cleghorn Springs and some continues to the east.

The light-range isotope value near flowpath 5 (fig. 26) is similar to values for Boxelder Creek and probably results from streamflow recharge that occurs within the isolated Madison outcrop on the east side of the anticline. $\delta^{18}\text{O}$ values for two sites that are farther east near Boxelder Creek are slightly heavier and probably indicate influence from areal recharge north of Boxelder Creek (flowpaths 6, 7, and 8).

The Boxelder Creek dye-tracer flowpath (fig. 23) coincides with $\delta^{18}\text{O}$ values in the light range

as well. The $\delta^{18}\text{O}$ values along flowpath 4 that are influenced by water originating from Boxelder Creek are isotopically heavier than the stream water due to mixing with areal recharge water. The two $\delta^{18}\text{O}$ values to the northeast of Rapid City in the light range indicate that flowpath 4 probably extends farther eastward in that direction.

Although light $\delta^{18}\text{O}$ at RC-5 and RC-8 (fig. 26) indicate the presence of water recharged from Boxelder Creek, dye was not detected in these wells. Non detection of dye does not necessarily indicate the absence of water recharged from Boxelder Creek, but does indicate that preferential flowpaths were not being sampled. Furthermore, flowpaths could be somewhat transient in nature, influenced by factors such as changing hydraulic head, pumping, or dual porosity.

Sufficient information is not available for estimation of flowpaths in the Minnelusa aquifer; however, increased ground-water circulation in the Minnelusa aquifer could, in part, be the result of collapse of solution features in the Madison aquifer where there is a convergence of preferential flowpaths in the high-flow area (fig. 11). The easterly bulge in the transition zone between low and high sulfate concentrations in the Minnelusa aquifer (fig. 12) is congruent with flowpath 4 (fig. 26). Some of this converging water in the Madison aquifer discharges to springs; some probably leaks upward through fractures, faults, and breccia pipes into the Minnelusa aquifer, then flows outward; and some flows eastward in the Madison aquifer. Much of the water that flows eastward in the Madison aquifer probably flows toward the zone of high transmissivity in the east-central part of the aquifer analysis area (fig. 9).

WATER-BUDGET ANALYSIS

Water-budget analysis of the Madison and Minnelusa hydrogeologic units included a 10-year period, WY88-97. Adequate data were available for this period, which includes periods of low and high recharge rates that represent long-term variability (Carter, Driscoll, and Hamade, 2001) fairly well.

Generally, ground-water levels declined during the first 5 or 6 years, then steadily rose during the remaining time (fig. 16). The 10-year period was

divided into 20 seasonal stress periods for analysis. Each water year was divided into a winter period (October 1 through March 31), which generally has relatively low precipitation, and a summer period (April 1 through September 30), which generally has greater precipitation.

The water-budget conceptual model (fig. 27) includes the inflows and outflows as well as the general flow interactions within the model. The northern and southern boundaries of the aquifer analysis area are approximately perpendicular to potentiometric contours (pls. 1 and 2) and, therefore, were assumed to be boundaries where ground-water flow does not cross (pl. 3). Isotropic conditions near boundaries also were assumed. In order to balance a water budget, it was necessary to include many other simplifying assumptions and approximations because of incomplete data in many cases.

General Concepts

General concepts and water-budget summaries are described in this section, followed by detailed discussions of methods and results for individual budget components. Three budgets were developed: (1) a dry-period budget for declining water levels, (2) a wet-period budget for rising water levels, and (3) a full-period budget. All inflows and outflows were estimated separately for the Madison and Minnelusa aquifers. In general, hydraulic head declined during the dry-period budget (October 1, 1987, to March 31, 1993, 5.5 years) resulting in a decrease in storage. Hydraulic head rose during the wet-period budget (April 1, 1993, to September 30, 1997, 4.5 years) resulting in an increase in storage. By simultaneously balancing three water budgets, initial estimates of recharge, discharge, change in storage, and hydraulic properties were refined.

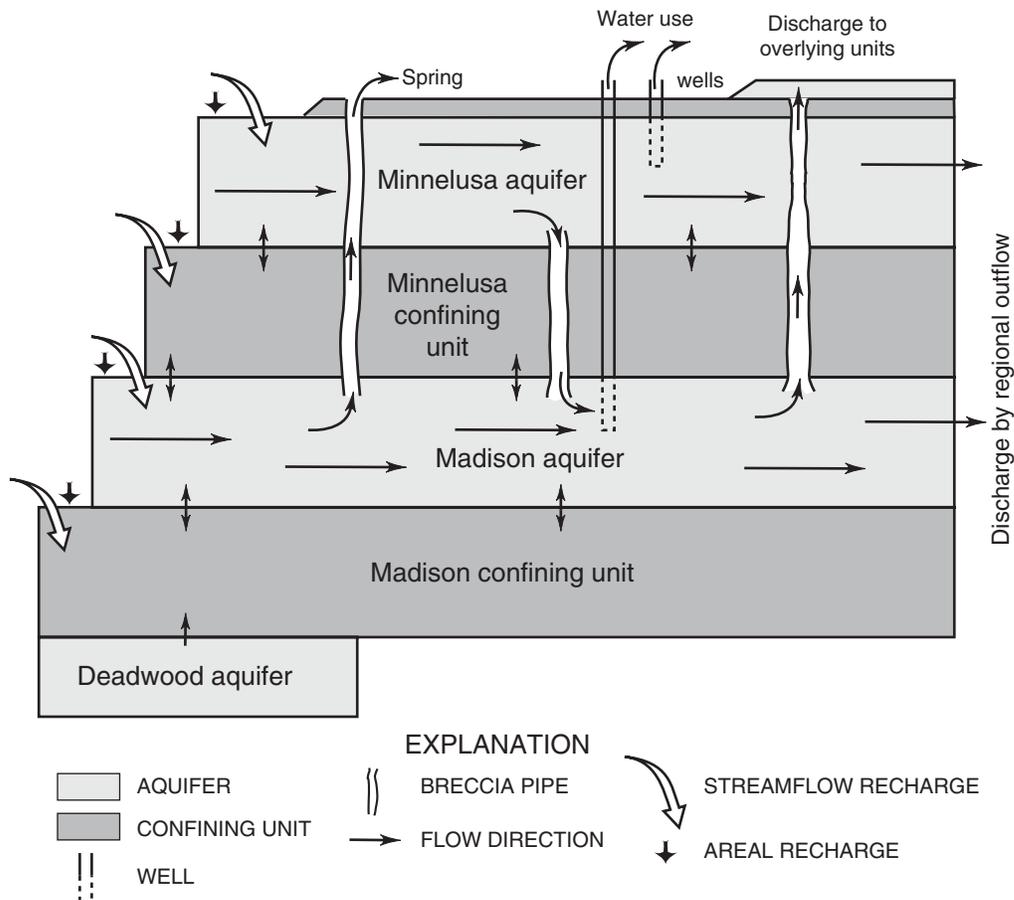


Figure 27. Conceptual model of water budget.

Water-budget results are summarized in tables 7 through 9. The equation for balancing the water budgets is the sum of inflows minus the sum of outflows, which is equal to the change in storage or:

$$\Delta S = (SD + SR + AR) - (SF + WU + OO + OE) \quad (2)$$

where

- ΔS = change in ground-water storage;
- SD = seepage from Deadwood aquifer;
- SR = streamflow recharge;
- AR = areal recharge;
- SF = springflow;
- WU = water use;
- OO = outflow to overlying units; and
- OE = outflow across eastern boundary.

Independent estimates of changes in storage for each of the three budgets could be made because there were two distinct periods of storage change during the 10-year period. Change in ground-water storage was computed by estimating the rise or fall in the potentiometric surface and multiplying this difference by area and specific yield for unconfined areas or by storage coefficient for confined areas. Hydraulic-head records for continuous-record observation wells (figs. 18 and 19, pls. 1 and 2) were used to estimate change in hydraulic head over the aquifer analysis area for the two periods. Some of the wells did not exist in October

1987, so water levels for part of the 10-year period were estimated based on comparisons to other wells with continuous records. Hydraulic head was interpolated between wells and extrapolated out to the boundaries of the aquifer analysis area. Most of the wells are located near the unconfined areas, and therefore gave a fairly accurate estimate of hydraulic head in the unconfined area. Potential error in the estimate of hydraulic-head change was estimated to be 15 percent.

Specific yield in the unconfined area is about three orders of magnitude larger than storage coefficient in the confined areas. Thus, change in storage in the confined areas is negligible by comparison, and the accuracy of hydraulic-head change in the confined areas is of little concern. The estimated hydraulic-head change over the aquifer analysis area was discretized into square cells 100 ft on a side to accurately quantify the change in storage in all areas.

Changes in hydraulic gradient across the eastern boundary were assumed to be small; therefore, regional outflow across the eastern boundary was assumed constant in all three budgets. Inflow from and outflow to adjacent hydrogeologic units also were assumed to be constant. Seepage from the Deadwood aquifer was estimated based on the approximate hydraulic head difference between the Madison and Deadwood aquifers and an estimated vertical hydraulic conductivity. A smaller amount was assumed to seep upward from the Minnelusa aquifer into overlying units.

Table 7. Average water budget for WY88-97 (full 10-year budget)

[Flow rate in cubic feet per second (ft³/s); Mdsn, Madison hydrogeologic unit; Mnls, Minnelusa hydrogeologic unit]

Component	Mdsn		Mnls		Total		Relative confidence in estimates	
	Flow rate (ft ³ /s)	Percent of Mdsn budget	Flow rate (ft ³ /s)	Percent of Mnls budget	Flow rate (ft ³ /s)	Percent of total budget		
Inflow	Streamflow recharge	38.8	63.4	6.5	32.2	45.3	61.4	High
	Areal recharge	16.1	26.3	6.1	30.2	22.2	30.1	Medium
	Seepage from Deadwood aquifer	6.3	10.3	0	0	6.3	8.5	Low
Outflow	Springflow	-30.8	-50.3	0.0	0.0	-30.8	41.7	High
	Water use	-6.7	10.9	-3.4	16.8	-10.1	13.7	High
	Leakage to units overlying Mnls	0	0	-2.0	9.9	-2.0	2.7	Low
	Regional outflow	-11.0	18.0	-11.2	55.4	-22.2	30.1	Medium
Leakage between Madison and Minnelusa hydrogeologic units		-7.6	12.4	7.6	37.6	0	0	Medium
Change in storage (as a flow rate)		5.1	8.3	3.6	17.8	8.7	11.8	Medium

Table 8. Average water budget for October 1987 through March 1993 (dry period)[Flow rate in cubic feet per second (ft³/s); Mdsn, Madison hydrogeologic unit; Mnls, Minnelusa hydrogeologic unit]

Component		Mdsn		Mnls		Total		Relative confidence in estimates
		Flow rate (ft ³ /s)	Percent of Mdsn budget	Flow rate (ft ³ /s)	Percent of Mnls budget	Flow rate (ft ³ /s)	Percent of total budget	
Inflow	Stream-loss recharge	24.1	51.9	2.8	16.7	26.9	46.7	High
	Areal recharge	8.2	17.7	3.1	18.5	11.3	19.6	Medium
	From Deadwood aquifer	6.3	13.6	0	0	6.3	10.9	Low
Outflow	Springflow	-25.3	54.5	0	0	-25.3	43.9	High
	Water use	-4.5	9.7	-3.6	21.4	-8.1	14.1	High
	Leakage to units overlying Mnls	0	0	-2.0	11.9	-2.0	3.5	Low
	Regional outflow	-11.0	23.7	-11.2	66.7	-22.2	38.5	Medium
Leakage between Madison and Minnelusa hydrogeologic units		-5.6	12.1	5.6	33.3	0	0	Medium
Change in storage (as a flow rate)		-7.8	16.8	-5.3	31.5	-13.1	22.7	Medium

Table 9. Average water budget for April 1993 to September 1997 (wet period)[Flow rate in cubic feet per second (ft³/s); Mdsn, Madison hydrogeologic unit; Mnls, Minnelusa hydrogeologic unit]

Component		Mdsn		Mnls		Total		Relative confidence in estimates
		Flow rate (ft ³ /s)	Percent of Mdsn budget	Flow rate (ft ³ /s)	Percent of Mnls budget	Flow rate (ft ³ /s)	Percent of total budget	
Inflow	Stream-loss recharge	56.9	63.9	11.1	35.6	68.0	61.8	High
	Areal recharge	25.9	29.1	9.8	31.4	35.7	32.5	Medium
	From Deadwood aquifer	6.3	7.1	0	0	6.3	5.7	Low
Outflow	Springflow	-37.4	42.0	0	0	-37.4	34.0	High
	Water use	-9.3	10.4	-3.2	10.3	-12.5	11.4	High
	Leakage to units overlying Mnls	0	0	-2.0	6.4	-2.0	1.8	Low
	Regional outflow	-11.0	12.3	-11.2	35.9	-22.2	20.2	Medium
Leakage between Madison and Minnelusa hydrogeologic units		-10.3	11.6	10.3	33.0	0	0	Medium
Change in storage (as a flow rate)		21.1	23.7	14.8	47.4	35.9	32.6	Medium

Streamflow recharge, springflow, and water use were known or estimated with a relatively high level of confidence because these estimates generally were based on measured values. Estimates of areal recharge, outflow across the eastern boundary, leakage between aquifer units, inflow and outflow to adjacent hydrogeologic units, and change in storage were less certain. Simultaneously balancing the three water budgets provided an additional constraint to test estimates of the less certain water-budget components. Preliminary estimates of these less certain components were modified within plausible ranges. Transmissivities were adjusted within reasonable ranges to modify calculations of outflow across the eastern boundary. Estimates of changes in storage were modified by adjusting specific yield and estimated hydraulic-head change. Leakage between the Madison and Minnelusa hydrogeologic units was estimated by balancing the three water budgets.

Although the solution to the budget equation was not unique, the requirement that all three budgets simultaneously balance constrained the solution and improved estimates of specific yield and aquifer transmissivity near the eastern boundary. The two short-period budgets were especially sensitive to changes in specific yield, and thus, storage volume. Because the net change in storage for the 10-year period was small, the 10-year budget was more sensitive to transmissivity near the eastern boundary, which affected regional outflow.

Flow rates for selected water-budget components are listed in table 10 for each 6-month stress period. Average streamflow recharge to the Madison hydrogeologic unit was about 2.4 times that of areal recharge, while streamflow recharge to the Minnelusa hydrogeologic unit was about equal to areal recharge (table 7). This contrast is primarily due to the larger loss thresholds on the Madison outcrop and because streams lose to the Madison outcrop first, which often leaves little or no flow to cross the Minnelusa outcrop.

The Minnelusa hydrogeologic unit received about 7.6 ft³/s or 38 percent of its total inflow (table 7) in the form of net leakage from the Madison hydrogeologic unit. The mechanisms that produce leakage between the Madison and Minnelusa aquifers are probably similar to those responsible for artesian springflow from the Madison aquifer. Therefore, the estimated net leakage from the Madison to the Minnelusa hydrogeologic unit of about 7.6 ft³/s is plausible in comparison to the average flow from all Madison aquifer springs passing through the Minnelusa hydrogeologic unit,

which was about 31 ft³/s (tables 7 and 10). In general, hydraulic head was higher at the end of the 10 years than at the beginning. The largest discharge component from the Minnelusa hydrogeologic unit was regional outflow, whereas the largest discharge from the Madison hydrogeologic unit was springflow.

In addition to the 10-year water budget, two additional water budgets representing the first and second parts of the 10-year period were useful for refining the estimates of less certain water budget components (tables 8 and 9). The three largest total-budget components for the 10-year period (table 7) were streamflow recharge, springflow, and areal recharge. The largest total-budget components for the dry period (table 8) were streamflow recharge, springflow, and regional outflow, whereas the largest components for the wet period (table 9) were streamflow recharge, springflow, and change in storage. The total recharge rate during the wet period was about 110 ft³/s or about 2.4 times the recharge rate during the dry period, which was 45 ft³/s.

Seepage from Deadwood Aquifer

Underlying the Madison hydrogeologic unit are older rocks that potentially provide an additional source of recharge to the Madison hydrogeologic unit. These rocks primarily consist of the Cambrian-age Deadwood Formation, which contains a sandstone aquifer, and underlying Precambrian-age igneous and metamorphic rocks. Although the lower part of the Madison hydrogeologic unit generally is a confining unit, fractured and weathered areas near the outcrop provide paths for movement of water from these older rocks into the Madison hydrogeologic unit.

The seepage rate from the Deadwood aquifer into the Madison aquifer was estimated as 6.3 ft³/s within the aquifer analysis area using Darcy's Law. Darcy's Law is given by the equation:

$$Q = K_v A \frac{\Delta H}{\Delta L} \quad (3)$$

where

Q = flow rate [V/T];

K_v = vertical hydraulic conductivity for the Madison confining unit [L/T];

A = area where upward leakage takes place [L²];

ΔH = hydraulic-head difference between the Deadwood and Madison aquifers [L]; and

ΔL = vertical distance that corresponds to the hydraulic head difference [L].

Table 10. Selected water-budget components for 6-month stress periods

[Flow rates in cubic feet per second (ft³/s)]

Stress period	Dates	Madison hydrogeologic unit				Minnelusa hydrogeologic unit			
		Streamflow recharge	Areal recharge	Springflow	Water use	Streamflow recharge	Areal recharge	Water use	
Dry period									
Winter 1988 (W-88)	October 1, 1987 - March 31, 1988	15.6	0.9	26.6	1.9	2.0	0.2	2.9	
Summer 1988 (S-88)	April 1, 1988 - September 30, 1988	19.0	1.9	25.7	4.7	2.2	.5	5.7	
Winter 1989 (W-89)	October 1, 1988 - March 31, 1989	12.3	1.6	25.4	1.7	1.8	.6	1.7	
Summer 1989 (S-89)	April 1, 1989 - September 30, 1989	18.0	10.0	25.1	3.4	2.1	4.0	3.7	
Winter 1990 (W-90)	October 1, 1989 - March 31, 1990	16.5	3.2	25.2	1.8	2.0	1.0	2.9	
Summer 1990 (S-90)	April 1, 1990 - September 30, 1990	35.3	7.4	25.2	4.2	3.2	4.1	4.9	
Winter 1991 (W-91)	October 1, 1990 - March 31, 1991	15.7	1.8	24.8	2.9	1.8	.5	3.3	
Summer 1991 (S-91)	April 1, 1991 - September 30, 1991	54.4	52.5	25.8	7.2	8.8	19.5	4.6	
Winter 1992 (W-92)	October 1, 1991 - March 31, 1992	27.5	2.4	25.0	5.4	2.2	.8	2.6	
Summer 1992 (S-92)	April 1, 1992 - September 30, 1992	29.9	5.9	24.8	12.5	2.2	2.3	4.3	
Winter 1993 (W-93)	October 1, 1992 - March 31, 1993	20.6	2.2	25.0	3.7	2.3	.5	2.6	
Average for dry period		24.1	8.2	25.3	4.5	2.8	3.1	3.6	
Wet period									
Summer 1993 (S-93)	April 1, 1993 - September 30, 1993	69.4	46.0	26.8	13.7	14.1	19.9	4.0	
Winter 1994 (W-94)	October 1, 1993 - March 31, 1994	39.6	2.9	26.3	6.2	3.9	.5	2.1	
Summer 1994 (S-94)	April 1, 1994 - September 30, 1994	47.2	2.0	26.2	15.1	9.4	1.0	4.1	
Winter 1995 (W-95)	October 1, 1994 - March 31, 1995	32.3	6.5	34.8	5.8	2.7	1.5	2.3	
Summer 1995 (S-95)	April 1, 1995 - September 30, 1995	67.4	72.7	36.8	11.0	14.9	25.7	3.7	
Winter 1996 (W-96)	October 1, 1995 - March 31, 1996	46.1	5.8	37.9	3.1	3.8	1.3	2.1	
Summer 1996 (S-96)	April 1, 1996 - September 30, 1996	71.5	31.1	39.1	11.3	17.5	11.5	4.0	
Winter 1997 (W-97)	October 1, 1996 - March 31, 1997	60.6	9.6	53.6	5.5	8.9	3.2	2.5	
Summer 1997 (S-97)	April 1, 1997 - September 30, 1997	77.8	56.3	55.0	12.0	24.4	23.3	4.1	
Average for wet period		56.9	25.9	37.4	9.3	11.1	9.8	3.2	
Overall average		38.8	16.1	30.8	6.7	6.5	6.1	3.4	

The area where upward seepage is considered to take place is between the western extent of the Madison outcrop and the Inyan Kara Group outcrop (171 mi²; fig. 4). A general range of K_v values for limestone and dolomite is about 10^{-4} to 10^{-2} ft/d (Domenico and Schwartz, 1990, p. 67). K_v is likely to be higher toward the outcrop because of uplift and fracturing and lower toward the east. East of the Inyan Kara Group outcrop, upward seepage is assumed to be minimal and is neglected. As an average for the area west of the Inyan Kara outcrop, K_v was taken as 3×10^{-4} ft/d. Hydraulic head in the Deadwood aquifer was estimated to be about 100 ft on average above the Madison aquifer in the seepage area. The estimated length of ΔL includes the thickness of the Madison confining unit (250 ft) plus about one-half of the Deadwood Formation thickness (100 ft) for a total of 350 ft. The Whitewood and Winnipeg Formations are absent throughout most of the aquifer analysis area.

Streamflow Recharge

Streams lose much or all of their flow into swallow holes and fractures on the Madison and Minnelusa outcrops. Swallow holes are solutional features that extend upward to the land surface and intercept stream water. The Madison outcrop receives preferential recharge because of its upstream location. Large streamflow recharge rates of more than 25 ft³/s to the Madison aquifer (Hortness and Driscoll, 1998) may have led to extensive karst development near streamflow-loss areas. Streamflow recharge to the Minnelusa aquifer also occurs but generally in smaller quantities. A description of methods used, a summary of streamflow-recharge estimates, and details on individual loss zones follow.

Methods

Drainage areas that contribute flow to the streamflow recharge are delineated for the western part of the study area (pl. 3). Although streamflow-loss zones are shown extending across the entire Madison and Minnelusa outcrop areas, losses are generally concentrated in certain areas of the outcrops. Because the Madison aquifer is more permeable, much of the streamflow lost to the confining unit located on the western part of the outcrop probably reaches the aquifer

via underground conduits. An example of this can be seen along Boxelder Creek where much of the streamflow lost to the western part of the Madison outcrop reemerges as springflow and then disappears again in the eastern part of the loss zone. Rahn and Gries (1973) determined from dye testing that Gravel, Doty, and Dome Springs (pls. 1 and 2) on the Madison outcrop along Boxelder Creek are directly connected to upstream losses. At outcrop areas of the Minnelusa hydrogeologic unit, ground water probably moves from confining unit to aquifer in a similar way because of weathering and increased permeability of the confining unit.

Streamflow recharge is calculated for 10 streams that cross the Madison and Minnelusa outcrops in the study area. Daily streamflow records are available for the larger streams that lose flow to the outcrops, including Battle, Spring, Rapid, Boxelder, and Elk Creeks (pl. 3 and table 11). Loss thresholds were determined by Hortness and Driscoll (1998) and were used if available, but were not determined for some of the smaller streams and were not always separated by formation (table 11). According to Hortness and Driscoll (1998), all of the flow in these streams up to a threshold is lost to outcrops of Paleozoic rocks. Measured or estimated daily streamflow up to an estimated loss threshold is assumed to recharge the Madison hydrogeologic unit, and once that threshold flow is exceeded, recharge to the Minnelusa hydrogeologic unit (not to exceed its threshold) can occur. A diagram representing streamflow losses from Elk Creek (fig. 28) illustrates that during low-flow periods, such as WY88-90, the Minnelusa hydrogeologic unit may receive little or no streamflow recharge.

In some cases, gages were not located at the western contact of the Madison hydrogeologic unit, but were farther upstream. For these streams, the gaged flow was adjusted proportional to drainage area (table 11). Some streams were continuously gaged for only part of the 10-year period, and a few smaller basins were not gaged at all. Missing data for continuously gaged streams were synthesized using linear regression of the measured streamflow against streamflow in a nearby basin. The equation of the regression line was used to estimate missing parts of the hydrograph. Streamflow records for ungaged streams were estimated by proportioning flows of nearby gaged streams relative to drainage area size.

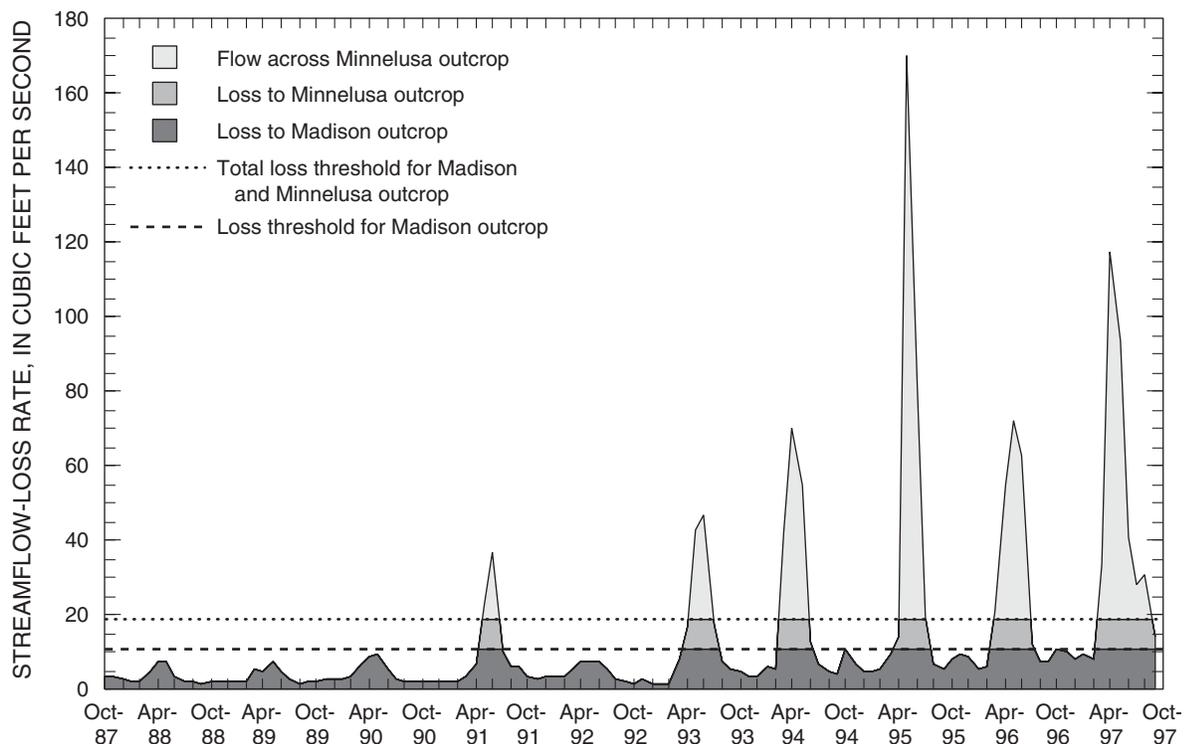


Figure 28. Hydrograph of monthly mean streamflow losses from Elk Creek to the Madison and Minnelusa outcrops. Loss thresholds estimated by Hortness and Driscoll (1998).

In the study area, the Minnelusa hydrogeologic unit contains “unsaturated areas,” as previously defined (see “Concepts of the Ground-Water Flow System” section), across about 73 percent of the outcrop. Plate 2 shows the extent of saturated and unsaturated areas in relation to the outcrops. About 36 percent of the total length of the losing streams crossing the Minnelusa outcrop is on these unsaturated areas. Much of the streamflow loss to the unsaturated areas of the Minnelusa outcrop probably reaches the Madison aquifer because of fractures and breccias that extend through the outcrop. According to Gott and others (1974), solution breccias in the Minnelusa Formation permit rapid infiltration of ground water that probably recharges the Madison aquifer. However,

because of easterly dipping beds, the movement of infiltrating water probably has a horizontal component and some will reach the Minnelusa hydrogeologic unit’s water table. Because of the lack of data to quantify the proportion, 50 percent of this water infiltrating the unsaturated area on the Minnelusa outcrop was assumed to recharge the Madison aquifer and 50 percent to recharge the Minnelusa aquifer. Streamflow losses on the Minnelusa outcrop were assumed to be evenly distributed across the length of the stream reach. Therefore, the fraction of redistributed recharge from the Minnelusa outcrop is equal to the ratio of the unsaturated-area reach length to the total Minnelusa outcrop reach length multiplied by one-half of the loss across the Minnelusa outcrop:

$$\text{Redistributed recharge} = \left(\frac{\text{Dry reach length}}{\text{Total outcrop reach length}} \right) \times \left(\frac{\text{Minnelusa outcrop loss}}{2} \right). \quad (4)$$

Table 11. Selected data for drainage areas, streamflow, and gaging stations

[WY, water year; Mdsn, Madison hydrogeologic unit; Mlns, Minnelusa hydrogeologic unit; mi², square miles; ft³/s, cubic feet per second; mi, miles; --, undetermined; NA, not applicable]

Drainage area identifier (pl. 3)	Drainage areas contributing to streamflow-loss zones							Streamflow-loss-zone data				Streamflow-gaging stations used in calculation of streamflow loss or springflow ¹			
	Name	Area (mi ²)	Average annual precipitation ² 1961-98 (inches)	Average annual streamflow, WY88-97 (ft ³ /s)	Average annual yield, WY88-97 (inches)	Loss-zone stream reach length		Approximate loss threshold		Gage-site number ³ (pl. 3)	Station identification number	Station name	Drainage area ⁴ (mi ²)		
						Mdsn (mi)	Mlns (mi)	Mdsn (ft ³ /s)	Mlns (ft ³ /s)						
A	Battle Creek	66.0	21.1	13.1	2.70	1.2	--	5 ¹ 14	6 ⁰	14	06404000	Battle Creek near Keystone	58.4		
B	Deadman Gulch	1.49	19.9	7.2	71.82	1.5	4.8	7 ²	7 ⁴						
C	Rockerville Gulch	3.68	19.5	7.7	72.58	.8	4.7	7 ²	7 ⁴						
D	Spring Creek	163	20.6	25.3	2.11	2.3	2.4	8 ² 1	5 ³ .5	24	06407500	Spring Creek near Keystone	163		
E	Victoria Creek	11.1	19.8	71.6	71.96	.6	NA	8 ² .1	NA						
F	Rapid Creek	355	22.4	59.0	2.26	2.2	1.8	8	2	30	06412200	Rapid Creek above Victoria Creek	355		
G	Unnamed tributary	.92	20.1	7.1	71.48	1.5	5.4	7 ²	7 ⁴						
H	Boxelder Creek	103	23.1	25.1	3.31	7.9	4.6	7 ³ 0	7 ¹ 6	34	06422500	Boxelder Creek near Nemo	96		
I	Little Elk Creek	11.6	23.4	71.9	72.22	.1	1.5	8 ^{.7}	8 ² .6						
J	Elk Creek	35.1	26.1	14.0	5.42	8.5	2.4	8 ¹ 1	8 ⁸	39	06424000	Elk Creek near Roubaix	21.5		
	NA	--	--	--	--	NA	NA	NA	NA	43	44182310324100	Elk Creek below trib from north, near Tilford	--		
	NA	--	--	--	--	NA	NA	NA	NA	44	441701103282700	Elk Creek below Madison outcrop	--		
	NA	--	--	--	--	NA	NA	NA	NA	45	441614103253300	Elk Creek at Minnekahta outcrop	--		

Table 11. Selected data for drainage areas, streamflow, and gaging stations—Continued

[WY, water year; Mdsn, Madison hydrogeologic unit; Mnlis, Minnelusa hydrogeologic unit; mi², square miles; ft³/s, cubic feet per second; mi, miles; --, undetermined; NA, not applicable]

Drainage areas contributing to streamflow-loss zones		Streamflow-loss-zone data			Streamflow-gaging stations used in calculation of streamflow loss or springflow ¹							
		Loss-zone stream reach length	Approximate loss threshold									
Drainage area identifier (pl. 3)	Name	Area (mi ²)	Average annual precipitation ² 1961-98 (inches)	Average annual streamflow, WY88-97 (ft ³ /s)	Average annual yield, WY88-97 (inches)	Mdsn (mi)	Mnlis (mi)	Mdsn (ft ³ /s)	Mnlis (ft ³ /s)	Gage-site number ³ (pl. 3)	Station name	Drainage area ⁴ (mi ²)
NA	--	--	--	--	--	NA	NA	NA	NA	⁹ 06413650	Lime Creek at mouth, at Rapid City ⁹	--
NA	--	--	--	--	--	NA	NA	NA	NA	⁹ 06413800	Deadwood Avenue drain at mouth, at Rapid City ⁹	--

¹Flow rates from U.S. Geological Survey (1989-98).

²Calculated from precipitation distribution for 1961-98 (Driscoll, Hamade, and Kenner, 2000).

³Site number corresponds to site number in Hortness and Driscoll, 1998.

⁴Drainage area from U.S. Geological Survey (1967-97) except for site number 14, which is a corrected value.

⁵Carter, Driscoll, and Hamade, 2001.

⁶Generally, there is a net gain in streamflow in this reach. During very dry periods, some streamflow loss to the Minnelusa hydrogeologic unit could be possible, however, the impact on the water budget was assumed to be negligible.

⁷Estimated.

⁸Hortness and Driscoll, 1998.

⁹Gaging station used to estimate springflow.

Estimation of Streamflow Recharge

Estimated streamflow recharge is presented in table 12, which summarizes recharge for both continuously-gaged and ungaged streams. Values in table 12 have been adjusted, when appropriate, to reflect redistribution of estimated recharge to the Minnelusa outcrop that infiltrates into the Madison hydrogeologic unit. Because most of the loss occurs on the Madison outcrop, total streamflow recharge to the Madison hydrogeologic unit was only increased by about 1 percent due to redistribution, but streamflow recharge to the Minnelusa hydrogeologic unit decreased by about 8 percent.

Total estimated streamflow recharge rates for the Madison hydrogeologic unit for summer periods ranged from about 18 ft³/s during dry years to almost 80 ft³/s during wet years (table 12). Total streamflow recharge rates for the Madison hydrogeologic unit for winter periods ranged from about 12 ft³/s during dry years to about 60 ft³/s during wet years. Average streamflow recharge to the Minnelusa hydrogeologic unit (about 7 ft³/s) was only about 14 percent of the combined streamflow recharge to the Madison and Minnelusa aquifers (45 ft³/s). Increases in recharge rates during wet years largely were due to increases in the duration and quantity of stream base flow that was maintained over longer periods of time.

Continuously Gaged Streams

Calculations of streamflow recharge to the Madison and Minnelusa hydrogeologic units for continuously gaged streams are described in this section. Different loss zones required different approaches depending on loss-zone characteristics and gage location.

Battle Creek

Estimated streamflow recharge from Battle Creek to the Madison hydrogeologic unit averaged about 2.7 ft³/s (table 12). Streamflow recharge to the Minnelusa hydrogeologic unit was assumed to be zero because the stream gains flow as a result of springflow along the Minnelusa outcrop (Hortness and Driscoll, 1998). Battle Creek exceeded its loss threshold to the Madison hydrogeologic unit 16 percent of the time during WY88-97 and did not flow at the gage upstream from the loss zone 6 percent of the time. Gage site 14 (pl. 3) is located about 2 mi upstream from the loss zone, and the drainage area for that location is about 88 percent of the total basin area contributing to the

loss zone. Therefore, the gaged flow was increased proportionately to account for the ungaged flow. This synthetic record was used to compute streamflow recharge.

Spring Creek

Estimated streamflow recharge from Spring Creek to the Madison and Minnelusa hydrogeologic units averaged 9.9 and 0.8 ft³/s, respectively (table 12). Although Spring Creek is impounded by a dam at Sheridan Lake, streamflow results primarily from uncontrolled overflow and fluctuates similarly to uncontrolled streams in the study area. Spring Creek has the second largest drainage area in the study area (table 11) and accounted for 24 percent of the total streamflow recharge to the Madison and Minnelusa hydrogeologic units during the 10-year period. Spring Creek exceeded its loss threshold of about 25 ft³/s to the Madison and Minnelusa hydrogeologic units 21 percent of the time and did not flow at the gage above the loss zone 5 percent of time during the 10-year period. The continuous gage above the Spring Creek loss zone (pl. 3, gage site 24) accounts for all of the flow contributing to the loss zone and, therefore, required no adjustments to the measured flow.

Rapid Creek

Estimated streamflow recharge from Rapid Creek to the Madison and Minnelusa hydrogeologic units averaged 8.0 and 2.0 ft³/s, respectively (table 12). Rapid Creek is regulated by releases from Pactola Reservoir, and releases greater than the loss threshold are generally maintained. Although Rapid Creek has the largest drainage area in the study area, the stream has a relatively small loss threshold of about 10 ft³/s (Hortness and Driscoll, 1998) for the Madison and Minnelusa hydrogeologic units combined. Despite the small loss threshold, Rapid Creek accounted for about 22 percent of the total streamflow recharge to the Madison and Minnelusa hydrogeologic units because flow was seldom less than the threshold. Hortness and Driscoll (1998) did not estimate separate loss thresholds for the two hydrogeologic units; however, investigations by Hines (1991) indicate that about 80 percent of the total loss threshold can be attributed to the Madison hydrogeologic unit.

Flow from Tittle Springs, located on the Madison outcrop near Rapid Creek (pl. 1), probably originates from Rapid Creek (Hines, 1991). Therefore, this springflow was not included in streamflow-recharge or water-budget calculations.

Table 12. Streamflow recharge rates to the Madison and Minnelusa hydrogeologic units

[Recharge rates in cubic feet per second. Mdsn, Madison; Mnl, Minnelusa; W, winter; S, summer (W-88 = winter 1988)]

Stress period	Continuously gaged streams									
	Battle Creek ¹		Spring Creek		Rapid Creek		Boxelder Creek		Elk Creek ¹	
	Mdsn	Mnl	Mdsn	Mnl	Mdsn	Mnl	Mdsn	Mnl	Mdsn	Mnl
Dry Period										
W-88	0.3	0.0	1.1	0.0	8.0	2.0	4.2	0.0	1.2	0.0
S-88	.5	.0	2.5	.0	8.0	2.0	5.7	.0	1.5	.0
W-89	.2	.0	.2	.0	7.9	1.7	2.8	.0	.8	.0
S-89	.7	.0	1.8	.0	8.0	2.0	5.3	.0	1.5	.0
W-90	1.1	.0	1.3	.0	8.0	1.9	4.3	.0	1.2	.0
S-90	4.1	.0	11.2	.9	8.0	2.0	7.7	.0	2.1	.0
W-91	.8	.0	3.1	.0	8.0	1.8	2.4	.0	.7	.0
S-91	4.4	.0	16.8	1.9	8.0	2.0	17.1	2.7	3.8	1.0
W-92	1.5	.0	6.7	.0	8.0	2.0	7.8	.0	1.9	.0
S-92	2.3	.0	8.2	.0	8.0	2.0	6.9	.0	2.9	.1
W-93	1.1	.0	4.1	.1	8.0	1.9	5.0	.1	1.3	.1
Average dry	1.5	.0	5.2	.3	8.0	1.9	6.3	.3	1.7	.1
Wet Period										
S-93	5.7	.0	19.9	2.6	8.0	2.0	25.3	5.5	4.8	2.3
W-94	3.3	.0	11.1	.2	8.0	2.0	11.2	.5	3.0	.7
S-94	2.1	.0	11.0	.9	8.0	2.0	19.2	3.8	4.1	1.6
W-95	2.0	.0	7.1	.1	8.0	2.0	9.7	.1	3.5	.2
S-95	5.0	.0	18.0	2.1	8.0	2.0	25.5	6.7	4.6	2.0
W-96	3.1	.0	13.1	.1	8.0	2.0	14.1	.5	4.2	.5
S-96	5.2	.0	20.3	2.5	8.0	2.0	28.8	7.6	3.4	3.4
W-97	4.6	.0	18.5	1.5	8.0	2.0	21.5	2.1	3.1	1.9
S-97	6.0	.0	21.0	3.4	8.0	2.0	32.3	12.6	3.0	3.9
Average wet	4.1	.0	15.6	1.5	8.0	2.0	20.8	4.4	3.7	1.8
Overall average	2.7	.0	9.9	.8	8.0	2.0	12.8	2.1	2.6	.9

Table 12. Streamflow recharge rates to the Madison and Minnelusa hydrogeologic units—Continued

[Recharge rates in cubic feet per second. Mdsn, Madison; Mnls, Minnelusa; W, winter; S, summer (W-88 = winter 1988)]

Stress period	Ungaged streams										Total of all streams		Total Mdsn Mnls
	Deadman Gulch		Rockerville Gulch		Victoria Gulch		Unnamed tributary		Little Elk Creek				
	Mdsn	Mnls	Mdsn	Mnls	Mdsn	Mnls	Mdsn	Mnls	Mdsn	Mnls	Mdsn	Mnls	
Dry Period													
W-88	0.1	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.4	0.0	15.6	2.0	17.6
S-88	.0	.0	.1	.0	.2	.0	.1	.0	.4	.2	19.0	2.2	21.2
W-89	.0	.0	.1	.0	.0	.0	.0	.0	.3	.1	12.3	1.8	14.1
S-89	.0	.0	.1	.0	.1	.0	.0	.0	.5	.1	18.0	2.1	20.1
W-90	.0	.0	.1	.0	.1	.0	.0	.0	.4	.1	16.5	2.0	18.5
S-90	.2	.0	.4	.0	.9	.0	.1	.0	.6	.3	35.3	3.2	38.5
W-91	.1	.0	.1	.0	.2	.0	.0	.0	.3	.0	15.7	1.8	17.5
S-91	.6	.1	1.2	.2	1.4	.0	.2	.0	.9	.9	54.4	8.8	63.2
W-92	.1	.0	.3	.0	.4	.0	.1	.0	.7	.2	27.5	2.2	29.7
S-92	.1	.0	.3	.0	.5	.0	.1	.0	.6	.1	29.9	2.2	32.1
W-93	.1	.0	.2	.0	.3	.0	.0	.0	.5	.1	20.6	2.3	22.9
Average dry	.1	.0	.3	.0	.4	.0	.1	.0	.5	.2	24.1	2.8	26.9
Wet Period													
S-93	.8	.0	1.7	.1	1.7	.0	.4	.0	1.1	1.6	69.4	14.1	83.5
W-94	.4	.0	.9	.0	.8	.0	.1	.0	.8	.5	39.6	3.9	43.5
S-94	.2	.0	.5	.0	.9	.0	.3	.0	.9	1.1	47.2	9.4	56.6
W-95	.2	.0	.4	.0	.5	.0	.1	.0	.8	.3	32.3	2.7	35.0
S-95	1.1	.1	2.1	.3	1.5	.0	.5	.1	1.1	1.6	67.4	14.9	82.3
W-96	.5	.0	1.2	.0	.9	.0	.1	.0	.9	.7	46.1	3.8	49.9
S-96	.8	.0	1.7	.1	1.7	.0	.5	.0	1.1	1.9	71.5	17.5	89.0
W-97	.7	.0	1.6	.0	1.4	.0	.2	.0	1.0	1.4	60.6	8.9	69.5
S-97	1.2	.1	2.5	.2	1.9	.0	.7	.1	1.2	2.1	77.8	24.4	102.2
Average wet	.7	.0	1.4	.1	1.3	.0	.3	.0	1.0	1.2	56.9	11.1	68.0
Overall average	.4	.0	.8	.0	.8	.0	.2	.0	.7	.7	38.8	6.5	45.3

¹Loss rate at model boundary. Table shows 50 percent of total loss assumed to enter the aquifer analysis area.

Boxelder Creek

Estimated streamflow recharge from Boxelder Creek to the Madison and Minnelusa hydrogeologic units averaged 12.8 and 2.1 ft³/s, respectively (table 12). Loss threshold estimates for Boxelder Creek were complicated by hydrogeologic features in the outcrop areas. Three springs are located along Boxelder Creek within the Madison outcrop: Gravel Spring, Doty Spring, and Dome Spring (pl. 1). Rahn and Gries (1973) determined from dye testing that these springs are directly connected to upstream losses. Although complicated by variable springflow, estimated thresholds reflect approximate net losses (Hortness and Driscoll, 1998), and therefore, these springflows were not included in streamflow-recharge or water-budget calculations. Hortness and Driscoll (1998) estimated general loss thresholds of greater than 25 ft³/s for the Madison outcrop, less than 20 ft³/s for the Minnelusa outcrop, less than 5 ft³/s for the Minnekahta outcrop, and a combined threshold for the three outcrops of approximately 50 ft³/s. These estimates, however, did not consider the isolated Madison outcrop near the anticline along Boxelder Creek (pl. 1).

An important effect of the anticline is that it separates the Minnelusa recharge area to the west from Minnelusa aquifer to the east causing much of the recharge on the Minnelusa outcrop to enter the Madison aquifer. A hydrogeologic section through this area illustrates this point, showing that a large area of the Minnelusa hydrogeologic unit is mostly above the water table west of the anticline (fig. 22, section D-D'). Because the Minnelusa hydrogeologic unit in this area is largely in the unsaturated zone, there is little horizontal Darcian flow, and recharge to the Minnelusa outcrop can infiltrate vertically into the underlying Madison aquifer under the force of gravity. Considering these various hydrogeologic conditions, the estimated loss thresholds for the Madison and Minnelusa hydrogeologic units for this report are 30 and 16 ft³/s, respectively, for a total of 46 ft³/s (table 11).

Boxelder Creek has the third largest drainage area in the study area but accounted for the largest streamflow recharge to the Madison and Minnelusa hydrogeologic units, about 33 percent during the 10-year period. This relates to the fact that Boxelder Creek is located in the northern part of the study area where precipitation is greater and the loss threshold is the largest for streams in the study area (table 11). Boxelder Creek flowed continually during the 10-year period but exceeded its estimated loss threshold to the

Madison and Minnelusa hydrogeologic units only 12 percent of the time. The continuous gage on Boxelder Creek above the loss zone (pl. 3, gage site 34) accounts for about 93 percent of the total basin area contributing to the loss zone. Therefore, the gaged flow was increased proportionately to account for the ungaged flow.

Elk Creek

Estimated streamflow recharge from Elk Creek to the Madison and Minnelusa hydrogeologic units averaged 2.6 and 0.9 ft³/s, respectively (table 12). Measured flow in Elk Creek just upstream of the Madison outcrop (pl. 3, gage site 39) was used to calculate streamflow recharge. Because data for this site were not collected before September 1991, a synthetic flow record was generated for the missing period by regressing measured streamflow in Elk Creek against flow in Boxelder Creek at gage sites 39 and 34 (pl. 3). Because the Elk Creek loss zone is located at the northern boundary of the aquifer analysis area, only one-half of the streamflow recharge was assumed to flow into the aquifer analysis area.

Elk Creek flowed continually during the 10-year period and exceeded its loss threshold 11 percent of time. This basin generally receives greater precipitation than Boxelder Creek but is smaller in size and has a smaller loss threshold. Elk Creek accounted for about 8 percent of the total streamflow recharge to the Madison and Minnelusa hydrogeologic units.

Four tributaries downstream from gage site 39 contribute to flow in the Elk Creek loss zone (pl. 3). The drainage basins for these tributaries are partially on the Madison outcrop. Because direct precipitation on the outcrop is accounted for in areal recharge, only the areas of the basins outside the outcrop were used to estimate additional streamflow below gage site 39. These basin areas outside the outcrop have a total area of 13.6 mi², which is 63.3 percent of the basin above gage site 39; thus, the flow record at the gage (partially synthetic) was increased by 63.3 percent.

Results of streamflow measurements for several reaches of Elk Creek that were compiled by Hortness and Driscoll (1998) are presented in table 13 along with additional measurements made after August 20, 1996. Loss thresholds of 11 ft³/s for the Madison outcrop and 8 ft³/s for the Minnelusa outcrop (table 11) were estimated by Hortness and Driscoll (1998) based

Table 13. Elk Creek streamflow-loss rates for the Madison and Minnelusa outcrops

[Modified from Hortness and Driscoll (1998). All values given in cubic feet per second. Site locations are shown on plate 3 and listed in table 11. --, undetermined]

Date	Flow rate at gage site 39	Madison outcrop loss rate between gage sites 39 and 43	Madison outcrop loss rate between gage sites 43 and 44	Total Madison outcrop loss rate	Minnelusa outcrop loss rate (gage sites 44 to 45)
04-24-96	31.9	6.8	3.3	10.1	7.9
05-07-96	26.6	6.5	4.8	11.3	8.1
07-01-96	12.1	7.6	-7.5	.1	6.4
07-12-96	9.9	8.1	-5.4	2.7	5.3
07-22-96	7.4	8.2	-5.1	3.1	4.8
08-20-96	4.7	7.0	-5.2	1.8	4.5
10-03-96	3.8	5.4	-3.0	2.4	--
10-21-99	¹ 5.2	--	-6.1	--	4.2

¹Mean daily value.

on the first two measurement dates (April 24 and May 7, 1996). Subsequent measurements, which were made during particularly wet climatic conditions, indicated that the loss rate on the Minnelusa outcrop decreased only slightly, but the loss rate on the Madison outcrop decreased substantially because of streamflow gains in the reach between gage sites 43 and 44. Measured losses between gage sites 39 and 43 remained relatively stable.

Hortness and Driscoll (1998) attributed the streamflow gain that occurred between sites 43 and 44 to springflow from the Madison aquifer and indicated that local areal recharge during a climatically wet period contributed to springflow. A laccolith, which is exposed on the northern side of the springflow area (Strobel and others, 1999), could cause areal recharge water to be perched on low-permeability igneous intrusive bodies. Water stored in perched areas might seep downgradient and discharge as springflow after periods of greater precipitation. Conversely, part of the springflow could result from reemerging upstream losses because of the larger streamflows during that period. Because streamflow losses and gains both can occur in the same stream reach at the same time, it is not known what effect springflow has on streamflow losses. The complex nature of this transient springflow precludes the determination of the ratio of areal-recharge source water to streamflow-recharge source water. Therefore, it was arbitrarily assumed that one-half of the estimated

springflow resulted from areal recharge and one-half resulted from streamflow recharge, and those estimates were adjusted accordingly (also see “Areal Recharge” section). In addition, estimated springflow was added to streamflow that could potentially be lost to the Minnelusa outcrop.

Based on streamflow gains (table 13) springflow was estimated as about 5 ft³/s for the latter part of the summer-1996 period (S-96), 3 ft³/s for the winter-1997 period (W-97), and 5 ft³/s for the summer-1997 period (S-97). Because the earlier part of the 10-year period was climatically dryer, springflow was assumed not to have occurred prior to S-96.

Ungaged Streams

Ungaged streams include Deadman Gulch, Rockerville Gulch, Victoria Creek, the unnamed tributary, and Little Elk Creek (table 11 and pl. 3). These smaller basins accounted for about 8 percent (3.5 ft³/s) of the total streamflow recharge to the Madison and Minnelusa hydrogeologic units (table 12).

Synthetic flow records were generated for smaller ungaged basins by correlating flow rates in nearby larger gaged basins. An assumption was made that flow rates are directly correlated to the size of the basin. Streamflow in Rapid Creek was not used to generate synthetic flow records because streamflow is regulated by Pactola Dam. Streamflow in Battle Creek was

used to create a synthetic flow record for Deadman Gulch and Rockerville Gulch (pl. 3). Streamflow in Spring Creek was used to create a synthetic flow record for Victoria Creek. Streamflow in Boxelder Creek was used to create a synthetic flow record for the unnamed tributary and for Little Elk Creek. Streamflow in Little Elk Creek was estimated based on Boxelder Creek rather than Elk Creek because precipitation for Little Elk Creek is similar to that of Boxelder Creek (table 11 and pl. 3).

Loss thresholds for Victoria Creek and Little Elk Creek were determined by Hortness and Driscoll (1998) but were not determined for Deadman Gulch, Rockerville Gulch, and the unnamed tributary. Thresholds for these streams were assumed to be small compared to those of the larger streams and were estimated as 2 and 4 ft³/s for the Madison and Minnelusa outcrops, respectively. The Minnelusa outcrop thresholds were assumed to be larger than thresholds for the Madison outcrop because stream reaches crossing the Minnelusa outcrop are longer than those of the Madison outcrop. Although these loss-threshold estimates are very uncertain, error in the estimate has a small effect on total calculated streamflow recharge because these basins account for less than 1 percent of the total area contributing to loss zones in the study area.

Areal Recharge

Areal recharge is recharge resulting from infiltration of precipitation on outcrops. Methods used in estimating areal recharge are discussed in the following section, after which estimates are presented.

Methods

The Madison and Minnelusa outcrop areas were each divided into five areal recharge zones, bounded by major streams that cross the outcrops. These zones include Battle Creek to Spring Creek (zone 1), Spring Creek to Rapid Creek (zone 2), Rapid Creek to Boxelder Creek (zone 3), Boxelder Creek to Little Elk Creek (zone 4), and Little Elk Creek to Elk Creek (zone 5) (table 14 and pl. 3). Average annual precipitation for each zone (table 14) shows that the northern outcrop areas receive a greater amount of precipitation than do the southern areas.

Evapotranspiration (ET) on the Precambrian core of the Black Hills could be estimated with greater

confidence than in other areas of the Black Hills. This relates to an assumption that precipitation on the Precambrian core that does not evapotranspire infiltrates and reemerges as streamflow and can, therefore, be measured for a given basin. Therefore, streamflow yield on the Precambrian core was used as a surrogate to indirectly estimate recharge on the Madison and Minnelusa outcrops. Because of the high permeability of the Madison and Minnelusa outcrops, runoff from the outcrops is considered negligible (Carter, Driscoll, and Hamade, 2001) and therefore, recharge is assumed to be the difference between ET and precipitation. This method also assumes that ET on the Madison and Minnelusa outcrops is similar to that of the Precambrian core.

ET on the Precambrian core was estimated by correlating precipitation on drainage basins in the study area with basin yield. The estimated ET was then extrapolated to the Madison and Minnelusa outcrop areas. Because of the general decreased porosity with depth in these rocks (Rahn, 1985, p. 161), ground water probably does not infiltrate deeper than about 500 ft; however, a small amount of ground water probably moves from the Precambrian core into the Madison hydrogeologic unit via upward seepage through the Deadwood aquifer. Therefore, the ultimate destination of precipitation falling on drainage basins in the Precambrian core can be divided into three categories: (1) evapotranspiration, (2) flow into streams either as shallow ground-water interflow or direct runoff, or (3) ground-water outflow into overlying Paleozoic rocks near the periphery of the Precambrian core. Therefore, the fraction of precipitation that is evapotranspired can be estimated from equation 5.

$$\left(\frac{ET}{P}\right)_{PC} = 1 - \left(\frac{Y + GW_O}{P}\right)_{PC} \quad (5)$$

where the subscript *PC* represents the Precambrian core and,

ET = evapotranspiration;

P = precipitation on basin;

Y = streamflow yield from basin in Precambrian core; and

GW_O = ground-water outflow from Precambrian core.

Table 14. Areal recharge zones and average annual precipitation on Madison and Minnelusa outcrops

[NA, not applicable]

Zone	Area covered	Area (square miles)		Average annual precipitation ¹ (inches)	
		Madison	Minnelusa	Madison	Minnelusa
1	Battle Creek to Spring Creek	6.6	15.1	19.9	19.4
2	Spring Creek to Rapid Creek	4.6	7.1	19.1	18.6
3	Rapid Creek to Boxelder Creek	9.8	12.5	19.6	18.9
4	Boxelder Creek to Little Elk Creek	27.3	15.2	20.0	19.2
5	Little Elk Creek to Elk Creek	10.1	3.6	24.0	22.3
Total		58.4	53.5	NA	NA

¹Calculated from precipitation data for WY61-98 (Driscoll, Hamade, and Kenner, 2000).

Because runoff is assumed to be zero on the Madison and Minnelusa outcrops, precipitation is equal to the sum of areal recharge and ET:

$$\left(\frac{R+ET}{P}\right)_{MM} = 1 \quad (6)$$

where the subscript *MM* represents the Madison and Minnelusa outcrops and *R* = areal recharge.

Based on assumptions described previously:

$$\left(\frac{ET}{P}\right)_{MM} = \left(\frac{ET}{P}\right)_{PC} \quad (7)$$

Therefore, equations 5, 6 and 7 can be combined as:

$$\left(\frac{R}{P}\right)_{MM} = \left(\frac{Y+GW_O}{P}\right)_{PC} \quad (8)$$

where the quantity, *Y + GW_O*, is the “total yield” from a drainage basin.

Four surface-water basins in the Precambrian core were analyzed to determine the terms on the right hand side of equation 8. These basins include Battle, Spring, Boxelder, and Elk Creeks measured above the Madison outcrop (table 11 and pl. 3). Although these basins mainly are composed of Precambrian rocks, small outcrop areas of Madison Limestone and Deadwood Formation exist near the western and eastern boundaries of some of the basins.

Monthly precipitation data (Driscoll, Hamade, and Kenner, 2000) were used to interpolate digital grids describing the distribution of precipitation for the drainage basins. These grids were used to compile average precipitation for each 6-month period for each of the drainage basins. Daily streamflow data for all four basins was separated into summer and winter seasons and averaged into 6-month time intervals (October 1 to March 31 and April 1 to September 30). Ground-water outflow from the Precambrian core (*GW_O*, eq. 5), which was estimated to be 6.3 ft³/s (see “Seepage from Deadwood Aquifer” section), was proportioned according to basin area among all of the basins in the Precambrian core in the study area. The proportioned amount was then added to measured streamflow to compute total yield and divided by average precipitation for each of the four basins (eq. 6). Total yield versus precipitation was plotted, and separate curves were fitted through data for the winter and summer periods (fig. 29) using a least-squares method for nonlinear regression. The nonlinear regression produced a better fit (higher R² value) than linear regression, especially for the summer period. This relates to the fact that during intense precipitation events, ET consumes a smaller percentage of precipitation than for smaller precipitation events.

These fitted curves were used for estimating areal recharge to the Madison and Minnelusa outcrops for 6-month periods. Based on equation 8, areal recharge on the Madison and Minnelusa outcrops as a

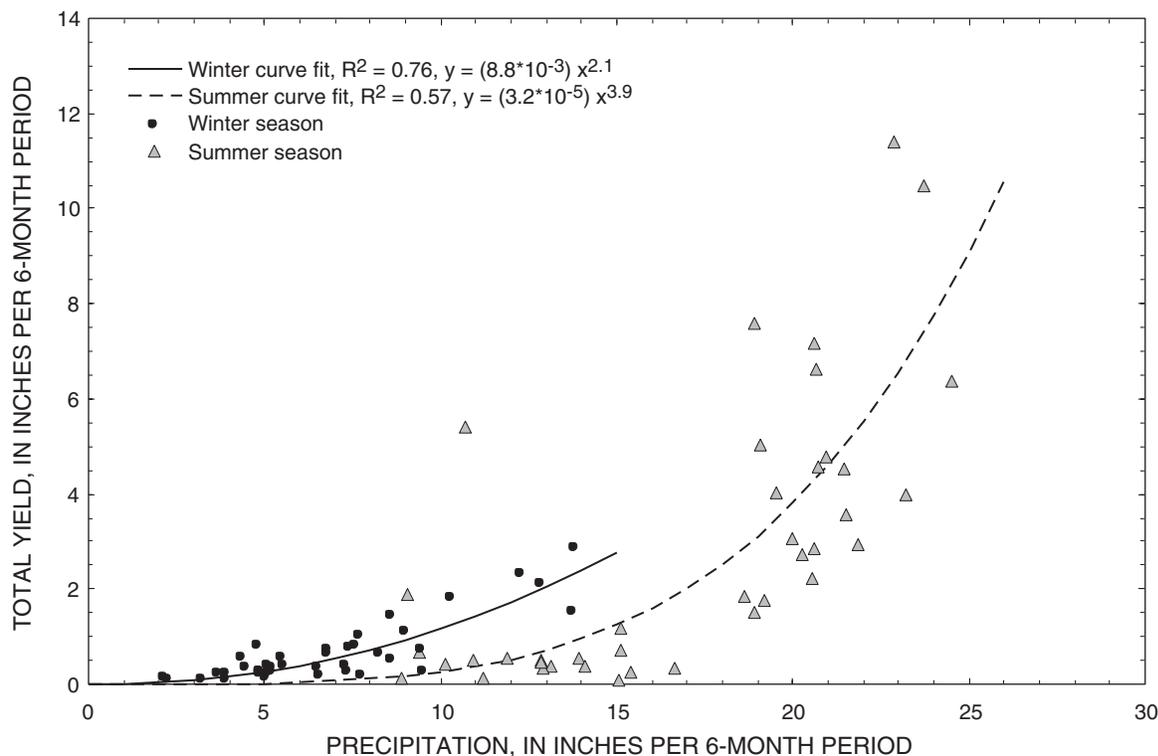


Figure 29. Correlation of total yield to precipitation on basins in Precambrian core.

function of precipitation was equated to total yield from basins in the Precambrian core. Precipitation for each areal recharge zone was calculated using the same method as for the Precambrian core and used to estimate areal recharge from the curves in figure 29. The winter curve shows that the colder months allow greater recharge for the same precipitation rate than the summer period. The summer curve shows substantially increasing total yield for precipitation exceeding 18 inches per 6-month period. The curves are not valid for precipitation exceeding the range of data shown in figure 29.

Areal recharge for the summer periods ranged from less than 1 inch to more than 5 inches per 6-month period with an average summer recharge of 2.3 inches (fig. 30). Areal recharge in the winter periods was less than 1 inch. The average areal recharge was 13 percent of precipitation. Areal recharge ranged from about 2 percent of precipitation in the summer of 1988 to about 26 percent in summer 1995 (fig. 31).

In the study area, the Minnelusa hydrogeologic unit contains “unsaturated areas,” as previously defined (see “Concepts of the Ground-Water Flow System” section), across about 73 percent of the

outcrop (pl. 2). Some of the precipitation infiltrating the unsaturated area of the Minnelusa outcrop probably infiltrates the underlying Madison aquifer. The same assumptions for the redistribution of streamflow recharge also were applied to areal recharge (table 15).

Estimation of Areal Recharge

Estimated areal recharge rates for each of the five areal recharge zones for the Madison and Minnelusa hydrogeologic units are shown in table 16. About 64 percent of areal recharge occurred north of Boxelder Creek (zones 4 and 5) because of larger outcrop areas and greater precipitation amounts than the zones to the south. Average total areal recharge was about 49 percent of streamflow recharge (table 7) for the study area. Total areal recharge rates in the summer ranged from less than 3 ft³/s during dry years to almost 100 ft³/s during wet years. Areal recharge rates in the winter ranged from about 1 ft³/s during dry years to about 12 ft³/s during wet years. During the extremely wet summer-1995 period (S-95), areal recharge exceeded that of streamflow recharge (tables 12 and 16).

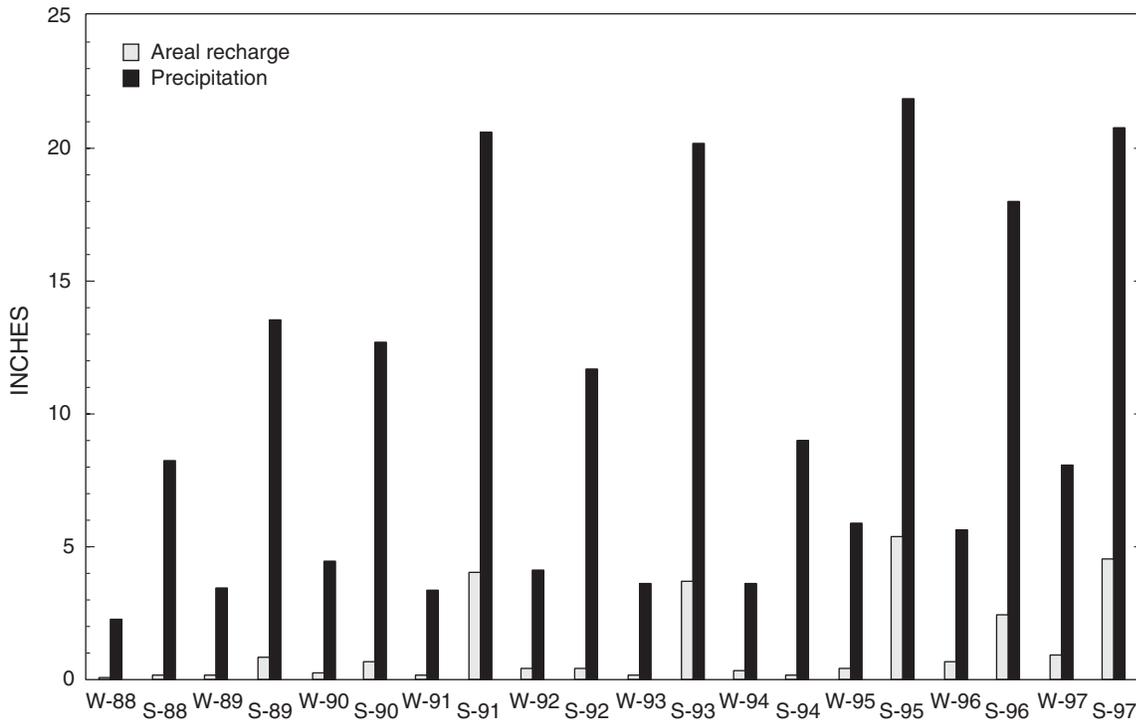


Figure 30. Spatially averaged precipitation and estimated areal recharge per 6-month period for the Madison and Minnelusa outcrops.

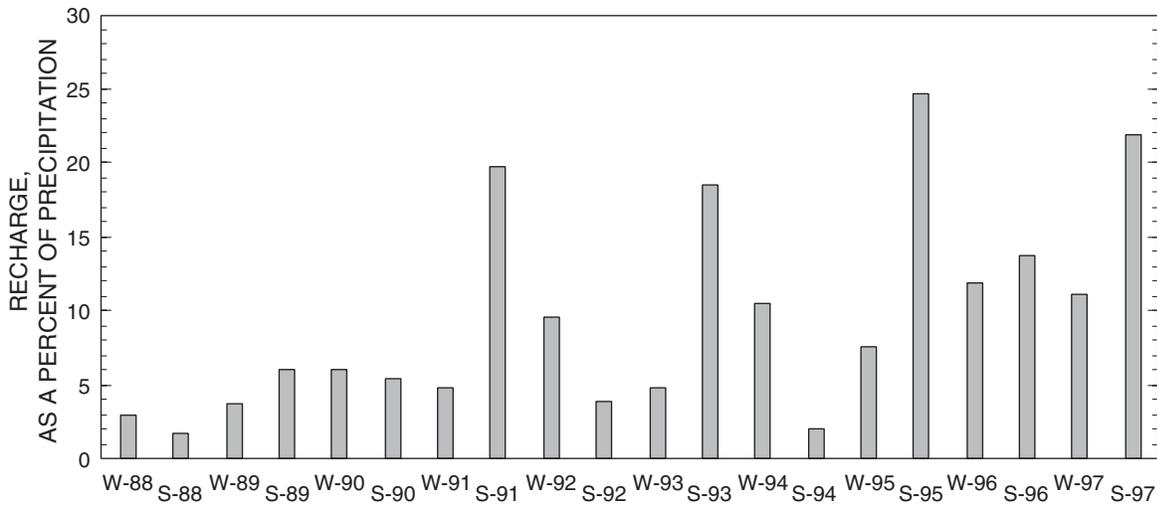


Figure 31. Spatially averaged areal recharge as a percentage of precipitation on the Madison and Minnelusa outcrops for winter (W) and summer (S).

Table 15. Redistribution of average areal recharge from the unsaturated area of the Minnelusa outcrop to the Madison aquifer in inches per 6-month period, WY88-97

Zone ¹	Recharge to Madison outcrop	Recharge to Minnelusa outcrop	Percentage of Minnelusa outcrop area unsaturated	Percentage of infiltration on Minnelusa outcrop redistributed	Adjusted Madison recharge	Adjusted Minnelusa recharge
	a	b	c	d	e	f
				$d = c/2$	$e = a+b*d/100$	$f = b*b*d/100$
1	1.2	0.9	59.4	29.7	1.5	0.7
2	1.0	.8	84.5	42.2	1.4	.5
3	1.4	1.1	70.0	35.0	1.8	.7
4	1.4	1.6	68.7	34.3	1.9	1.0
5	1.9	1.7	70.1	35.0	2.4	1.1

¹Zones are described in table 14.

Table 16. Areal recharge rates to the Madison and Minnelusa hydrogeologic units by zones

[Recharge rates in cubic feet per second (ft³/s); W, winter; S, summer (W-88 = winter 1988); Mdsn, Madison, Mnl, Minnelusa]

Stress period	Madison recharge by zone ¹					Minnelusa recharge by zone ¹					Total		Total Mdsn Mnl
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Mdsn	Mnl	
Dry Period													
W-88	0.0	0.0	0.1	0.3	0.5	0.0	0.0	0.0	0.1	0.1	0.9	0.2	1.1
S-88	.2	.1	.1	.6	.9	.2	.0	.1	.1	.1	1.9	.5	2.4
W-89	.1	.1	.3	.6	.5	.1	.0	.2	.2	.1	1.6	.6	2.2
S-89	.9	1.6	2.0	3.1	2.4	1.0	.8	1.0	.9	.3	10.0	4.0	14.0
W-90	.2	.1	.3	1.1	1.5	.2	.1	.2	.3	.2	3.2	1.0	4.2
S-90	2.3	.8	1.2	2.2	.9	2.2	.5	.6	.7	.1	7.4	4.1	11.5
W-91	.1	.1	.2	.6	.8	.1	.0	.1	.2	.1	1.8	.5	2.3
S-91	4.5	5.5	11.0	24.0	7.5	4.3	2.6	4.9	6.4	1.3	52.5	19.5	72.0
W-92	.3	.1	.3	.8	.9	.3	.1	.1	.2	.1	2.4	.8	3.2
S-92	.5	.4	.9	3.1	1.0	.6	.2	.4	.9	.2	5.9	2.3	8.2
W-93	.1	.1	.2	.7	1.1	.1	.0	.1	.2	.1	2.2	.5	2.7
Average dry	.8	.8	1.5	3.4	1.6	.8	.4	.7	.9	.2	8.2	3.1	11.3
Wet Period													
S-93	6.2	4.0	6.2	19.6	10.0	7.1	2.3	3.5	5.3	1.7	46.0	19.9	65.9
W-94	.1	.0	.2	.8	1.8	.0	.0	.1	.2	.2	2.9	.5	3.4
S-94	.4	.1	.3	.8	.4	.4	.1	.1	.3	.1	2.0	1.0	3.0
W-95	.3	.1	.6	2.4	3.1	.2	.0	.3	.6	.4	6.5	1.5	8.0
S-95	5.5	2.1	10.9	35.8	18.4	5.5	1.1	4.6	11.6	2.9	72.7	25.7	98.4
W-96	.2	.1	.5	2.2	2.8	.2	.1	.2	.5	.3	5.8	1.3	7.1
S-96	3.0	1.5	4.3	17.8	4.5	3.0	.9	2.1	4.4	1.1	31.1	11.5	42.6
W-97	.5	.4	1.3	4.8	2.6	.5	.2	.7	1.2	.6	9.6	3.2	12.8
S-97	3.1	1.8	10.6	35.0	5.8	3.3	1.1	5.9	11.6	1.4	56.3	23.3	79.6
Average wet	2.1	1.1	3.9	13.2	5.5	2.2	.6	1.9	4.0	1.0	25.9	9.8	35.7
Overall average	1.4	1.0	2.6	7.8	3.4	1.5	.5	1.3	2.3	.6	16.1	6.1	22.2

¹See table 14 for description of zones.

Springflow

Springs in the aquifer analysis area that are included in water-budget calculations are Jackson-Cleghorn Springs, City Springs, Deadwood Avenue Springs, and springs along Boxelder and Elk Creeks (pl. 3). Geochemical analysis indicates that the largest spring complex in the aquifer analysis area, Jackson-Cleghorn, flows from the Madison aquifer (Back and others, 1983; Anderson and others, 1999). All of these springs are located in areas where hydraulic head in the Madison aquifer is generally higher than in the Minnelusa aquifer. Because of the upward hydraulic gradient, and for simplicity, it is assumed that the source of all springs considered is the Madison aquifer.

Flow from some springs can be relatively steady, whereas flow from others may fluctuate considerably. Topographic altitude, hydraulic head variation, and

hydraulic properties of the overlying material may affect springflow rates. Flows from Tittle Springs, Gravel Spring, Doty Spring, and Dome Spring occur within the Madison streamflow-loss zones (pl. 1). Because estimated streamflow-loss thresholds represent approximate net loss (Hortness and Driscoll, 1998), flow from these springs was accounted for in streamflow loss estimates and, therefore, was omitted from water-budget calculations. A summary of springflow estimates and details on individual springs follow.

Estimation of Springflow

Springs included in the water budget area are listed in table 17. A total of about 31 ft³/s is the estimated average flow from these springs for WY88-97. Total springflow averaged 25.3 ft³/s for the dry period and 37.4 ft³/s for the wet period.

Table 17. Summary of estimated springflow

[Discharge rates in cubic feet per second; W, winter; S, summer (W-88 = winter 1988)]

Stress period	Jackson-Cleghorn Springs	City Springs	Deadwood Avenue Springs	Boxelder Springs	Elk Springs	Total
Dry Period						
W-88	21.6	1.9	2.8	0.0	0.3	26.6
S-88	21.6	1.0	2.8	.0	.3	25.7
W-89	21.6	1.0	2.8	.0	.0	25.4
S-89	21.6	.7	2.8	.0	.0	25.1
W-90	21.6	.8	2.8	.0	.0	25.2
S-90	21.6	.8	2.8	.0	.0	25.2
W-91	21.6	.3	2.8	.0	.1	24.8
S-91	21.6	1.3	2.8	.0	.1	25.8
W-92	21.6	.6	2.8	.0	.0	25.0
S-92	21.6	.4	2.8	.0	.0	24.8
W-93	21.6	.3	2.8	.2	.1	25.0
Average dry	21.6	.8	2.8	.0	.1	25.3
Wet Period						
S-93	21.6	2.1	2.8	.2	.1	26.8
W-94	21.6	1.5	2.8	.0	.4	26.3
S-94	21.6	1.4	2.8	.0	.4	26.2
W-95	21.6	1.3	2.8	.5	8.6	34.8
S-95	21.6	3.3	2.8	.5	8.6	36.8
W-96	21.6	2.8	2.8	2.5	8.2	37.9
S-96	21.6	4.0	2.8	2.5	8.2	39.1
W-97	21.6	3.5	2.8	6.8	18.9	53.6
S-97	21.6	4.9	2.8	6.8	18.9	55.0
Average wet	21.6	2.8	2.8	2.2	8.0	37.4
Overall average	21.6	1.7	2.8	1.0	3.7	30.8

Jackson-Cleghorn Springs

Anderson and others (1999) estimated springflow from Jackson-Cleghorn Springs to be about 21.6 ft³/s during WY88-89 using a control-volume analysis. This spring complex probably is a regional discharge point with a relatively stable flow (see “Hydraulic Response to Recharge” and “Flowpaths” sections). Therefore, in the absence of further data, the springflow was estimated to be constant at 21.6 ft³/s for the 10-year period.

City Springs

Flow from City Springs and some unnamed springs about 0.3 mi to the east were estimated from the streamflow record at gage site 90 (table 11 and pl. 3), which is located about 2 mi downstream on a tributary of Rapid Creek. Base flow at this site was assumed to be equal to springflow and was estimated by using a hydrograph separation program called HYSEP (Sloto and Crouse, 1996). Estimated springflow for 6-month periods varied from 0.3 to 4.9 ft³/s with an average of 1.7 ft³/s.

Deadwood Avenue Springs

Flow from Deadwood Avenue Spring no. 1 was estimated from the streamflow record for gage site 91 (pl. 3 and table 11), which is located about 1 mi downstream on a tributary of Rapid Creek. Gage site 91 was measured continuously during WY88-90. Base flow at this site was assumed to be equal to flow from spring no. 1 and was estimated by using the hydrograph separation program HYSEP (Sloto and Crouse, 1996). The estimated base flow was relatively steady with a mean of 2.4 ft³/s, a maximum and minimum daily rate of 1.8 and 3.3 ft³/s, respectively, and standard deviation of 0.3. Because flow records were available only for a 3-year period, the mean value of 2.4 ft³/s was used in water-budget calculations for the entire 10-year period for spring no. 1.

On October 18, 2000, Deadwood Avenue Springs nos. 1 and 2 were measured at 2.22 and 0.43 ft³/s, respectively, at the locations where flow enters Rapid Creek. The fall of 2000 was very dry, and all flow in these streams was assumed to have originated from the springs. Because flow from spring no. 1 on this date was nearly equal to the estimated average, it was assumed that the measured flow from spring no. 2 was also equal to the average rate for that spring. Therefore, total flow for the two springs was estimated to be constant at 2.8 ft³/s.

Boxelder Springs and Elk Springs

Springs along Boxelder Creek 2 mi west of I-90 and Elk Creek near I-90 (pl. 3) generally flow only when hydraulic head in the Madison aquifer is estimated to be above the land surface. Annual flow from these springs was estimated for WY87-97 by Carter, Driscoll, Hamade, and Jarrell (2001). These annual springflow estimates were included as 6-month time steps for this report by assuming flow remained constant during winter and summer for each year. Springflow was negligible during the early part of the analysis period until 1995 when flow increased rapidly due to rising water levels. The combined estimated flow from these springs during WY97 was about 26 ft³/s.

Water Use

Locations of public supply, irrigation, and industrial wells are shown on plate 3. The city of Rapid City maintained water-use records that were used to compile data for water-budget calculations. Water use from public-supply wells outside of Rapid City was estimated by extrapolating per capita water use in Rapid City to populations served by other public water supplies. Irrigation and industrial water use was estimated based on water-permit information including pump capacities and acreage. A summary of water-use estimates follows, which is followed by separate descriptions of water use from Rapid City wells, other public-supply wells, irrigation, and industrial sources.

Estimation of Water Use

Rapid City withdrew an average of 3.8 ft³/s (2,500,000 gal/d) from the Madison aquifer and 1.0 ft³/s (680,000 gal/d) from the Minnelusa aquifer during WY88-97 (table 18), which was about 48 percent of all water use from the Madison and Minnelusa aquifers in the aquifer analysis area. In the 1980's, the city of Rapid City obtained much of its water from the Minnelusa aquifer. Madison aquifer production surpassed the Minnelusa aquifer production after 1991 as new city wells were completed. Other public-supply wells and domestic wells accounted for about 36 percent of all Madison and Minnelusa aquifer water use during WY88-97, while irrigation and industrial wells accounted for about 16 percent.

Water use from the Madison and Minnelusa aquifers accounts for about 14 percent of the total water budget for WY88-97 (table 7). Total withdrawal rates from the Madison aquifer averaged 6.7 ft³/s and ranged from about 2 to 15 ft³/s. Total withdrawal rates from the Minnelusa aquifer averaged 3.4 ft³/s and ranged from about 2 to 5 ft³/s (table 18).

Rapid City Wells

Rapid City's production wells (pl. 3) are completed primarily in the Madison aquifer (table 4). In response to drought conditions in the late 1980's, the city initiated a drilling program in the Madison aquifer to reduce dependence on surface water and infiltration galleries along Rapid Creek (Anderson and others,

Table 18. Water use from Madison and Minnelusa aquifers

[Rates in cubic feet per second; W, winter; S, summer (W-88 = winter 1988)]

Stress period	Madison aquifer				Minnelusa aquifer				Total Madison Minnelusa
	Rapid City	Other public and domestic water supplies	Industrial and irrigation	Total	Rapid City	Other public and domestic water supplies	Industrial and irrigation	Total	
Dry Period									
W-88	0.0	1.3	0.6	1.9	1.5	1.2	0.2	2.9	4.8
S-88	.0	3.4	1.3	4.7	1.4	3.1	1.2	5.7	10.4
W-89	.0	1.1	.6	1.7	.5	1.0	.2	1.7	3.4
S-89	.1	2.0	1.3	3.4	.7	1.8	1.2	3.7	7.1
W-90	.0	1.2	.6	1.8	1.6	1.1	.2	2.9	4.7
S-90	.9	2.0	1.3	4.2	1.9	1.8	1.2	4.9	9.1
W-91	1.0	1.4	.6	3.0	1.8	1.3	.2	3.3	6.3
S-91	3.3	2.2	1.7	7.2	1.6	2.0	1.0	4.6	11.8
W-92	3.6	1.2	.6	5.4	1.3	1.1	.2	2.6	8.0
S-92	9.1	2.1	1.3	12.5	1.2	1.9	1.2	4.3	16.8
W-93	1.7	1.4	.6	3.7	1.1	1.3	.2	2.6	6.3
Average dry	1.8	1.8	1.0	4.5	1.3	1.6	.6	3.6	8.1
Wet Period									
S-93	10.6	1.9	1.1	13.6	1.1	1.8	1.1	4.0	17.6
W-94	4.2	1.4	.6	6.2	.6	1.3	.2	2.1	8.3
S-94	10.9	2.8	1.3	15.0	.3	2.6	1.2	4.1	19.1
W-95	3.7	1.4	.7	5.8	.8	1.3	.2	2.3	8.1
S-95	7.5	2.3	1.2	11.0	.6	2.1	1.0	3.7	14.7
W-96	.9	1.6	.7	3.2	.5	1.4	.2	2.1	5.3
S-96	7.6	2.6	1.2	11.4	.6	2.4	1.0	4.0	15.4
W-97	3.2	1.6	.7	5.5	.8	1.5	.2	2.5	8.0
S-97	8.4	2.3	1.2	11.9	.9	2.2	1.0	4.1	16.0
Average wet	6.3	2.0	1.0	9.3	.7	1.8	.7	3.2	12.5
Overall average	3.8	1.9	1.0	6.7	1.0	1.7	.7	3.4	10.1

1999). Estimated water use for all Rapid City ground-water and surface-water sources is shown in table 19 and averaged about 20 ft³/s during summer periods and 12 ft³/s during winter periods. Average production from the Madison and Minnelusa aquifers is shown in table 20 and sometimes accounted for more than one-half of the total water use, with withdrawals from the Madison aquifer exceeding 10 ft³/s during S-93 and S-94. The average withdrawal after 1991, when most of the Madison wells were completed, was about 7 ft³/s. Table 19 shows total Rapid City water use as a fraction of the average for WY97 so that water use could be calculated for other public-supply wells based on Rapid City population equivalents in 1997.

Other Public-Supply Wells

The Madison and Minnelusa aquifers are used extensively as public water supplies outside of Rapid City. Most of these wells are located within a band about 2 to 3 mi wide, on or adjacent to the Minnelusa outcrop (pl. 3). These public water supplies predominantly serve small suburban developments and commercial establishments (tables 21 and 22).

To estimate the water use from public water supplies outside of Rapid City, per capita water use was assumed to be similar to that of Rapid City. Average withdrawal from each public-supply well was estimated based on the population served by that well and the per capita water use within Rapid City. This assumption would, however, overestimate water use from public supplies outside of Rapid City because per capita commercial water use inside of Rapid City is greater than that outside. However, this overestimation of water use from public water supplies was assumed to be offset by water use from private domestic wells outside of Rapid City, which was neglected.

The estimated per capita water use for Rapid City during the winter-1997 period (W-97) was 123 gal/d and the summer-1997 period (S-97) was 177 gal/d. These were calculated by dividing water use for Rapid City in WY97 (table 19) by the population equivalent of 73,000 in 1997 (South Dakota Department of Environment and Natural Resources, written commun., 1999). Water use for each public water supply for WY97 was based on Rapid City population equivalents. Water use for each 6-month period was determined by multiplying by the water-use fraction of WY97 (table 19). Average water use for each public supply well for the 10-year period is shown in tables 21

and 22. The average withdrawal rate from the Madison aquifer totaled about 1.9 ft³/s and ranged from 0.01 to 0.47 ft³/s for individual water supplies. The average withdrawal rate from the Minnelusa aquifer totaled about 1.7 ft³/s and ranged from 0.01 to 0.20 ft³/s for individual water supplies.

Table 19. Total Rapid City water use as an average per stress period

[Includes all surface- and ground-water sources. Mgal/d, million gallons per day; ft³/s, cubic feet per second; W, winter; S, summer (W-88 = winter 1988)]

Stress period	Total water use (Mgal/d) ¹	Total water use (ft ³ /s)	Water use as fraction of average WY97 water use for each season
Dry Period			
W-88	6.94	10.74	0.77
S-88	18.79	29.07	1.46
W-89	6.03	9.33	.67
S-89	10.99	17.01	.85
W-90	6.67	10.32	.74
S-90	10.9	16.87	.85
W-91	7.59	11.74	.84
S-91	11.91	18.43	.92
W-92	6.8	10.52	.76
S-92	11.57	17.90	.90
W-93	7.79	12.05	.87
Wet Period			
S-93	10.58	16.37	.82
W-94	7.90	12.22	.88
S-94	15.55	24.06	1.21
W-95	7.81	12.08	.87
S-95	12.81	19.82	.99
W-96	8.46	13.09	.94
S-96	14.19	21.96	1.10
W-97	8.99	13.91	1.00
S-97	12.89	19.95	1.00

¹Rapid City Water Department, written commun., 1999.

Table 20. Rapid City production well withdrawals

[Rate in cubic feet per second; Mdsn, Madison aquifer; Mnl, Minnelusa aquifer; W, winter; S, summer (W-88 = winter 1988). Source is Rapid City Water Department, written commun., 1999]

Stress period	Well name and the aquifer the well is completed in										Total	
	RC-1 ¹ Mdsn	RC-1 ¹ Mnl	RC-3 ² Mnl	RC-4 Mnl	RC-5 Mdsn	RC-6 ³ Mdsn	RC-8 Mdsn	RC-9 Mdsn	RC-10 Mdsn	RC-11 Mdsn	Mdsn	Mnl
Dry Period												
W-88	0.00	0.00	0.59	0.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.53
S-88	.00	.00	.52	.90	.00	.00	.00	.00	.00	.00	.00	1.42
W-89	.00	.00	.52	.01	.00	.00	.00	.00	.00	.00	.00	.53
S-89	.07	.07	.48	.18	.00	.00	.00	.00	.00	.00	.07	.73
W-90	.00	.00	.60	1.03	.00	.00	.00	.00	.00	.00	.00	1.63
S-90	.21	.21	.69	.97	.71	.00	.00	.00	.00	.00	.92	1.87
W-91	.10	.10	.74	.96	.34	.52	.00	.00	.00	.00	.96	1.80
S-91	.32	.32	.30	.96	2.18	.48	.36	.00	.00	.00	3.34	1.58
W-92	.31	.31	.00	1.00	3.12	.00	.14	.00	1.35	.00	4.92	1.31
S-92	.31	.31	.00	.87	2.06	.64	.76	3.86	.26	.16	8.05	1.18
W-93	.31	.31	.00	.80	.00	.06	.18	.85	1.99	.05	3.44	1.11
Wet Period												
S-93	.33	.33	.00	.79	.75	.81	1.21	5.22	1.62	.32	10.26	1.12
W-94	.32	.32	.00	.32	.18	.65	.71	.48	2.53	.19	5.06	.64
S-94	.31	.31	.00	.02	1.05	1.01	1.18	4.19	2.03	.65	10.42	.33
W-95	.08	.08	.00	.73	.56	.16	.10	.53	2.14	.24	3.81	.81
S-95	.00	.00	.00	.63	1.17	.59	1.11	2.07	.62	.39	5.95	.63
W-96	.00	.00	.00	.48	.09	.00	.00	.19	1.86	.00	2.14	.48
S-96	.00	.00	.00	.64	.94	.87	1.02	2.39	1.82	.51	7.55	.64
W-97	.00	.00	.00	.83	.38	.16	.04	.72	2.07	.06	3.43	.83
S-97	.00	.00	.00	.87	1.76	.47	.98	2.65	.00	.46	6.32	.87
Average	.13	.13	.22	.70	.77	.32	.39	1.16	.91	.15	3.83	1.05

¹Minnelusa and Madison aquifer withdrawals were each estimated as 0.4 times the total withdrawal because the well is open to the Minnelusa, Madison, and Deadwood aquifers.

²Also may produce from Madison aquifer.

³Also may produce from Minnelusa aquifer.

Table 21. Public water supply withdrawals from Madison aquifer excluding Rapid City wells

[gal/min, gallons per minute; ft³/s, cubic feet per second; WY, water year; Well information (excluding withdrawals) is from South Dakota Department of Environment and Natural Resources, written commun., 1999]

Site number (pl. 3)	Public water-supply identification number	Name	Year of construction	Population equivalent ¹	Average estimated WY88-97 withdrawal (gal/min)	Average estimated WY88-97 withdrawal ² (ft ³ /s)
1	4602159	Stagebarn Subdivision	1993	165	18	0.04
2	4600893	Stagebarn Elementary School	1980	360	36	.08
3	4602000	Peaceful Pines	1976	102	9	.02
4	4600043a	Black Hawk Water Company	1986	900	90	.20
5	4600862	Weston Heights	1985	220	22	.05
6	4602106	Cavalry Trails Homeowner Association	1980	54	4	.01
7	4602150	Coca Cola Bottling Company	1991	70	9	.02
8	4600046	Box Elder	1982	2,137	211	.47
9	4600863a	Ponderosa Ridge	1974	45	4	.01
10	4600863	Ponderosa Ridge	1977	45	4	.01
11	4600253	Westberry Trails Water Users Association	1972	157	13	.03
12	4602084	Rimrock Ridge Water Association	1978	36	4	.01
13	4600264	Chapel Lane Water Company	1975	1,200	117	.26
14	4600265	Carriage Hills	1980	270	27	.06
15	4600274	Rapid Valley Sanitary District	1991	1,360	94	.21
16	4600405	Ponderosa Park	1950	54	4	.01
17	4602149	CPH - Countryside South	1972	35	4	.01
18	4600263a	CPH - Whispering Pines	1964	35	4	.01
19	4600263	CPH - Whispering Pines	1976	35	4	.01
20	4600050	Highland Hills	1986	40	4	.01
21	4600015	Spring Canyon Water Company	1968	42	4	.01
22	4600528	Bear Country	1975	304	31	.07
23	4600910a	Hart Ranch	1984	600	58	.13
24	4600910	Hart Ranch	1984	20	45	.10
25	4600948	Pine Grove	1983	270	27	.06
Total				8,556	847	1.90

¹When the reported population for a public water supply included more than one well location, the population was prorated based on estimates from water managers or the well capacity.

²Average withdrawals less than 0.01 ft³/s were rounded up to 0.01 ft³/s for several smaller public water supplies.

Table 22. Public water supply withdrawals from Minnelusa aquifer excluding Rapid City wells

[gal/min, gallons per minute; ft³/s, cubic feet per second; WY, water year. Well information (excluding withdrawals) is from South Dakota Department of Environment and Natural Resources, written commun., 1999]

Site number (pl. 3)	Public water-supply identification number	Name	Year of construction	Population equivalent ¹	Average WY88-97 withdrawal (gal/min)	Average WY88-97 withdrawal ² (ft ³ /s)
26	4600929	Elk Creek Steakhouse	1978	104	8	0.02
27	4600630	Elk Creek Resort	1994	60	5	.01
28	4602133	Covered Wagon Resort	--	390	40	.09
29	4602123	Dakotah Spirit Resort	--	100	8	.02
30	4600239	Elk Creek Water Company	1973	321	31	.07
31	4600421a	Wonderland Homes	1982	325	31	.07
32	4600639	Piedmont Medical Center	1976	75	8	.02
33	4600421	Wonderland Homes	1975	325	31	.07
34	4601000a	East Ridge Acres	1972	55	5	.01
35	4600402	The Niche	1974	50	5	.01
36	4600515	Midland Heights	1975	177	17	.04
37	4601000	East Ridge Acres	1978	55	5	.01
38	4600041a	Pine Hills Park	1984	150	13	.03
39	4600041	Pine Hills Park	1972	155	13	.03
40	4600516	Golden Meadows	1978	114	8	.02
41	4602165	Fort Welikit Family Campground	1994	27	4	.01
42	4600587	Heritage Park	1963	188	17	.04
43	4600042	Woodland Hills	1945	110	8	.02
44	4600043	Black Hawk Water Company	1982	885	85	.19
45	4600040	Valley View Mobile Home Park	1973	291	26	.06
46	4600257	Cimarron Park	1972	200	17	.04
47	4600514	Northdale Sanitary District	1978	489	49	.11
48	4600258	Leos Trailer Court	1990	25	4	.01
49	4602122	B & J Mobile Home Park	1994	156	5	.01
50	4600260	Ponderosa Mobile Home Ranch	1963	100	8	.02
51	4600269	Hidden Valley Water Association Inc.	1954	50	5	.01
52	4602039	Buck N Gator Bar	1960	100	8	.02
53	4602070	Dacotah Cement - North	1941	35	4	.01
54	4600643	Dacotah Cement - East/west	1923	75	8	.02
55	4600643a	Dacotah Cement - East/west	1934	75	8	.02
56	4600253a	Westberry Trails Water Users Association	1974	20	4	.01
57	4602182	Sioux San Hospital	1960	200	17	.04
58	4601062	Cedar Canyon Wesleyan Camp	1956	93	8	.02
59	4600908	Lake Park Motel	1976	80	8	.02
60	4602134	Ponderosa Water Company	1985	38	4	.01
61	4602153	Pineview Water Association	1984	34	4	.01
62	4601115	Memorial Christian School	1976	177	17	.04
63	4600589	Travelodge	1992	175	8	.02

Table 22. Public water supply withdrawals from Minnelusa aquifer excluding Rapid City wells—Continued

[gal/min, gallons per minute; ft³/s, cubic feet per second; WY, water year. Well information (excluding withdrawals) is from South Dakota Department of Environment and Natural Resources, written commun., 1999]

Site number (pl. 3)	Public water-supply identification number	Name	Year of construction	Population equivalent ¹	Average WY88-97 withdrawal (gal/min)	Average WY88-97 withdrawal ² (ft ³ /s)
64	4601037	Rushmore Waterslide	1984	500	49	0.11
65	4600890	Reptile Gardens Inc.	1965	900	89	.20
66	4601061	Flying T Chuckwagon Suppers	1993	204	17	.04
67	4602118	Dairy Barn - Hayloft B&b	1994	42	5	.01
68	4600669	Happy Holiday Inc.	1965	67	5	.01
Total				7,792	719	1.65

¹When the reported population for a public water supply included more than one well location, the population was prorated based on estimates from water managers or the well capacity.

²Average withdrawals less than 0.01 ft³/s were rounded up to 0.01 ft³/s for several smaller public water supplies.

Irrigation and Industrial Water Use

Irrigation and industrial withdrawals from the Madison and Minnelusa aquifers were estimated from water-rights permit information (South Dakota Department of Environment and Natural Resources, written commun., 1999) including well capacity and acreage. Average withdrawal rates totaled about 0.95 ft³/s from the Madison aquifer (table 23) and ranged from 0.03 to 0.55 ft³/s for individual wells. Average withdrawal rates totaled 0.65 ft³/s from the Minnelusa aquifer (table 24) and ranged from 0.04 to 0.2 ft³/s for individual wells.

Table 23. Industrial and irrigation withdrawals from Madison aquifer

[gal/min, gallons per minute; ft³/s, cubic feet per second; WY, water year]

Site number (pl. 3)	Water-rights permit number ¹	Year of construction	Average WY88-97 withdrawal ¹ (gal/min)	Average WY88-97 withdrawal (ft ³ /s)
69	2286-2	1993	31	0.07
70	2256-2	1992	76	.17
71	2313-2	1994	13	.03
72	454-2	1957	246	.55
73	1911-2	1984	58	.13
Total			424	.95

¹Well information compiled from South Dakota Department of Environment and Natural Resources, written commun., 1999.

Table 24. Industrial and irrigation withdrawals from Minnelusa aquifer

[gal/min, gallons per minute; ft³/s, cubic feet per second; WY, water year]

Site number (pl. 3)	Water-rights permit number ¹	Year of construction	Average WY88-97 withdrawal ¹ (gal/min)	Average WY88-97 withdrawal (ft ³ /s)
74	842-1	1968	35	0.08
75	1656-2	1954	89	.20
76	1798-2	1956	22	.05
77	815-2	1923	89	.20
78	2137-2	1990	35	.08
79	1901-2	1984	17	.04
Total			287	.65

¹Well information compiled from South Dakota Department of Environment and Natural Resources, written commun., 1999.

Leakage to Overlying Aquifers

Water from the Minnelusa aquifer under artesian pressure probably moves into overlying units including the Minnekahta and Inyan Kara aquifers through fractures or breccia pipes. According to Davis and others (1961), the Inyan Kara aquifer probably receives some recharge from underlying aquifers because recharge on its outcrop is relatively small. Gott and others (1974) suggest that the upward leakage occurs through breccia pipes. Behal (1988) applied statistical analysis to water quality in the Inyan Kara aquifer, in which t-tests

indicated water near lineaments was different from water away from lineaments for some constituents but not others. This statistical analysis also indicated that water near lineaments was geochemically similar to a mixture of Madison and Minnelusa aquifer water for some constituents but not others. Although these results were not conclusive, the analysis indicated a strong possibility that ground water leaks upward from the Madison and Minnelusa aquifers through fractures or breccia pipes.

Because very little data were available to estimate the upward leakage from the Minnelusa aquifer, the overall water-budget calculation was used to estimate this amount to be about 2 ft³/s or about 3 percent of the total budget (table 7).

Regional Outflow

Regional outflow occurs from the Madison and Minnelusa aquifers across the eastern boundary of the

aquifer analysis area and was calculated by Darcy's Law using the hydraulic gradient from plates 1 and 2 and estimated transmissivity (*T*). *T* along the eastern boundary was adjusted in balancing the water budgets. The eastern boundary was subdivided into 14 zones (pl. 3), and outflow from each zone was calculated separately (table 25). The values listed in table 25 are within the ranges of effective *T* shown in figures 9 and 10 and represent the *T* tensor perpendicular to the boundary. The northern and southern boundaries were assumed to be parallel to flow and, therefore, would have no flow across them. Outflow from the confining units was assumed to be negligible.

Hydraulic gradient along the eastern boundary was assumed to remain relatively constant; hence, estimated regional outflow also was constant throughout the 10-year period. Regional outflow was estimated to be about 11 ft³/s for both the Madison and Minnelusa hydrogeologic units (table 25).

Table 25. Outflow from boundary zones

[Boundary zones shown on plate 3. ft, feet; ft²/d, square feet per day; ft³/s, cubic feet per second; T, transmissivity]

Boundary zone	Boundary width (ft)	Madison aquifer			Minnelusa aquifer		
		Hydraulic gradient	T (ft ² /d)	Outflow (ft ³ /s)	Hydraulic gradient	T (ft ² /d)	Outflow (ft ³ /s)
1	14,492	0.004	664	0.4	0.006	600	0.6
2	14,492	.006	664	.7	.007	600	.7
3	14,492	.005	664	.6	.009	600	.9
4	14,492	.003	664	.3	.012	600	1.2
5	14,492	.001	1,005	.2	.010	600	1.0
6	14,492	.000	3,096	.0	.012	600	1.2
7	14,217	.005	3,310	2.7	.008	600	.8
8	14,217	.004	1,009	.7	.009	600	.9
9	14,217	.007	664	.8	.008	600	.8
10	14,217	.011	664	1.2	.007	600	.7
11	14,217	.010	664	1.1	.007	600	.7
12	14,217	.007	664	.8	.007	600	.7
13	14,217	.007	664	.8	.007	600	.7
14	14,217	.006	664	.7	.003	600	.3
Total outflow across eastern boundary				11.0	11.2		

SUMMARY

The Madison and Minnelusa aquifers are important sources of water for Rapid City and surrounding communities. To provide information for effective management of these important aquifers, a conceptual model of ground-water flow was developed. The western part of the study area includes drainage areas that contribute streamflow recharge to the Madison and Minnelusa aquifers. The eastern part of the study area is referred to as the aquifer analysis area and includes the part of the study area where the Madison and the Minnelusa aquifers exist.

In the study area, the Madison and Minnelusa hydrogeologic units outcrop on the eastern flank of the Black Hills and dip easterly. Recharge to the Madison and Minnelusa hydrogeologic units is from streamflow losses and areal recharge on outcrop areas. The Madison hydrogeologic unit includes the karstic Madison aquifer, which is the upper, more permeable 100 to 200 ft of the Madison Limestone, and the Madison confining unit, which consists of the lower, less permeable part of the Madison Limestone and the Englewood Formation. Reported well yields are as high as 2,500 gal/min. Overlying the Madison hydrogeologic unit is the Minnelusa hydrogeologic unit. This unit includes the Minnelusa aquifer, which is the upper, more permeable 200 to 300 ft of the Minnelusa Formation, and the Minnelusa confining unit, which consists of the lower, less permeable part. Reported well yields are as high as 700 gal/min.

Important concepts described in the conceptual model include streamflow recharge, areal recharge, ground-water flow, storage, unsaturated areas west of the unconfined areas, leakage between aquifers, springflow, and regional outflow.

Hydraulic properties described for the hydrogeologic units include transmissivity, vertical hydraulic conductivity, storage coefficient, and specific yield. Estimates of effective transmissivity for the Madison aquifer range from 500 to 20,000 ft²/d with the highest values in the Jackson-Cleghorn Springs area and the lowest values in the northeastern and southeastern parts of the aquifer analysis area. Generalized estimated transmissivity distributions for the Minnelusa aquifer ranged from 500 to 10,000 ft²/d with the highest values in the Jackson-Cleghorn Springs area and the lowest values in the eastern part of the aquifer analysis area. Anisotropic transmissivity in the Madison aquifer may be localized in orientation and has been documented to have tensor ratios as high as 45:1. Vertical hydraulic

conductivities for the Minnelusa confining unit determined from aquifer tests in the Rapid City area range from 1.3×10^{-3} to 3.0×10^{-1} ft/d. Leakage between the Madison and Minnelusa aquifers is spatially variable, which is consistent with the large range of vertical hydraulic conductivity. The confined storage coefficient for the Madison and Minnelusa hydrogeologic units was estimated as 3×10^{-4} . Specific yield was estimated as 0.09 for the Madison and Minnelusa aquifers and 0.03 for the Madison and Minnelusa confining units.

Potentiometric surfaces for the Madison and Minnelusa aquifers interpreted from hydraulic head in wells show a general easterly gradient with many local variations and changes in slope. The hydraulic gradient was estimated to be about 70 ft/mi on average for both aquifers. Temporal hydraulic-head change during WY88-97 ranged from about 5 to 95 ft in continuous-record observation wells. Temporal hydraulic-head change is small in the Jackson-Cleghorn Springs area and increases with distance from the springs. Confined and unconfined areas are identified based on the structural tops of formations and the potentiometric surface. The location where the average potentiometric surfaces contact the top and bottom of the aquifers and the confining units determine the boundaries of unconfined zones. The areas of Madison and Minnelusa hydrogeologic units unconfined zones are about 53 and 36 mi², respectively. Although the unconfined area represents a small part of the entire aquifer analysis area (629 mi²), change in storage in the unconfined area is orders of magnitude larger than that of the confined area.

Dye-tracer tests, stable isotopes, and hydrogeologic features were analyzed conjunctively to estimate generalized ground-water flowpaths in the Madison aquifer and to analyze their influence on the Minnelusa aquifer. Streamflow losses to the Madison hydrogeologic unit from Boxelder Creek generally flow southward from the loss zone along structural features before flowing eastward. Rapid Creek streamflow loss generally flows north from its loss zone before moving towards Jackson-Cleghorn Springs or toward the east. Most of the streamflow loss from Spring Creek moves north towards Jackson-Cleghorn Springs. The western Rapid City area between Boxelder Creek and Spring Creek is described as a high-flow area and is characterized as having undergone extensive tectonic activity, greater brecciation in the Minnelusa Formation, high transmissivities, generally upward hydraulic gradients

from the Madison to Minnelusa aquifer, many karst springs, and converging flowpaths.

Water-budget analysis of the Madison and Minnelusa hydrogeologic units for WY88-97 was divided into 6-month stress periods representing winter and summer seasons. WY88-97 included periods of both low and high recharge rates and were representative of the range of hydrologic conditions during the last 30 years. Three budgets were developed for the water-budget analysis: (1) a dry-period budget for declining water levels, October 1987 through March 1993; (2) a wet-period budget for rising water levels, April 1993 through September 1997; and (3) a full 10-year period budget. By simultaneously balancing these three water budgets, initial estimates of recharge, discharge, change in storage, and related properties were refined. Compiled water-budget flow components include streamflow recharge, areal recharge, seepage from Deadwood aquifer, water use, outflow to overlying units, regional outflow, springflow, and change in ground-water storage.

Total streamflow recharge increased from about 27 ft³/s during the dry period to 68 ft³/s during the wet period and accounted for 45 ft³/s or 61 percent of the total budget for the 10-year period. Streamflow recharge to the Minnelusa hydrogeologic unit was only 14 percent of the total streamflow recharge. Total areal recharge for the dry and wet periods was 11 and 36 ft³/s, respectively, and 22 ft³/s or 30 percent of the 10-year budget.

Average springflow for the dry and wet periods was 25 and 37 ft³/s, respectively, and accounted for 31 ft³/s or 42 percent of the 10-year budget. Water use increased from about 8 ft³/s during the dry period to 13 ft³/s during the wet period with a slight decrease in Minnelusa aquifer withdrawals and an increase in Madison aquifer withdrawals resulting from newly completed wells. Water use accounted for 10 ft³/s or 14 percent of the 10-year budget. Regional ground-water outflow was 22 ft³/s or 30 percent of the 10-year budget. Leakage to hydrogeologic units overlying the Minnelusa aquifer was about 2 ft³/s for the 10-year budget. Average net leakage from the Madison hydrogeologic unit to the Minnelusa hydrogeologic unit was 8 ft³/s.

Ground-water storage was initially estimated from changes in hydraulic head in confined and unconfined areas, specific yields, and storage coefficients. These properties were refined based on water-budget balances. Total storage decreased by about 8 ft³/s for

the dry period and increased 21 ft³/s for the wet period with a net increase in storage for the 10-year period of 5.0 ft³/s.

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APPENDICES

APPENDIX A: AQUIFER TEST AT RC-9

An aquifer test of the Madison aquifer was conducted in October 1995 by pumping well RC-9 and measuring drawdown in wells CHLN-2, RC-11, CL-2, and SP-2 (fig. 9). Industrial and municipal withdrawals from the Madison aquifer were discontinued in the area 9 days before the aquifer test began, during the pumping period, and for 6 days after pumping. The pumping rate from RC-9 was about 2,550 gal/min. A schematic diagram of RC-9 is shown in figure 32, and conceptual illustration of the aquifer test is shown in figure 33. Hydraulic-head trends were measured for 5 days prior to the test. Based on this trend and the level of recovery after a period equivalent to that of pumping (6 days), a hydraulic-head trend was estimated for the pumping and recovery period (fig. 34). The estimated trend line reflects the fact that full recovery does not take place after a period equivalent to that of pumping

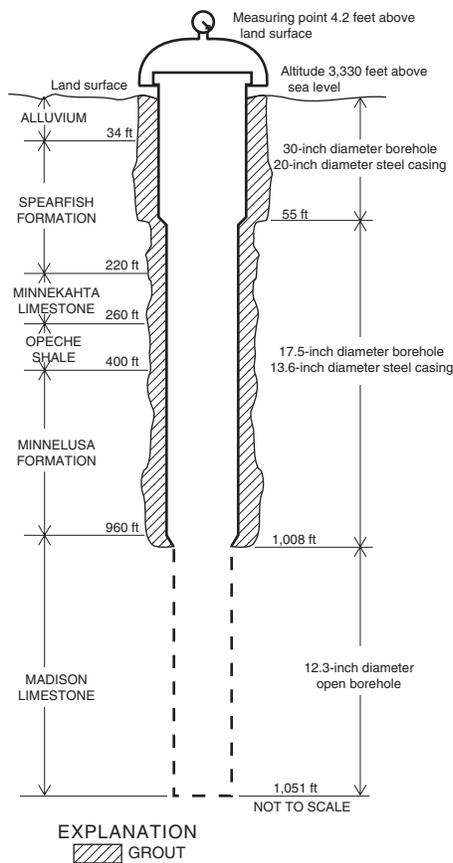


Figure 32. Schematic showing construction details of Rapid City well no. 9 (RC-9, site 49, table 28, plate 1) completed in the Madison aquifer.

(Driscoll, 1986, p. 252-253). Drawdown was calculated as the difference between this trend line and the measured hydraulic head (fig. 35). The trend line was checked by extrapolating the drawdown curve that would occur if pumping had continued through the recovery period. The extrapolated drawdown curve was calculated by requiring that $L_1 = L_2$ for every Δt value (fig. 35) (Ferris and others, 1962, p. 100-102). If the extrapolated drawdown curve appeared reasonable, the trend line was assumed to be a good estimate.

Before any analysis of data, all measurements were corrected for fluctuations induced by changes in barometric pressure (Ferris and others, 1962; Kruseman and de Ridder, 1991). Prior to the aquifer test, the relationship between barometric pressure and hydraulic head in each observation well was established. This relationship was used to correct the data so that it represents drawdown under conditions of constant barometric pressure. Measured drawdown corrected for trend and barometric effects is listed in table 27 at the end of this section.

The drawdown portion of the curves was analyzed using the method of Hantush (1960) for estimating aquifer properties in a leaky confined aquifer. The method assumes there is storage in the intervening confining unit(s). The analysis computes T , S , and β , which is given by the following equation:

$$\beta = \frac{r}{4} \left[\sqrt{\frac{K_v' S'}{b' TS}} + \sqrt{\frac{K_v'' S''}{b'' TS}} \right] \quad (9)$$

where

β = a dimensionless “lumped” parameter;

r = distance from the pumped well to the observation well [L];

T = transmissivity of the pumped aquifer [L^2/T];

K_v' = vertical hydraulic conductivity of the overlying confining unit [L/T];

K_v'' = vertical hydraulic conductivity of the underlying confining unit [L/T];

S = storage coefficient of the pumped aquifer [dimensionless];

S' = storage coefficient of the overlying confining unit [dimensionless];

S'' = storage coefficient of the underlying confining unit [dimensionless];

b' = thickness of the overlying confining unit [L]; and

b'' = thickness of the underlying confining unit [L].

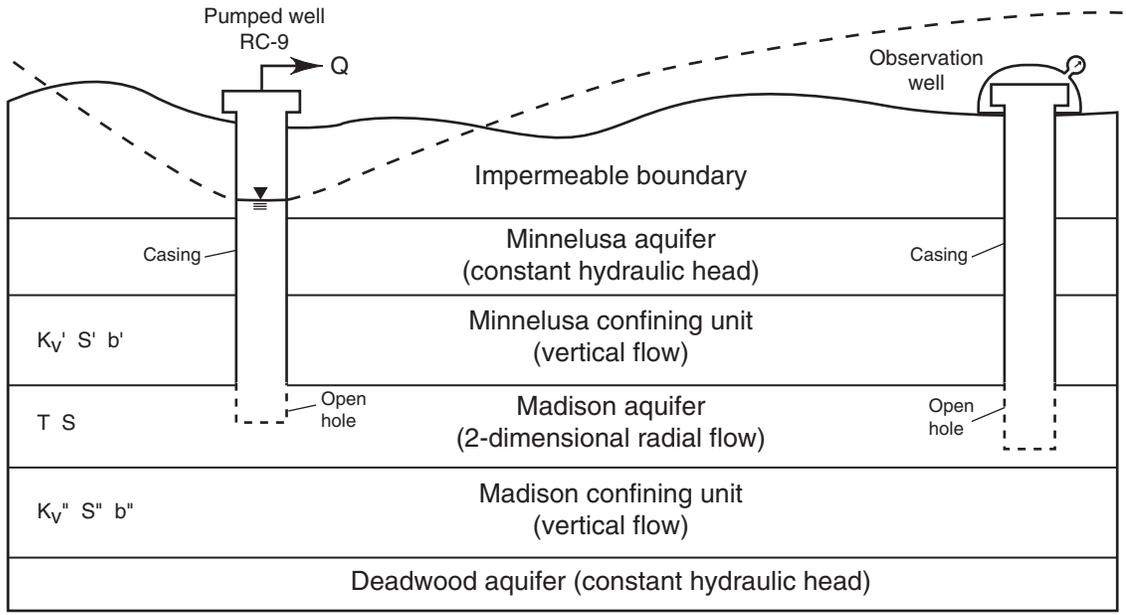


Figure 33. Diagram showing aquifer test conceptual model for multiple aquifer system.

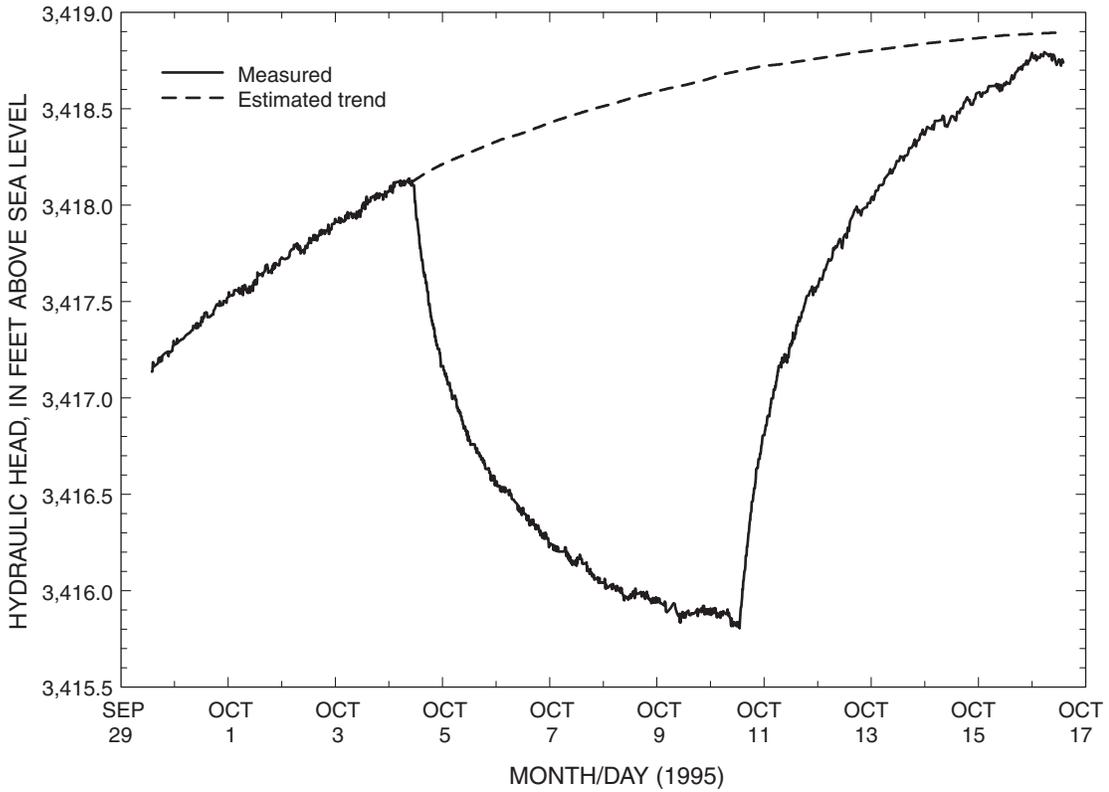


Figure 34. Aquifer test well hydrograph for CL-2 (site 50, table 28, plate 1). The trend line is the estimated water level that would have occurred without pumping.

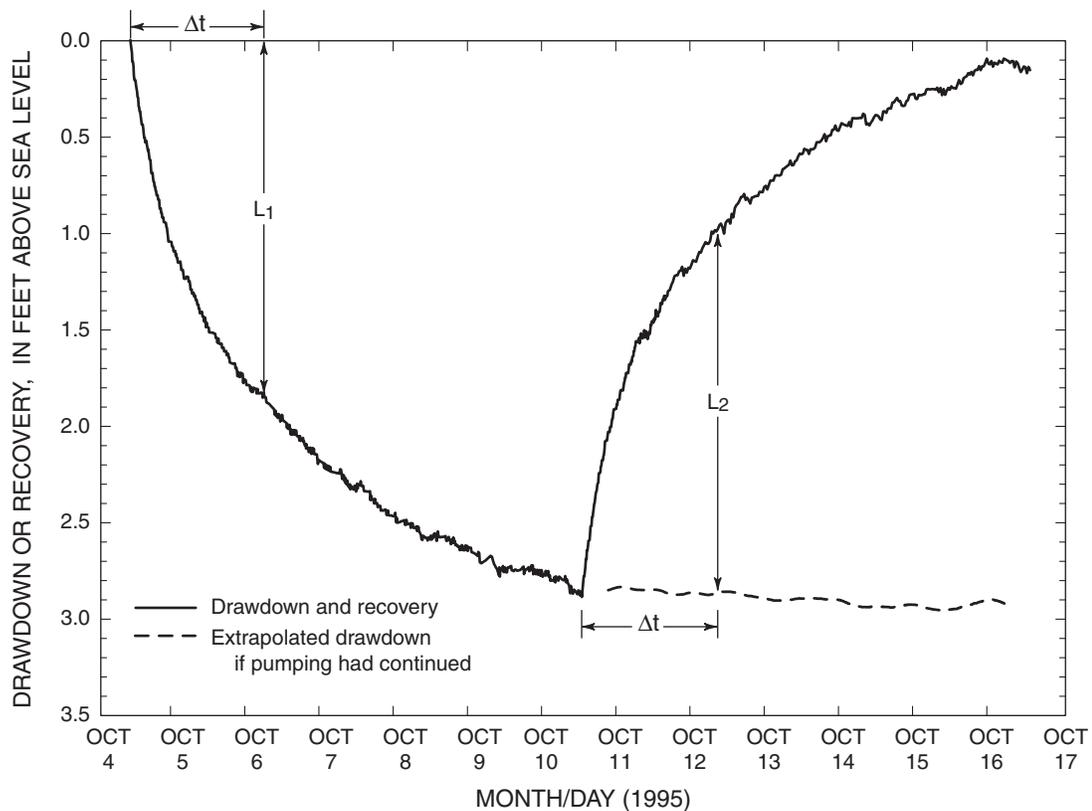


Figure 35. Drawdown and recovery curves for CL-2 (site 50, table 28 and plate 1). Curve shows drawdown if pumping had continued. For the extrapolated drawdown, $L_2 = L_1$ for every Δt .

Aquifer properties were estimated using a non-linear least squares parameter estimation technique to achieve a best fit of the drawdown data (fig. 36). Although this curve fitting method allows upper and lower limits to be placed on parameter values to be estimated, estimates were all within reasonable ranges without any constraints imposed. Table 26 shows the properties estimated by the Hantush (1960) method. K_v for the Minnelusa confining unit was computed using equation 9 by assuming that S' for the Minnelusa confining unit is 10^{-4} and b' is 300 ft. It was also assumed that K_v for the Minnelusa confining unit was at least one order of magnitude greater than that of the Madison confining unit, which makes the second term in equation 9 negligible. Because of this, no values of K_v or S for the Madison confining unit are reported.

Except for RC-11, the pumped well and observation wells do not fully penetrate the aquifer. The flow pattern to partially penetrating wells is different from fully penetrating wells. However, these effects are negligible when the distance from pumped well to observation well is larger than twice the saturated aquifer thickness (Todd, 1980, p. 149-150). This was

confirmed because the aquifer test analysis produced the same results with and without applying corrections for partial penetration.

Interference in the aquifer test occurred in well SP-2 when well BHPL (fig. 9) began pumping about 2 days into the test. The increased drawdown in SP-2 was estimated and corrected for by applying the method of Hantush and Jacob (1955) to the variable pumping rate of BHPL. This method was used because it was applied in a previous investigation whereby well RC-5 was pumped and drawdown measured in SP-2 (Greene, 1993). That aquifer test was interpreted as indicating the presence of anisotropic transmissivity. Because these three wells are nearly in a line, it was assumed that the directional T and other aquifer properties between RC-5 and SP-2 were similar to that between BHPL and SP-2. Therefore, by applying the same analytical model as in Greene (1993) and using the same properties, the drawdown at SP-2 resulting only from pumping at BHPL could be estimated because of the principle of superposition (Reilly and others, 1987). This drawdown was then subtracted from the total drawdown to obtain the drawdown resulting from withdrawal at RC-9.

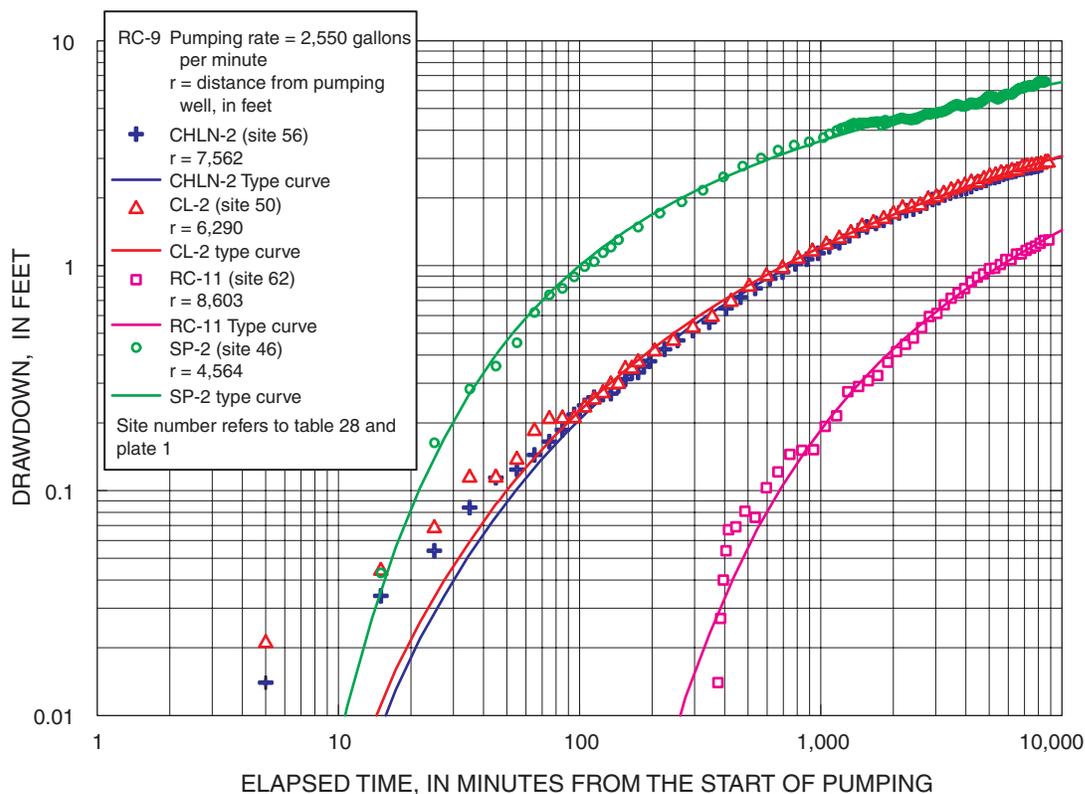


Figure 36. Drawdown curves and curve fit for the Hantush (1960) method for RC-9 aquifer test, October 1995.

Table 26. Aquifer properties for the Madison aquifer estimated by the Hantush (1960) method

[ft, feet; ft^2/d , feet squared per day; ft/d , feet per day; r , distance from pumped well; T , transmissivity; S , storage coefficient; β , lumped parameter; K_v , vertical hydraulic conductivity]

Observation well and site number (pl. 1)	r (ft)	T (ft^2/d)	S (dimensionless)	β (dimensionless)	K_v of Minnelusa confining unit (ft/d)
CL-2 (50)	6,290	14,700	2.1×10^{-5}	2.1	1.7
RC-11 (62)	8,603	11,500	2.7×10^{-4}	1.2	2.7
CHLN-2 (56)	7,562	14,100	1.4×10^{-5}	2.3	.9
SP-2 (46)	4,564	13,900	6.8×10^{-5}	.36	.3

Table 27. Drawdown data for the RC-9 aquifer test

Observation well CHLN-2 (site 56)		Observation well CL-2 (site 50)		Observation well RC-11 (site 62)		Observation well SP-2 (site 46)	
Elapsed time since start of pumping (minutes)	Drawdown (feet)						
5	0.01	5	0.02	375	0.01	15	0.04
15	.03	15	.04	385	.03	25	.16
25	.05	25	.07	395	.04	35	.28
35	.08	35	.11	405	.05	45	.36
45	.11	45	.11	415	.07	55	.45
55	.12	55	.14	445	.07	65	.62
65	.14	65	.18	485	.08	75	.74
75	.17	75	.21	535	.08	85	.79
85	.19	85	.21	595	.10	95	.89
95	.22	95	.21	665	.12	105	.99
105	.24	105	.23	745	.14	115	1.04
115	.26	115	.25	835	.15	125	1.14
125	.27	125	.27	935	.15	135	1.21
135	.27	135	.30	1,045	.19	145	1.30
145	.29	145	.30	1,165	.22	175	1.48
155	.31	155	.35	1,295	.28	215	1.71
165	.33	165	.35	1,435	.29	265	1.92
175	.34	175	.37	1,575	.31	325	2.16
185	.36	205	.42	1,725	.33	395	2.48
195	.38	245	.46	1,895	.37	475	2.77
225	.43	295	.53	2,065	.42	565	3.01
255	.46	355	.59	2,245	.45	665	3.26
295	.51	425	.69	2,425	.48	775	3.44
345	.56	505	.81	2,625	.53	895	3.55
405	.65	595	.90	2,825	.59	1,025	3.71
465	.72	695	.97	3,035	.61	1,165	3.99
535	.79	805	1.07	3,255	.67	1,305	4.17
615	.87	925	1.16	3,475	.72	1,455	4.31
695	.94	1,055	1.24	3,715	.76	1,625	4.33
785	1.02	1,195	1.32	3,955	.79	1,795	4.37
875	1.07	1,335	1.40	4,215	.85	1,085	3.85
975	1.14	1,485	1.49	4,465	.89	1,225	4.08
1,085	1.21	1,655	1.55	4,735	.92	1,365	4.28

Table 27. Drawdown data for the RC-9 aquifer test—Continued

Observation well CHLN-2 (site 56)		Observation well CL-2 (site 50)		Observation well RC-11 (site 62)		Observation well SP-2 (site 46)	
Elapsed time since start of pumping (minutes)	Drawdown (feet)						
1,195	1.27	1,825	1.61	5,005	0.97	1,515	4.31
1,315	1.36	2,005	1.70	5,275	.98	1,685	4.37
1,435	1.43	2,185	1.80	5,565	1.01	1,855	4.43
1,555	1.49	2,385	1.82	5,855	1.07	1,165	3.99
1,695	1.54	2,585	1.85	6,155	1.06	1,215	4.07
1,825	1.59	2,795	1.97	6,475	1.13	1,265	4.13
1,965	1.65	3,015	2.01	6,785	1.13	1,325	4.22
2,115	1.71	3,235	2.08	7,105	1.17	1,385	4.28
2,265	1.75	3,475	2.16	7,445	1.20	1,435	4.28
2,425	1.78	3,715	2.22	7,775	1.22	1,495	4.30
2,585	1.84	3,965	2.27	8,125	1.26	1,555	4.30
2,745	1.90	4,215	2.34	8,465	1.30	1,615	4.33
2,915	1.97	4,485	2.34	8,825	1.30	1,665	4.34
3,085	2.01	4,755	2.43			1,725	4.37
3,265	2.06	5,025	2.49			1,785	4.21
3,445	2.10	5,315	2.52			1,855	4.26
3,635	2.15	5,605	2.57			1,915	4.34
3,825	2.19	5,905	2.58			1,975	4.39
4,015	2.21	6,215	2.64			2,035	4.45
4,215	2.25	6,525	2.65			2,105	4.49
4,425	2.32	6,845	2.73			2,165	4.54
4,625	2.35	7,175	2.77			2,225	4.50
4,845	2.39	7,505	2.78			2,295	4.48
5,055	2.46	7,855	2.79			2,355	4.45
5,275	2.46	8,195	2.81			2,425	4.46
5,495	2.50	8,555	2.86			2,495	4.48
5,725	2.55	8,765	2.87			2,555	4.56
5,955	2.58					2,625	4.63
6,195	2.61					2,695	4.69
6,435	2.63					2,765	4.74
6,675	2.68					2,835	4.70
6,915	2.69					2,905	4.76
7,175	2.72					2,975	4.75

Table 27. Drawdown data for the RC-9 aquifer test—Continued

Observation well CHLN-2 (site 56)		Observation well CL-2 (site 50)		Observation well RC-11 (site 62)		Observation well SP-2 (site 46)	
Elapsed time since start of pumping (minutes)	Drawdown (feet)						
7,435	2.73					3,045	4.77
7,695	2.75					3,115	4.81
7,955	2.77					3,185	4.82
8,215	2.80					3,265	4.87
						3,335	4.93
						3,405	4.99
						3,485	5.08
						3,555	5.12
						3,625	5.20
						3,705	5.21
						3,775	5.15
						3,855	5.13
						3,935	5.11
						4,005	5.14
						4,095	5.19
						4,175	5.29
						4,255	5.30
						4,335	5.23
						4,405	5.25
						4,485	5.24
						4,565	5.31
						4,645	5.34
						4,725	5.43
						4,815	5.52
						4,895	5.61
						4,975	5.69
						5,055	5.65
						5,135	5.64
						5,225	5.63
						5,305	5.58
						5,385	5.51
						5,475	5.52
						5,555	5.56

Table 27. Drawdown data for the RC-9 aquifer test--Continued

Observation well CHLN-2 (site 56)		Observation well CL-2 (site 50)		Observation well RC-11 (site 62)		Observation well SP-2 (site 46)	
Elapsed time since start of pumping (minutes)	Drawdown (feet)						
						5,645	5.68
						5,725	5.69
						5,815	5.76
						5,895	5.79
						5,985	5.80
						6,075	5.77
						6,155	5.77
						6,245	5.81
						6,335	5.90
						6,425	5.97
						6,515	6.04
						6,605	6.10
						6,695	6.16
						6,775	6.13
						6,865	6.17
						6,955	6.19
						7,055	6.28
						7,165	6.24
						7,255	6.30
						7,345	6.29
						7,435	6.32
						7,525	6.27
						7,625	6.31
						7,715	6.32
						7,805	6.41
						7,905	6.48
						7,995	6.56
						8,085	6.61
						8,185	6.59
						8,275	6.54
						8,375	6.52
						8,465	6.60
						8,565	6.57

APPENDIX B: ADDITIONAL TABLES AND HYDROGRAPHS

Table 28. Water wells completed in the Madison aquifer

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 1)	Station identification number	Local number	Name	Adjusted hydraulic head	Land surface altitude	Use code	Depth (feet)
				(feet above sea level)			
1	441759103261202	4N6E19AABA2	MD-90A Tilford No. 2 (TF-2)	3,621	3,637	1	840
2	441500103253501	3N6E 5CACC		3,655	3,690	4	238
3	441337103225002	3N6E15ABB2	MD-94A Piedmont No. 2 (PDMT-2)	3,603	3,475	1	880
4	441220103213601	3N6E23ACD		3,341	3,540	2	918
5	441157103234301	3N6E21DDCD		3,854	3,900	4	71
6	440958103253401	2N6E 5BAC		4,340	4,640	4	400
7	440934103252001	2N6E 5CAD		4,280	4,465	4	245
8	440933103250701	2N6E 5DBD		4,280	4,500	4	282
9	441636103183801	2N7E 8BBC	Blackhawk Water Company No. 4	3,511	3,530	2	1,160
10	440851103044801	2N9E 7CDCC	Ellsworth AFB	2,687	3,230	4	4,640
11	440828103222601	2N6E10DD		3,895	4,120	4	380
12	440826103174701	2N7E 8DDCC2		3,450	3,600	4	790
13	440823103162701	2N7E16AAB		3,448	3,400	3	1,530
14	440820103232601	2N6E15BBBD		3,981	4,290	4	372
15	440811103222201	2N6E15ADAA	PE-95C Doty Madison	3,808	4,059	1	425
16	440807103225801	2N6E15BDA		3,973	4,260	4	340
17	440804103230501	2N6E15BDB		3,976	4,260	4	370
18	440804103223001	2N6E15AD		3,874	4,160	4	420
19	440804103222701	2N6E15ADDB		3,774	4,140	4	400
20	440753103110801	2N8E13BDCC	Ellsworth AFB No. 3	--	3,190	4	4,440
21	440758103225601	2N6E15CBDD		3,913	4,260	4	540
22	440753103232401	2N6E15CBBD		3,980	4,260	4	410
23	440749103221501	2N6E14CBC		3,772	4,120	4	560
24	440744103223401	2N6E15DDB		3,876	4,210	4	407
25	440658103213001	2N6E23DBAB		3,660	3,860	4	420
26	440655103140501	2N7E23DACD	Rapid City No. 8 (RC-8)	3,423	3,527	2	2,680
27	440650103193201	2N7E19CDAD		3,528	3,990	4	745
28	440631103211201	2N6E26AAD		3,645	3,940	4	357
29	440630103192501	2N7E30BADC		3,536	4,000	4	745
30	440629103040901	2N9E29BBCC	City of Box Elder	2,575	3,043	2	4,450
31	440622103152701	2N7E27ACAB	Coke Plant	3,481	3,400	3	1460
32	440612103152001	2N7E27DABB	Rapid City No. 10 (RC-10)	3,444	3,363	2	1,790

Table 28. Water wells completed in the Madison aquifer—Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 1)	Station identification number	Local number	Name	Adjusted hydraulic head	Land surface altitude	Use code	Depth (feet)
				(feet above sea level)			
33	440544103180002	2N7E32ABBC2	PE-89C City Quarry No. 2 (CQ-2)	3,451	3,492	1	826
34	440540103211301	2N6E35AADA2		3,646	4,120	2	740
35	440526103173001	2N7E32ADDD	Rapid City No. 6 (RC-6)	3,447	3,440	2	1,300
36	440523103155701	2N7E34BDCC	Black Hills Power & Light (BHPL)	3,424	3,300	3	--
37	440518103193001	2N7E31CAB		3,477	3,670	4	420
38	440512103215701	2N6E35CAC		3,734	4,130	4	436
39	440508103220701	2N6E35CCAB		3,764	4,140	4	450
40	440500103193601	2N7E31CCCA	Westberry Trails No. 2 (WT-2)	3,520	3,974	2	680
41	440453103184001	1N7E 5BBBC		3,405	3,785	4	560
42	440446103193201	1N7E 6BACB		3,430	4,020	4	770
43	440446103161701	1N7E 3BBCC	Lime Creek (LC)	3,417	3,314	1	1,390
44	440441103193301	1N7E 6BDCCD		3,428	4,080	4	930
45	440432103191401	1N7E 6ACCC		3,405	3,940	4	770
46	440430103160202	1N7E 3CBAA2	PE-65A Sioux Park No. 2 (SP-2)	3,423	3,297	1	1,170
47	440427103131701	1N7E 1DBBB	Rapid City No. 7 (RC-7, Star Village)	3,146	3,396	1	3,280
48	440337103191801	1N7E 7ACBD		3,418	3,640	4	380
49	440342103160701	1N7E10BCDB	Rapid City No. 9 (RC-9)	3,415	3,330	2	1,051
50	440338103173302	1N7E 8ADDD2	PE-89A Canyon Lake (CL-2)	3,418	3,371	1	700
51	440334103095601	1N8E 9CAB2	Rapid Valley No. 4	2,655	3,108	4	3,800
52	440326103180702	1N7E 8DBCC	Jackson Springs Well 1A (JS-1A)	3,418	3,380	4	640
53	440310103173802	1N7E 8DDCD2	Chapel Lane No. 3 (CHLN-3)	3,418	3,410	2	940
54	440308103184601	1N7E18AAAD	PE-96A Cleghorn (CLEG)	3,417	3,414	1	200
55	440308103180701	1N7E17ABCC		3,419	3,430	4	460
56	440300103173501	1N7E17AAAC	Chapel Lane No. 2 (CHLN-2)	3,419	3,433	2	820
57	440247103192401	1N7E18AACB		3,415	3,720	4	400
58	440302103194601	1N7E18BDBA		3,438	3,640	4	450
59	440247103191701	1N7E18ACCC		3,434	3,540	4	150
60	440238103185201	1N7E18DADB		3,416	3,620	4	321
61	440223103173201	1N7E17DDDA	Carriage Hills No. 1	3,426	3,871	2	725
62	440220103164001	1N7E16DCDC	Rapid City No. 11 (RC-11)	3,423	3,487	2	1,280
63	440205103172001	1N7E21BCAB		3,445	3,900	4	--
64	440054103173801	1N7E29DAAC		3,475	3,900	4	1,000
65	440523103194201	1N7E31BCAD		3,806	4,260	4	598
66	440004103174001	1N7E32DABA	Highland Hills	3,531	3,999	2	780

Table 28. Water wells completed in the Madison aquifer—Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 1)	Station identification number	Local number	Name	Adjusted hydraulic head	Land surface altitude	Use code	Depth (feet)
				(feet above sea level)			
67	435937103184101	1S7E 5BAA		3,626	3,920	2	--
68	435916103161801	1S7E 3CDBD	PE-86A Reptile Gardens (RG)	3,497	3,520	1	1,220
69	435903103181301	1S7E 8ABAA		3,594	4,100	4	754
70	435851103184201	1S7E 8BDBA		3,580	4,180	4	640
71	435851103143501	1S7E11ACAB	Hart Ranch No. 2	3,498	3,466	2	1,740
72	435746103160601	1S7E15CBBB		3,488	3,985	4	820
73	435718103130301	1S8E19BBBB	Hart Ranch No. 1	3,498	3,555	2	2,600
74	435635103181401	1S7E20DCAD	Pine Grove	3,515	4,120	2	903
75	435619103161901	1S7E27BACA		3,509	4,140	4	1,190
76	435518103173001	1S7E33BDBD		3,530	4,090	4	680
77	435227103185301	2S7E17CCAA	PE-95A Hayward (HWRD)	3,542	3,932	1	540
Wells Not Shown on Plate 1 (unreliable hydraulic heads)							
78	442217103272201	5N5E26ABDA		3,129	3,625	4	1,460
79	440443103161301	1N7E 3BBCD	Rapid City No. 5 (RC-5)	--	3,310	2	1,292
80	442058103273001	5N5E36DBCB		3,204	3,720	2	1,050
81	441845103352001	4N4E13B		4,890	5,050	4	227
82	441838103344301	4N4E13A		4,720	4,880	4	227
83	441830103312701	4N5E16BDD		4,540	4,620	4	115
84	441817103311901	4N5E16DBC		4,455	4,620	4	360
85	440933103253301	2N6E 5CAC		4,300	4,500	4	245
86	440908103193401	2N7E 7BAC		3,439	3,679	4	--
87	440805103223001	2N6E15AD		3,786	4,160	4	430
88	440810103234401	2N6E15BC		4,022	4,300	4	505
89	440755103231801	2N6E15CBA		4,015	4,320	4	480
90	440758103214301	2N6E14CAC		3,804	4,150	4	540
91	440737103222501	2N6E15DDD		3,781	4,160	4	415
92	440636103214701	2N6E26BAAC		3,694	3,950	4	340
93	440602103194201	2N7E31BCB		3,393	3,770	4	525
94	440244103191901	1N7E18BAC		3,417	3,620	4	380
95	440254103191801	1N7E18ACB		3,420	3,630	4	320
96	440248103195001	1N7E18BCC		3,585	3,600	4	32
97	440245103192501	1N7E18CAAB		3,410	3,500	4	280
98	440242103192301	1N7E18CAA		3,342	3,440	4	280
99	440241103194001	1N7E18CBA		3,650	3,700	4	185
100	435143103184401	2S7E20BDC		3,490	3,890	4	624

Table 29. Water wells completed in the Minnelusa aquifer

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head	Land surface altitude	Use code	Depth (feet)
				(feet above sea level)			
102	441812103230501	4N6E16DCB		3,454	3,460	4	1,460
103	441826103263301	4N6E17CCDA		3,564	3,578	4	590
104	441759103261201	4N6E19AABA	MD-84B Tilford No. 1 (TF-1)	3,608	3,636	1	302
105	441701103251101	4N6E29ABC	Piedmont East (PDMT-East)	3,515	3,542	1	180
106	441656103261601	4N6E30A		3,592	3,860	4	340
107	441649103262401	4N6E30ADCC		3,593	3,930	4	540
108	441620103255301	4N6E29CCC		3,529	3,630	4	240
109	441612103252801	4N6E32BAA		3,532	3,590	4	265
110	441606103252501	4N6E32BAD		3,557	3,620	4	225
111	441556103253201	4N6E32BBDD		3,514	3,680	4	280
112	441504103230301	3N6E 3BCBC		3,428	3,460	4	755
113	441500103240601	3N6E 4		3,422	3,520	4	300
114	441453103243801	3N6E 4CB		3,486	3,570	4	328
115	442221103245501	3N6E 5DA		3,527	3,590	4	250
116	441314103233301	3N6E10ABAA		3,412	3,400	4	425
117	441424103243601	3N6E 9BBCD		3,506	3,780	4	320
118	441421103242302	3N6E 9BCBB2		3,510	3,740	4	365
119	441400103231501	3N6E10BDDDB		3,478	3,435	4	625
120	441358103241801	3N6E 9CABB		3,526	3,760	4	260
121	441643103232801	3N6E10CCC		3,490	3,530	4	275
122	441339103232701	3N6E16AAAB		3,530	3,570	4	237
123	441338103233201	3N6E16AABA		3,528	3,590	4	190
124	441337103225001	3N6E15ABBB	MD-84A Piedmont No. 1 (PDMT-1)	3,481	3,475	1	440
125	441335103223202	3N6E15AAB		3,414	3,490	4	110
126	441335103223201	3N6E15AB		3,414	3,490	4	100
127	441333103222801	3N6E15AAAC		3,457	3,470	4	640
128	441331103230701	3N6E15BA3		3,454	3,530	4	160
129	441322103234202	3N6E16AD2		3,547	3,660	4	260
130	441322103234201	3N6E16AD		3,581	3,660	4	340
131	441315103224001	3N6E15DABBB		3,489	3,530	4	365
132	441257103222501	3N6E15DAA		3,458	3,590	4	263
133	441241103183401	3N7E20BB2		3,268	3,460	4	340

Table 29. Water wells completed in the Minnelusa aquifer—Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head	Land surface altitude	Use code	Depth (feet)
				(feet above sea level)			
134	441219103204801	3N6E24CABB		3,414	3,570	2	1,005
135	441242103215701	3N6E23CAB		3,495	3,730	4	288
136	441216103215801	3N6E23CABD		3,477	3,700	4	460
137	441210103215101	3N6E23CADA		3,483	3,570	4	328
138	441212103201501	3N6E24DBDA		3,366	3,840	2	1,542
139	441211103213701	3N6E23DBCA		3,458	3,560	4	375
140	441202103211301	3N6E23DDAC		3,476	3,558	4	860
141	441318103221301	3N6E24CADD		3,449	3,600	4	824
142	442137103213801	3N6E23DCB 4		3,444	3,600	4	300
143	441202103213301	3N6E23DC		3,474	3,580	4	360
144	441200103213001	3N6E23DCCB		3,471	3,605	4	305
145	441157103213701	3N6E23DDDC		3,445	3,580	4	440
146	441220103214001	3N6E23DCDC		3,451	3,608	4	360
147	441151103213002	3N6E26AABB		3,459	3,600	4	395
148	441147103270001	3N7E30BCAD		3,413	3,870	2	1,600
149	441136103221301	3N6E26ACAD		3,415	3,680	4	360
150	441134103211601	3N6E26ADBB		3,460	3,645	4	300
151	441131103200101	3N6E25ADDA		3,418	3,615	4	783
152	441130103205601	3N6E25BCDC		3,466	3,630	4	400
153	441119103210301	3N6E25CBCB		3,453	3,680	4	303
154	441105103192001	3N7E30CDD		3,454	3,650	4	1,120
155	441125103203001	3N6E25DCCD		3,413	3,690	4	500
156	441038103203001	3N6E36BADB		3,403	3,735	4	420
157	441049103203701	3N6E36BADD		3,423	3,725	4	400
158	441047103203301	3N6E36BDAA		3,423	3,720	4	400
159	441323103232301	3N6E36BDCA		3,496	3,780	4	520
160	441040103203201	3N6E36BDDA		3,438	3,740	4	--
161	441038103203002	3N6E36B		3,492	3,820	4	400
162	441037103203502	3N6E36BDD2		3,472	3,760	4	360
163	441037103203501	3N6E36BDD		3,450	3,760	4	360
164	441033103193001	3N7E31CAA		3,463	3,630	4	520
165	441031103195201	3N7E31CBBC		3,443	3,690	4	462

Table 29. Water wells completed in the Minnelusa aquifer—Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head	Land surface altitude	Use code	Depth (feet)
				(feet above sea level)			
166	441024103201301	3N6E36DBD		3,487	3,720	4	440
167	441023103204001	3N6E36CADD		3,474	3,780	4	565
168	441023103203101	3N6E36DBCC		3,440	3,810	4	540
169	441023103203001	3N6E36DBBD		3,423	3,740	4	312
170	441007103201101	2N6E 1AABB		3,432	3,725	4	340
171	440930103175201	2N7E 5DBDD		3,489	3,460	4	--
172	440936103191801	2N7E 6CDAC	Blackhawk Water Co. No. 3	3,447	3,545	2	340
173	440919103170501	2N7E 4CDCD		3,416	3,405	4	920
174	440929103163501	2N7E 4DDC		3,379	3,435	4	1,025
175	440916103163301	2N7E 9AABB		3,392	3,420	4	1,260
176	440907103183501	2N7E 8BBCD	Blackhawk Water Co. No. 2	3,386	3,510	2	750
177	440908103193101	2N7E 7BACA		3,462	3,720	4	480
178	440901103184801	2N7E 7ADAB	Blackhawk Water Co. No. 1	3,403	3,580	2	600
179	440829103183801	2N7E 8CCC		3,414	3,560	4	590
180	440826103174601	2N7E 8DDCC		3,410	3,600	4	815
181	440818103180801	2N7E17BAAD	PE-84B Blackhawk No. 1 (BLHK-1)	3,422	3,500	1	560
182	440818103174701	2N7E17BACA		3,449	3,500	4	650
183	440800103163001	2N7E16		3,313	3,360	4	320
184	440738103173901	2N7E17DDBD		3,409	3,450	4	371
185	440736103173701	2N7E17DDAA		3,412	3,450	2	400
186	440719103174801	2N7E20ABAD		3,434	3,480	4	263
187	440636103152001	2N7E27AABA		3,400	3,435	4	992
188	440635103161801	2N7E27BBCB		3,420	3,450	3	--
189	440607103155901	2N7E27CAAB		3,383	3,360	3	615
190	440606103174701	2N7E29DACB		3,419	3,600	4	349
191	440605103174701	2N7E29DAC1		3,419	3,600	4	349
192	440552103173401	2N7E29DAC5		3,421	3,570	4	220
193	440603103174501	2N7E29DAC3		3,427	3,600	4	190
194	440552103162301	2N7E28DACD		3,336	3,360	3	300
195	440557103174401	2N7E29DDB		3,414	3,600	4	308
196	440556103174801	2N7E29DDBD2		3,449	3,620	4	320
197	440542103172501	2N7E28CC		3,410	3,500	4	320

Table 29. Water wells completed in the Minnelusa aquifer—Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head	Land surface altitude	Use code	Depth (feet)
				(feet above sea level)			
198	440639103173701	2N7E29DDCA		3,443	3,620	4	340
199	440545103173501	2N7E32AAAC		3,438	3,610	4	300
200	440544103180001	2N7E32ABBD	PE-89D City Quarry No. 1 (CQ-1)	3,450	3,492	1	--
201	440544103174301	2N7E32AABD		3,444	3,640	4	302
202	440544103173601	2N7E32AAA		3,468	3,640	4	340
203	440540103194601	2N7E31BBCD		3,553	3,810	4	270
204	440539103205401	2N6E36BBD		3,769	4,080	4	390
205	440538103161001	2N7E34B		3,328	3,340	4	220
206	440534103174801	2N7E32AACD		3,467	3,640	4	195
207	440534103171401	2N7E33BCAA		3,450	3,460	4	200
208	440533103193801	2N7E31BCAA		3,416	3,720	4	440
209	440528103161001	2N7E34BCCA	PE-64A Cement Plant (CP)	3,412	3,331	1	400
210	440528103155201	2N7E34BDAD		3,406	3,350	4	585
211	440521103184401	2N7E32BCCC		3,471	3,602	4	--
212	440532103182001	2N7E32CADA		3,462	3,510	4	310
213	440514103161401	2N7E34CBCD		3,403	3,340	3	371
214	450512103182101	2N7E32CAC		3,434	3,520	4	230
215	440516103194001	2N7E31CDCB	Westberry Trails No. 1 (WT-1)	3,406	3,860	2	565
216	440501103181501	2N7E32CDAD		3,475	3,520	4	200
217	440459103181001	2N7E32CDDD		3,450	3,480	4	180
218	440458103181101	2N7E32CDDDB		3,450	3,480	4	180
219	440452103155301	1N7E 3BABD	South Dakota ARNG	3,396	3,340	4	600
220	440449103181501	1N7E 5ABCA		3,435	3,490	4	207
221	440446103181801	1N7E 5BAC		3,415	3,700	4	430
222	440445103181601	1N7E 5BACA		3,470	3,700	4	360
223	440430103160201	1N7E 3CBAA	PE 64B Sioux Park No. 1 (SP-1)	3,392	3,300	1	570
224	440423103180501	1N7E 5DBCA	West Camp Rapid No. 3 (WCR-3)	3,400	3,580	1	224
225	440403103183701	1N7E 5CDD		3,382	3,580	4	330
226	440347103190501	1N7E 7ACA		3,435	3,497	4	--
227	440344103190801	1N7E 7AC		3,456	3,506	4	152
228	440344103173701	1N7E 8AC		3,360	3,460	4	140
229	440338103173301	1N7E 8ADDD	PE-89B Canyon Lake No. 1 (CL-1)	3,360	3,371	1	--

Table 29. Water wells completed in the Minnelusa aquifer—Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head	Land surface altitude	Use code	Depth (feet)
				(feet above sea level)			
230	440331103155101	1N7E10CADD		3,396	3,410	4	700
231	440326103180703	1N7E 8DBCC2	Jackson Springs Well 1B (JS-1B)	3,395	3,380	1	--
232	440321103181001	1N7E 8CDAA		3,365	3,460	4	135
233	440310103173801	1N7E 8DDCD	Chapel Lane No. 1 (CHLN-1)	3,383	3,410	1	360
234	440309103170101	1N7E16BAAB		3,360	3,430	4	183
235	440308103183001	1N7E17BBA		3,435	3,480	4	--
236	440308103172501	1N7E16BBB		3,378	3,580	4	312
237	440308103144301	1N7E14BABD		3,353	3,833	4	1,817
238	440336103165301	1N7E16BBBB		3,353	3,575	4	250
239	440307103181501	1N7E17BABD		3,399	3,724	4	--
240	440305103164501	1N7E16BADA2		3,364	3,440	4	250
241	440211103165601	1N7E16BADA		3,370	3,440	4	207
242	440301103165701	1N7E16BAD		3,350	3,440	4	300
243	440300103170901	1N7E16BAC		3,380	3,500	4	220
244	440257103171101	1N7E16BACC		3,355	3,520	4	240
245	440252103172201	1N7E16BC		3,336	3,540	4	280
246	440249103182101	1N7E17BDC		3,450	3,480	4	115
247	440247103165401	1N7E16BDBB		3,342	3,500	4	235
248	440242103170801	1N7E16CAB		3,386	3,500	4	260
249	440244103154102	1N7E15CBBD2		3,374	3,475	4	460
250	440236103145801	1N7E14CBCA		3,351	3,880	4	1,650
251	440233103170501	1N7E16CACD		3,387	3,580	4	258
252	440223103161701	1N7E15CCBC		3,381	3,440	2	360
253	440224103172601	1N7E16CCCA	Carriage Hills No. 2	3,372	3,840	2	612
254	440214103153501	1N7E15DCCA		3,388	3,600	2	780
255	440211103165201	1N7E21BADA		3,401	3,650	4	422
256	440211103164301	1N7E21ABDB		3,409	3,570	4	200
257	440204103150001	1N7E23BCB		3,392	3,858	4	1,680
258	440203103143601	1N7E23BDAB		3,390	3,840	4	1,870
259	440158103160401	1N7E22BDCC	Spring Brook South No. 3	3,429	3,565	2	445
260	440149103164901	1N7E21DBBD	Wildwood North	3,412	3,675	1	--
261	440130103163401	1N7E21DDCD	Wildwood South	3,429	3,720	1	400

Table 29. Water wells completed in the Minnelusa aquifer—Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head	Land surface altitude	Use code	Depth (feet)
				(feet above sea level)			
262	440103103144801	1N7E26BCDA		3,376	3,720	4	1545
263	440059103154101	1N7E27DADB		3,456	3,815	4	1,430
264	440048103145001	1N7E26CCAA		3,455	3,820	4	1,460
265	440038103172601	1N7E28CCC		3,475	3,840	4	600
266	440031103162701	1N7E33AAA		3,459	3,830	4	560
267	440028103160801	1N7E34BAC		3,412	3,815	4	660
268	440027103161001	1N7E34BBCA		3,499	3,840	4	516
269	440022103163401	1N7E33AABC		3,494	3,850	4	623
270	440007103165301	1N7E33ADBB		3,455	3,840	4	540
271	440010103154201	1N7E34		3,404	3,820	4	700
272	435916103161802	1S7E 3CDBD2	PE-94A Reptile Gardens No. 2 (RG-2)	3,493	3,519	1	660
273	435858103155701	1S7E10ABBD		3,476	3,518	4	515
274	435803103160301	1S7E15ABC		3,539	3,680	4	245
275	445809103162201	1S7E15CABA		3,548	3,765	4	430
276	435720103141601	1S7E13BCBA	Hart Ranch No. 3	3,547	3,780	2	1,525
277	435352103170801	2S7E 4ACDB		3,558	3,800	4	358
278	435325103171701	2S7E 9CBDA		3,527	3,960	4	580
279	435225103172801	2S7E16CACA		3,551	3,700	4	240
280	435119103175001	2S7E21CCC		3,536	3,865	4	500
281	435115103170501	2S7E21DDC		3,511	3,750	4	350
Wells Not Shown on Plate 2 (unreliable hydraulic heads)							
282	442213103283101	5N5E26ABD		3,124	3,620	4	1,375
283	442158103284701	5N5E26		3,248	3,800	4	1,140
284	442146103272001	5N5E25CADB		3,113	3,710	2	1,000
285	442108103270301	5N5E36ADD		3,164	3,690	2	1,120
286	441903103261601	4N6E7DDBB		3,464	3,710	4	700
287	441641103252001	4N6E29BCAD		3,627	3,700	4	176
288	441648103264001	4N6E30BDA		3,743	4,000	4	540
289	441640103245901	4N6E29DAB		3,612	3,620	4	220
290	441549103252002	4N6E32(2)		3,480	3,618	4	220
291	441544103253001	4N6E32CA		3,628	3,640	4	260
292	441538103255601	4N6E32CCB		3,770	3,800	4	300

Table 29. Water wells completed in the Minnelusa aquifer—Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head	Land surface altitude	Use code	Depth (feet)
				(feet above sea level)			
Wells Not Shown on Plate 2 (unreliable hydraulic heads)—Continued							
293	441522103252501	3N6E 5BAB		3,430	3,700	4	558
294	441443103223701	3N6E 3DD		3,305	3,420	4	1260
295	441441103252301	3N6E 5CD		3,620	3,650	4	140
296	441228103185301	3N7E19ADCA		3,429	3,540	4	1,200
297	441108103205701	3N6E25CC		3,383	3,670	4	--
298	441118103210001	3N6E25CCDD		3,400	3,720	4	370
299	441051103205901	3N6E36BBCA		3,363	3,760	4	570
300	441029103202201	3N6E36DB		3,547	3,722	4	338
301	440930103190501	2N7E 6DCD		3,426	3,520	4	--
302	440927103173501	2N7E 5DDA		3,380	3,440	4	885
303	440913103194001	2N7E 7BB		--	3,520	4	380
304	440820103164701	2N7E16ABBD		3,267	3,400	4	445
305	440747103174901	2N7E17D		3,399	3,460	4	440
306	440702103181401	2N7E20CAAC		3,300	3,580	4	380
307	440605103182801	2N7E29DBD		3,505	3,685	4	330
308	440525103171701	2N7E33BCD		3,340	3,430	4	240
309	440522103185301	2N7E31ADCD		3,534	3,680	4	247
310	440518103163604	2N7E33DAB4		3,388	3,400	4	220
311	440517103194801	2N7E31CBBD		3,672	3,800	4	260
312	440508103221001	2N6E35CCBA		3,827	4,180	4	582
313	440458103180101	2N7E32CCDC		3,400	3,640	4	--
314	440447103183101	1N7E 5BBDB		3,394	3,770	4	500
315	440414103164601	1N7E 4DCB	Rapid City No. 4 (RC-4)	--	3,350	2	1,080
316	441351103171301	1N7E 9BBCA	Rapid City No. 3 (RC-3)	--	3,376	2	902
317	440338103171601	1N7E 9BCDC	Rapid City No. 1 (RC-1)	--	3,360	2	1,460
318	440331103200301	1N6E12DAAC		3,560	3,860	4	415
319	440328103191001	1N7E7DBC		3,640	3,700	4	155
320	440302103172601	1N7E16BAD2		3,415	3,440	4	222
321	440255103172601	1N7E16BCB		3,432	3,560	4	200
322	440249103172701	1N7E16BCC		3,404	3,580	4	317
323	440246103180801	1N7E17		3,683	3,700	4	78

Table 29. Water wells completed in the Minnelusa aquifer—Continued

[Use codes: 1, continuous-record observation well; 2, public supply well; 3, industrial/commercial; 4, other/unknown. --, no data available]

Site number (pl. 2)	Station identification number	Local number	Name	Adjusted hydraulic head	Land surface altitude	Use code	Depth (feet)
				(feet above sea level)			
Wells Not Shown on Plate 2 (unreliable hydraulic heads)—Continued							
324	440331103142701	1N7E11DBAD		3,164	3,560	4	1,755
325	440234103171201	1N7E16CACC		3,415	3,600	4	300
326	440202103165801	1N7E21BDA		3,384	3,760	4	565
327	440158103165601	1N7E21(2)		3,622	3,740	4	240
328	440155103165001	1N7E21ACC		3,574	3,660	4	--
329	440149103144301	1N7E23CAB		3,425	3,810	4	1,563
330	440148103164101	1N7E21DBA		3,388	3,620	4	602
331	440130103153901	1N7E22DCC		3,365	3,780	4	875
332	440129103161301	1N7E22CCC		3,591	3,650	4	315
333	440022103171301	1N7E33(3)		3,693	3,860	4	430
334	435845103163401	1S7E10BCAC		3,476	3,700	4	300
335	435340103161001	2S7E10BAD		3,366	3,660	4	675
336	435053103170001	2S7E28ADCB		3,492	3,760	4	300
337	435052103182801	2S7E29		3,661	3,800	4	--
338	435052103172901	2S7E28BDCA		3,459	3,825	4	425
339	435050103170501	2S7E28ACDC		3,608	3,700	4	167
340	435050103165301	2S7E28ADD		3,571	3,740	4	320
341	435042103180301	2S7E29DACA		3,527	3,590	4	75
342	435048103171301	2S7E28CABA		3,439	3,545	4	320
343	435031103173401	2S7E28CDBC		3,488	3,560	4	77
344	435028103240601	2S7E28DDCB		3,477	3,760	4	309
345	435018103155801	2S7E34ABBA	CU-83A West Hermosa (WH)	3,554	3,478	1	510
346	435019103173101	2S7E33BABA		3,533	3,820	4	468
347	435010103173001	2S7E33BAC		3,500	3,760	4	292
348	435008103162501	2S7E34BDBC		3,477	3,500	4	225
349	435006103163801	2S7E34BCB		3,590	3,560	4	240

Some wells were monitored discontinuously or were monitored continuously for brief periods (figs. 37-39). Although very few hydraulic-head measurements have been made at the Hart Ranch wells,

the measurements indicate that a continuous hydrograph at these locations probably would be very similar to that of well RG (fig. 37).

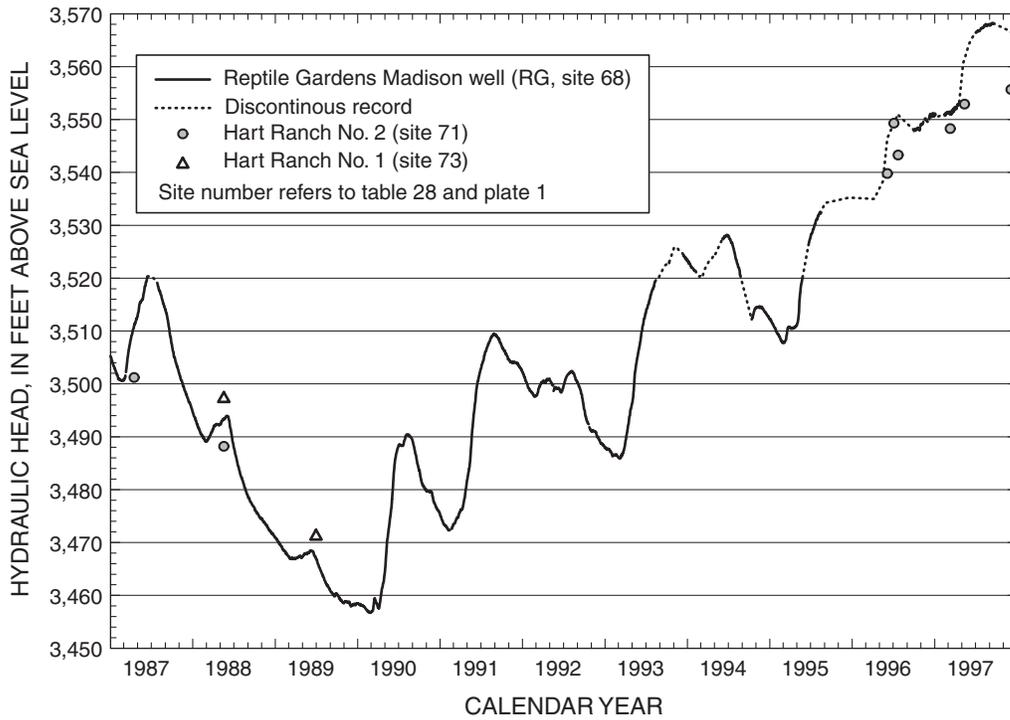


Figure 37. Hydraulic head in Hart Ranch No. 1 and 2 wells plotted with the Reptile Gardens (RG) Madison well. The three wells were completed in the Madison aquifer. The plot shows the similarity of hydraulic head in the Hart Ranch wells to that of the Reptile Gardens well.

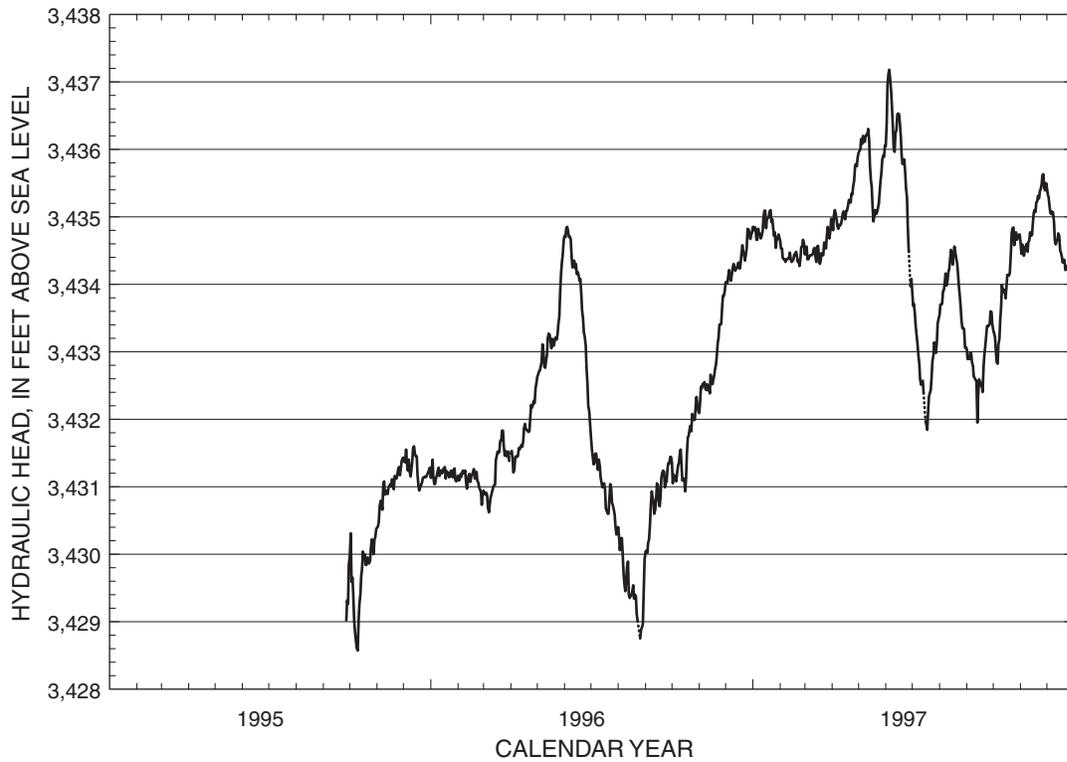


Figure 38. Hydraulic head in well RC-11 (site 62, table 28 and plate 1) completed in the Madison aquifer. The well is influenced by pumping during the summer months.

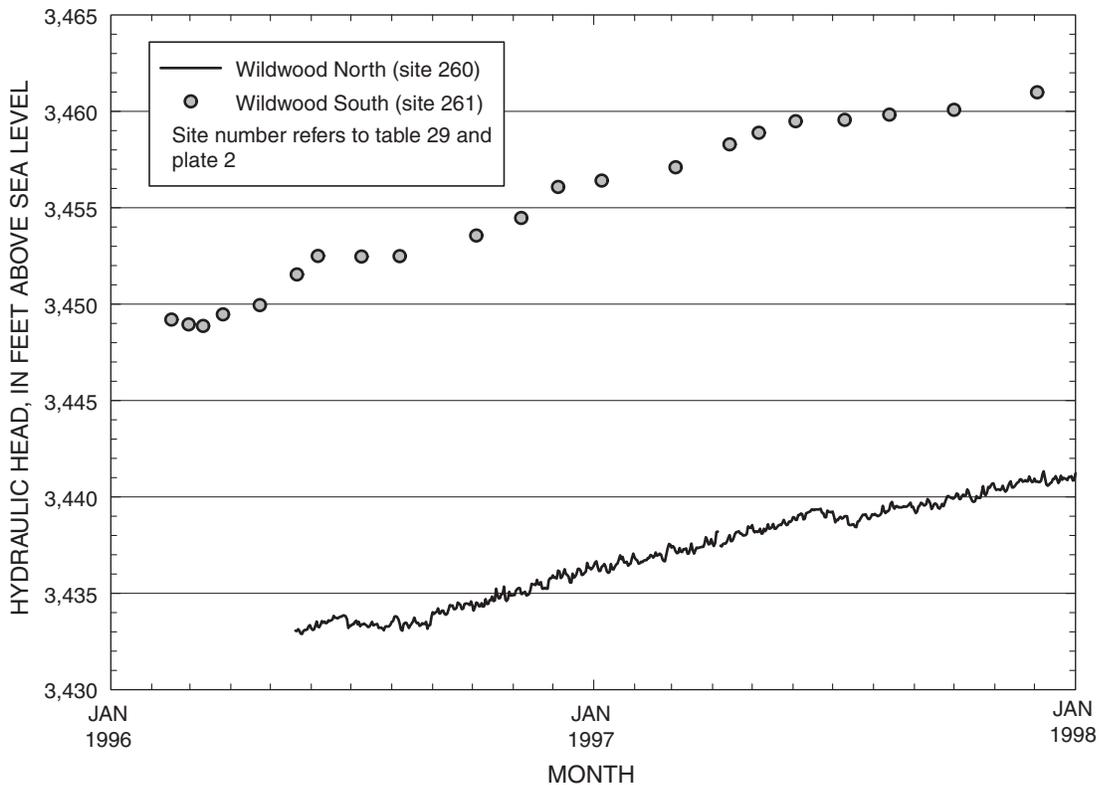


Figure 39. Hydraulic head in the Wildwood North and South wells completed in the Minnelusa aquifer.