Hydrologic Conditions and Budgets for the Black Hills of South Dakota, Through Water Year 1998

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ABSTRACT

The Black Hills are an important recharge area for aquifers in the northern Great Plains. The surface-water hydrology of the area is highly influenced by interactions with the Madison and Minnelusa aquifers, including large springs and streamflow loss zones. Defining responses of ground water and streamflow to a variety of hydrogeologic influences is critical to development of hydrologic budgets for ground- and surface-water systems.

Hydrographs for 52 observation wells and 1 cave site are used to show ground-water response to cumulative precipitation departures. Aquifers considered include the Precambrian, Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara aquifers, with wells completed in the Inyan Kara aquifer generally showing small response to precipitation patterns. Many wells completed in the other aquifers have large short- and long-term fluctuations in water levels. Madison and Minnelusa wells in the southern Black Hills show a general tendency for smaller water-level fluctuations than in other areas.

Streamflow characteristics and relations with precipitation are examined for 33 gaging stations representative of five different hydrogeologic settings that are identified. The "limestone headwater" setting occurs within outcrops of the Madison Limestone and Minnelusa Formation along the "Limestone Plateau," where direct runoff is uncommon and streamflow consists almost entirely of base flow originating as ground-water discharge from headwater springs. Thus, variability in daily, monthly, and annual flow is small. Annual streamflow correlates poorly with precipitation; however, consideration of "moving averages" (involving up to 11 years of annual precipitation data for some stations) improves relations substantially.

The "crystalline core" area is encircled by the outcrop band of the Madison and Minnelusa Formations and is dominated by igneous and metamorphic rocks. Base flow ranges from about 41 to 73 percent for representative streams; however, monthly flow records demonstrate short-term response to precipitation, which probably indicates a relatively large component of interflow. Streamflow generally correlates well with annual precipitation, with r^2 values ranging from 0.52 to 0.87.

Downgradient from the crystalline core area is the "loss zone" setting, where streamflow losses occur to outcrops of the Madison and Minnelusa Formations. Relations between streamflow and annual precipitation are defined by a power equation for the only two representative gages in this setting. The loss zone and "artesian spring" areas are combined because many artesian springs are located along stream channels that are influenced

by streamflow losses and several artesian springs are within outcrops of the Minnelusa Formation. Streamflow characteristics for artesian springs generally have small variability and poor correlations with annual precipitation because of large influence from relatively stable ground-water discharge. The "exterior" setting is located downgradient from the outcrop of the Inyan Kara Group, which coincides with the outer extent of the loss zone/artesian spring setting. Large flow variability is characteristic for this setting, and base flow generally is smaller than for other settings.

Basin yields are highly variable, with the largest yields occurring in high-altitude areas of the northern Black Hills that receive large annual precipitation. Relations between annual yield efficiency and precipitation were applied by previous investigators in developing a method for estimating annual precipitation recharge, based on annual precipitation. The resulting "yield-efficiency algorithm" compares spatial distributions for annual precipitation, average annual precipitation, and efficiency of basin yield. This algorithm is applied in estimating precipitation recharge on aquifer outcrops and in estimating streamflow yield from various outcrop areas, for purposes of developing average hydrologic budgets for water years 1950-98.

For the entire study area, precipitation averaged 18.98 inches or about 5.2 million acre-ft per year. Of this amount, total yield is estimated as 441,000 acre-ft per year (608 ft^3/s), which is equivalent to 1.59 inches over the study area. Ground-water budgets are developed for the major bedrock aquifers within the study area (Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara aquifers) and for additional minor bedrock aquifers. Annual recharge to all bedrock aquifers is estimated as 252,000 acre-ft per year (348 ft^3/s), of which 292 ft^3/s is recharge to the Madison and Minnelusa aquifers. Of this amount, 200 ft^3/s is from precipitation recharge and 92 ft^3/s is from streamflow losses. Discharge of all wells and springs is about 259 ft^3/s, of which the Madison and Minnelusa aquifers account for 206 ft^3/s of springflow and 28 ft^3/s of well withdrawals. Estimated springflow and well withdrawals from the Deadwood aquifer are 12.6 ft^3/s and 1.4 ft^3/s, respectively. Estimated well withdrawals from other aquifers account for about 11 ft^3/s. These estimates are used in calculating net ground-water outflow (outflow minus inflow) from the study area as 89 ft^3/s, which is dominated by net ground-water outflow of 58 ft^3/s from the Madison and Minnelusa aquifers.

Surface-water inflows and outflows average 252 and 553 ft^3/s, respectively. Reservoir storage increased by about 7 ft^3/s during 1950-98; thus, net tributary flows (flows less depletions) generated within the study area are calculated as 308 ft^3/s. Consideration of combined ground- and surface-water budgets is used to estimate consumptive streamflow withdrawals of 140 ft^3/s. Total consumptive use is estimated as 218 ft^3/s, by including estimates of reservoir evaporation and storage changes (38 ft^3/s) and well withdrawals (40 ft^3/s).

The largest error potential associated with development of hydrologic budgets is the use of the yield-efficiency algorithm for estimating precipitation recharge and streamflow yield. The ability to balance overall hydrologic budgets within realistic ranges provides confidence that the method systematically produces reasonable estimates when applied over sufficiently large spatial extents and time frames. This conclusion is especially important because estimation of precipitation recharge for the Madison and Minnelusa aquifers is critical to developing realistic hydrologic budgets for the Black Hills area.

INTRODUCTION

The Black Hills area is an important resource center that provides an economic base for western South Dakota through tourism, agriculture, the timber industry, and mineral resources. In addition, water originating from the area is used for municipal, industrial, agricultural, and recreational purposes throughout much of western South Dakota. The Black Hills also are an important recharge area for aquifers in the northern Great Plains.

Population growth, resource development, and periodic droughts have the potential to affect the quantity, quality, and availability of water within the Black Hills area. Because of this concern, the Black Hills Hydrology Study was initiated in 1990 to assess the quantity, quality, and distribution of surface water and ground water in the Black Hills area of South Dakota (Driscoll, 1992). This long-term study is a cooperative effort between the U.S. Geological Survey (USGS), the South Dakota Department of Environment and Natural Resources, and the West Dakota Water Development District, which represents various local and county cooperators.

Ground-water levels and streamflow in the Black Hills area are heavily influenced by geology and climatic conditions. Both also are influenced by human effects, such as reservoirs, diversions, and withdrawals. Defining responses of ground-water levels and streamflow to hydrogeologic and climatic factors and quantifying hydrologic budgets for ground- and surface-water systems are important for managing the water resources in the Black Hills area. Hydrologic budgets for the Madison and Minnelusa aquifers are especially important because the surface-water hydrology of the area is highly influenced by complex interactions with these aquifers. Readers are specifically referred to other publications that provide detailed descriptions of recharge conditions (Carter, Driscoll, and Hamade, 2001) and hydrologic budgets (Carter, Driscoll, Hamade, and Jarrell, 2001) for these aquifers.

Purpose and Scope

The purposes of this report are to describe hydrologic conditions and to present hydrologic budgets for the Black Hills area. Specifically, this report describes: (1) precipitation patterns and the corresponding responses of ground-water levels and streamflow; and (2) the relations between precipitation and streamflow. Hydrologic budgets are presented for ground water, surface water, and combined ground-water/surface-water systems. Ground-water budgets are presented for five major bedrock aquifers (Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara aquifers) and several minor bedrock aquifers.

The primary period considered for hydrologic budgets is water years 1950-98; however, other periods are considered for various purposes, especially for comparisons between precipitation and hydrologic response. Hydrologic analyses within this report generally are by water year, which represents the period from October 1 through September 30, and discussions of timeframes refer to water years, rather than calendar years, unless specifically noted otherwise.

Description of Study Area

The study area for the Black Hills Hydrology Study consists of the topographically defined Black Hills and adjacent areas located in western South Dakota (fig. 1). Outcrops of the Madison Limestone and Minnelusa Formation, as well as the generalized outer extent of the Inyan Kara Group, which approximates the outer extent of the Black Hills area, also are shown in figure 1. The study area includes most of the larger communities in western South Dakota and contains about one-fifth of the State's population.

Physiography, Land Use, and Climate

The Black Hills uplift formed as an elongated dome about 60 to 65 million years ago during the Laramide orogeny (DeWitt and others, 1986). The dome trends north-northwest and is about 120 mi long and 60 mi wide. Land-surface altitudes range from 7,242 ft above sea level at Harney Peak to about 3,000 ft in the adjacent plains. Most of the higher altitudes are heavily forested with ponderosa pine, which is the primary product of an active timber industry. White spruce, quaking aspen, paper birch, and other native trees and shrubs are found in cooler, wetter areas (Orr, 1959). The lower altitude areas surrounding the Black Hills primarily are urban, suburban, and agricultural. Numerous deciduous species such as cottonwood, ash, elm, oak, and willow are common along stream bottoms in the lower altitudes. Rangeland, hayland, and winter wheat farming are the principal agricultural uses for dryland areas. Alfalfa, corn, and vegetables are produced in bottom lands and in irrigated areas. Various other crops, primarily for cattle fodder, are produced in both dryland areas and in bottom lands.

Since the 1870's, the Black Hills have been explored and mined for many mineral resources including gold, silver, tin, tungsten, mica, feldspar, bentonite, beryl, lead, zinc, uranium, lithium, sand, gravel, and oil (U.S. Department of Interior, 1967). Mines within the study area have utilized placer mining, small surface pits, underground mines, and open-pit mines.

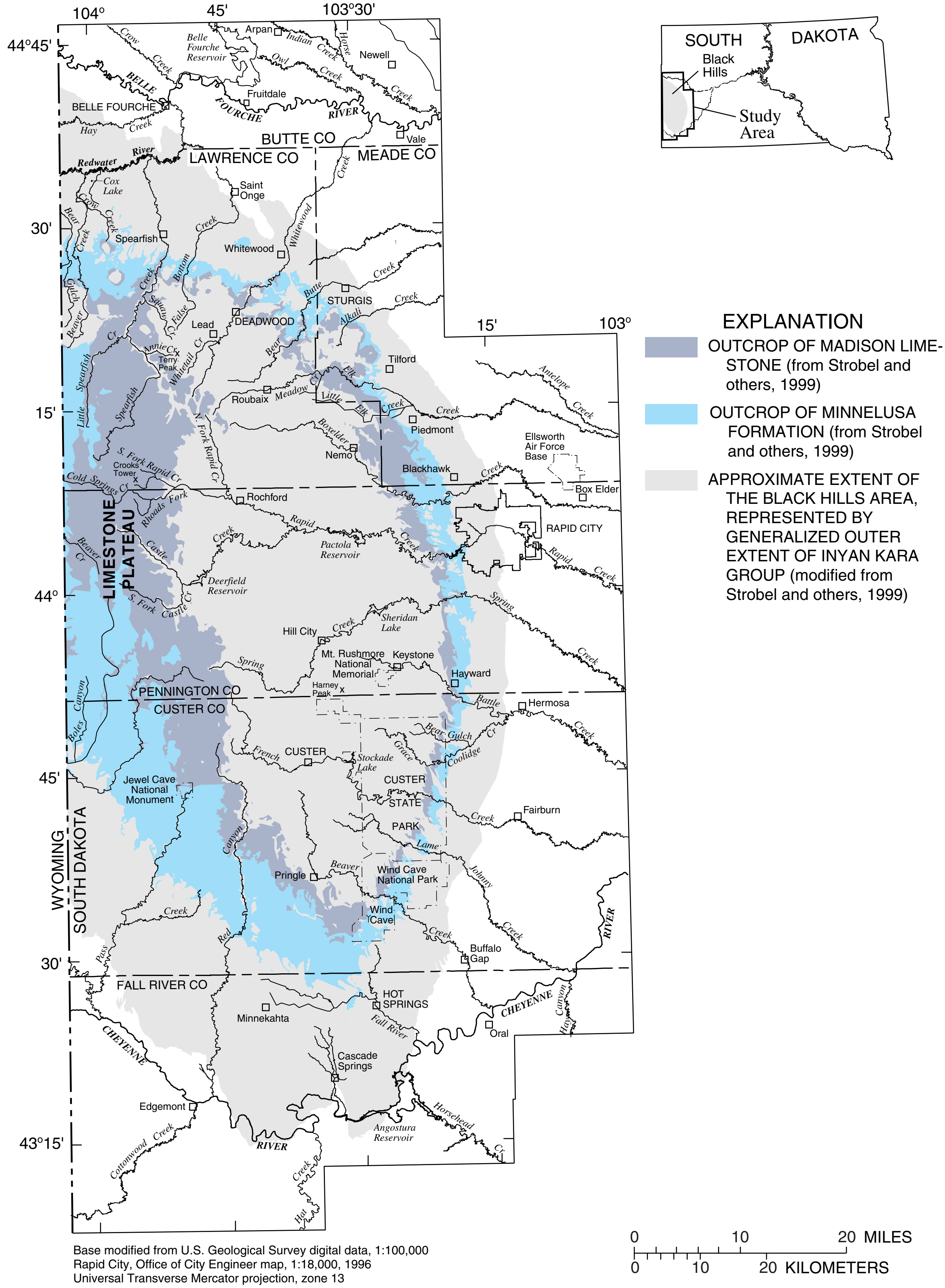

Figure 1. Area of investigation for the Black Hills Hydrology Study.

The overall climate of the study area is continental, with generally low precipitation amounts, hot summers, cold winters, and extreme variations in both precipitation and temperatures (Johnson, 1933). Climatic conditions are affected by regional patterns, with the northern Black Hills influenced more by moist air currents out of the northwest than the southern Black Hills. Local climatic conditions are affected by topography, with generally lower temperatures and higher precipitation at the higher altitudes.

The average annual precipitation for the study area (water years 1931-98) is 18.61 inches and has ranged from 10.22 inches for 1936 to 27.39 inches for 1995 (Driscoll, Hamade, and Kenner, 2000). Annual averages for counties within the study area range from 16.35 inches for Fall River County to 23.11 inches for Lawrence County. The largest precipitation amounts typically occur in the northern Black Hills near Lead, where average annual precipitation exceeds 28 inches. The average annual temperature is 43.9°F (National Oceanic and Atmospheric Administration, 1998) and ranges from 48.7°F at Hot Springs to approximately 37°F near Deerfield Reservoir. Average annual evaporation potential generally exceeds average annual precipitation throughout the study area. Average pan evaporation for April through October is about 30 inches at Pactola Reservoir and about 50 inches at Oral.

Water Use

The largest consumptive use of water within the study area is surface-water withdrawals for irrigation supplies (Amundson, 1998). The largest withdrawals are associated with irrigation projects along Rapid Creek and the Cheyenne and Belle Fourche Rivers, where Bureau of Reclamation storage reservoirs provide reliable water supplies. Angostura Reservoir (fig. 1) supplies the Angostura Unit; Deerfield and Pactola Reservoirs supply the Rapid Valley Project; and Keyhole (located in northeastern Wyoming) and Belle Fourche Reservoirs supply the Belle Fourche Project (Bureau of Reclamation, 1999). Details about these reservoirs, along with storage records through 1993, were reported by Miller and Driscoll (1998).

Large irrigation withdrawals also are made from Beaver Creek near Buffalo Gap and from Spearfish Creek and the Redwater River in the northern Black Hills, where streamflow is sufficiently reliable to provide consistent supplies. Smaller irrigation withdrawals are made from many other area streams.

Streamflow in many area streams is influenced by a variety of other generally non-consumptive diversions and regulation mechanisms (such as smaller reservoirs). Diversions from Rapid, Elk, and Spearfish Creeks have historically provided water for mining operations (Homestake Mining Company) and municipal supplies (Lead and Deadwood) in the Whitewood Creek Basin (Miller and Driscoll, 1998). Homestake Mining Company also diverts water from Spearfish Creek for two hydropower plants; however, these flows are returned to Spearfish Creek. Substantial withdrawals for municipal supplies also are made from Rapid Creek.

Ground-water withdrawals for irrigation were smaller during 1995 than for combined municipal, domestic, and commercial/industrial uses (Amundson, 1998), which have increased steadily with increasing population in the study area. Rapid City, which is the largest supplier of municipal water in the area, obtains water from a combination of bedrock, alluvial, and surface sources (Anderson and others, 1999). The Madison and Minnelusa aquifers are the most heavily utilized bedrock sources of ground water in the study area. A detailed compilation of withdrawals from the Madison and Minnelusa aquifers is provided by Carter, Driscoll, Hamade, and Jarrell (2001).

Hydrogeology

The oldest geologic units in the study area are the Precambrian crystalline (igneous and metamorphic) rocks (fig. 2), which form a basement under the Paleozoic, Mesozoic, and Cenozoic rocks and sediments. The Precambrian rocks range in age from 1.7 to about 2.5 billion years, and were eroded to a gentle undulating plain at the beginning of the Paleozoic Era (Gries, 1996). The Precambrian rocks are highly variable, but are composed mostly of igneous rocks or metasedimentary rocks, such as schists and graywackes. The Paleozoic and Mesozoic rocks were deposited as nearly horizontal beds. Subsequent uplift during the Laramide orogeny and related erosion exposed the Precambrian rocks in the crystalline core of the Black Hills, with the Paleozoic and Mesozoic sedimentary rocks exposed in roughly concentric rings around the core. Deformation during the Laramide orogeny contributed to the numerous fractures, folds, and other structural features present throughout the Black Hills. Tertiary intrusive activity also contributed to rock fracturing in the northern Black Hills where numerous intrusions exist.

ERATHEM	SYSTEM	ABBREVIATION FOR STRATIGRAPHIC INTERVAL	STRATIGRAPHIC UNIT	THICKNESS IN FEET	DESCRIPTION
CENOZOIC	QUATERNARY & TERTIARY (?)	QTac	UNDIFFERENTIATED ALLUVIUM AND COLLUVIUM	0-50	Sand, gravel boulders, and clay.
		Tw	WHITE RIVER GROUP	0-300	Light colored clays with sandstone channel fillings and local limestone lenses.
	TERTIARY	Tui	INTRUSIVE IGNEOUS ROCKS	--	Includes rhyolite, latite, trachyte, and phonolite.
MESOZOIC	CRETACEOUS	Kps	PIERRE SHALE	1,200-2,700	Principal horizon of limestone lenses giving teepee buttes. Dark-gray shale containing scattered concretions. Widely scattered limestone masses, giving small teepee buttes. Black fissile shale with concretions.
			NIOBRARA FORMATION	[1]80-300	Impure chalk and calcareous shale.
			CARLILE SHALE: Turner Sandy Member; Wall Creek Member	[1]350-750	Light-gray shale with numerous large concretions and sandy layers. Dark-gray shale
			GREENHORN FORMATION	225-380	Impure slabby limestone. Weathers buff. Dark-gray calcareous shale, with thin Orman Lake limestone at base.
			GRANEROS GROUP: BELLE FOURCHE SHALE	150-850	Gray shale with scattered limestone concretions. Clay spur bentonite at base.
			GRANEROS GROUP: MOWRY SHALE	125-230	Light-gray siliceous shale. Fish scales and thin layers of bentonite.
			GRANEROS GROUP: MUDDY SANDSTONE / NEWCASTLE SANDSTONE	0-150	Brown to light-yellow and white sandstone.
			GRANEROS GROUP: SKULL CREEK SHALE	150-270	Dark-gray to black siliceous shale.
		Kik	INYAN KARA GROUP: FALL RIVER FORMATION	10-200	Massive to thin-bedded, brown to reddish-brown sandstone.
			INYAN KARA GROUP: LAKOTA FM: Fuson Shale; Minnewaste Limestone; Chilson Member	10-190 0-25 25-485	Yellow, brown, and reddish-brown massive to thin-bedded sandstone, pebble conglomerate, siltstone, and claystone. Local fine-grained limestone and coal.
	JURASSIC	Ju	MORRISON FORMATION	0-220	Green to maroon shale. Thin sandstone.
			UNKPAPA SS	0-225	Massive fine-grained sandstone.
			SUNDANCE FORMATION: Redwater Member; Lak Member; Hulett Member; Stockade Beaver Mem.; Canyon Spr Member	250-450	Greenish-gray shale, thin limestone lenses. Glauconitic sandstone; red sandstone near middle.
			GYPSUM SPRING FORMATION	0-45	Red siltstone, gypsum, and limestone.
	TRIASSIC	ŦRPs	SPEARFISH FORMATION Goose Egg Equivalent	375-800	Red silty shale, soft red sandstone and siltstone with gypsum and thin limestone layers. Gypsum locally near the base.
PALEOZOIC	PERMIAN	Pmk	MINNEKAHTA LIMESTONE	[1]25-65	Thin to medium-bedded, fine-grained, purplish gray laminated limestone.
		Po	OPECHE SHALE	[1]25-150	Red shale and sandstone.
		Pℙm	MINNELUSA FORMATION	[1]375-1,175	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.
	PENNSYLVANIAN				
	MISSISSIPPIAN	MDme	MADISON (PAHASAPA) LIMESTONE	[1]<200-1,000	Massive light-colored limestone. Dolomite in part. Cavernous in upper part.
	DEVONIAN		ENGLEWOOD FORMATION	30-60	Pink to buff limestone. Shale locally at base.
	ORDOVICIAN	Ou	WHITEWOOD (RED RIVER) FORMATION	[1]0-235	Buff dolomite and limestone.
			WINNIPEG FORMATION	[1]0-150	Green shale with siltstone.
	CAMBRIAN	OЄd	DEADWOOD FORMATION	[1]0-500	Massive to thin-bedded buff to purple sandstone. Greenish glauconitic shale, flaggy dolomite, and flat-pebble limestone conglomerate. Sandstone, with conglomerate locally at the base.
PRECAMBRIAN		pЄu	UNDIFFERENTIATED IGNEOUS AND METAMORPHIC ROCKS		Schist, slate, quartzite, and arkosic grit. Intruded by diorite, metamorphosed to amphibolite, and by granite and pegmatite.

[1]Modified based on drill-hole data

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

Figure 2. Stratigraphic section for the Black Hills.

Surrounding the crystalline core is a layered series of sedimentary rocks (fig. 3) including outcrops of the Madison Limestone (also locally known as the Pahasapa Limestone) and the Minnelusa Formation. In this report, references to the outcrop of the Madison Limestone also include the Englewood Formation, which was grouped with the Madison Limestone as a hydrogeologic unit (fig. 3) by Strobel and others (1999). The bedrock sedimentary units typically dip away from the uplifted Black Hills at angles that can approach or exceed 15 to 20 degrees near the outcrops, and decrease with distance from the uplift to less than 1 degree (Carter and Redden, 1999a, 1999b, 1999c, 1999d, 1999e) (fig. 4).

The Precambrian basement rocks generally have low permeability and form the lower confining unit for the series of sedimentary aquifers in the Black Hills area. Localized aquifers occur in Precambrian rocks in many locations in the crystalline core of the Black Hills, where enhanced secondary permeability results from weathering and fracturing. The thickness of these aquifers is estimated to be less than 500 ft (Rahn, 1985). Water-table (unconfined) conditions generally prevail in these aquifers, and land-surface topography can strongly control ground-water flow directions. Many wells completed in the Precambrian rocks are located along stream channels.

The hydrogeologic setting of the Black Hills area is schematically illustrated in figure 5. Many of the sedimentary units contain aquifers, both within and beyond the study area. Within the Paleozoic rock interval, aquifers in the Deadwood Formation, Madison Limestone, Minnelusa Formation, and Minnekahta Limestone are used extensively and all are considered major aquifers within the study area. These aquifers receive recharge from infiltration of precipitation on outcrops, and the Madison and Minnelusa aquifers also receive significant recharge from streamflow losses. These aquifers are collectively confined by the underlying Precambrian rocks and the overlying Spearfish Formation. Individually, these aquifers are separated by minor confining units or by relatively impermeable layers within the individual units. In general, ground-water flow in these aquifers is radially outward from the crystalline core of the Black Hills. Although the lateral component of ground-water flow predominates, extremely variable leakage can occur between these aquifers (Peter, 1985; Greene, 1993).

The Jurassic rock interval generally is considered to be a semiconfining unit with interbedded shales, sandstones, and gypsum (Strobel and others, 1999). The sandstones within the Sundance Formation form a minor aquifer where saturated. Aquifers in various other formations are used locally to lesser degrees.

Within the Mesozoic rock interval, the Inyan Kara aquifer is used extensively. Aquifers in various other units, such as the Newcastle Sandstone, are used locally to lesser degrees. The Inyan Kara aquifer receives recharge primarily from precipitation on the outcrop. The Inyan Kara aquifer also may receive recharge from leakage from the underlying aquifers (Swenson, 1968; Gott and others, 1974). As much as 4,000 ft of Cretaceous shales act as the upper confining layer to aquifers in the Mesozoic rock interval.

Artesian (confined) conditions generally exist within the aforementioned aquifers, where an upper confining layer is present. Under artesian conditions, water in a well rises above the top of the aquifer in which it is completed. Flowing wells result when drilled in areas where the potentiometric surface is above the land surface. Flowing wells and artesian springs that originate from confined aquifers are common around the periphery of the Black Hills.

Streamflow within the study area is affected by both topography and geology. The base flow of most streams in the Black Hills originates in the higher altitudes, where relatively large precipitation and small evapotranspiration result in more water being available for springflow and streamflow. Numerous streams have significant headwater springs originating from the Paleozoic carbonate (limestone and dolomite) rocks along the "Limestone Plateau" (fig. 1) on the western side of the study area. This area is both a large recharge and discharge area for aquifers in the Paleozoic rock interval, especially for the Madison aquifer. The headwater springs provide significant base flow for several streams that flow across the crystalline core.

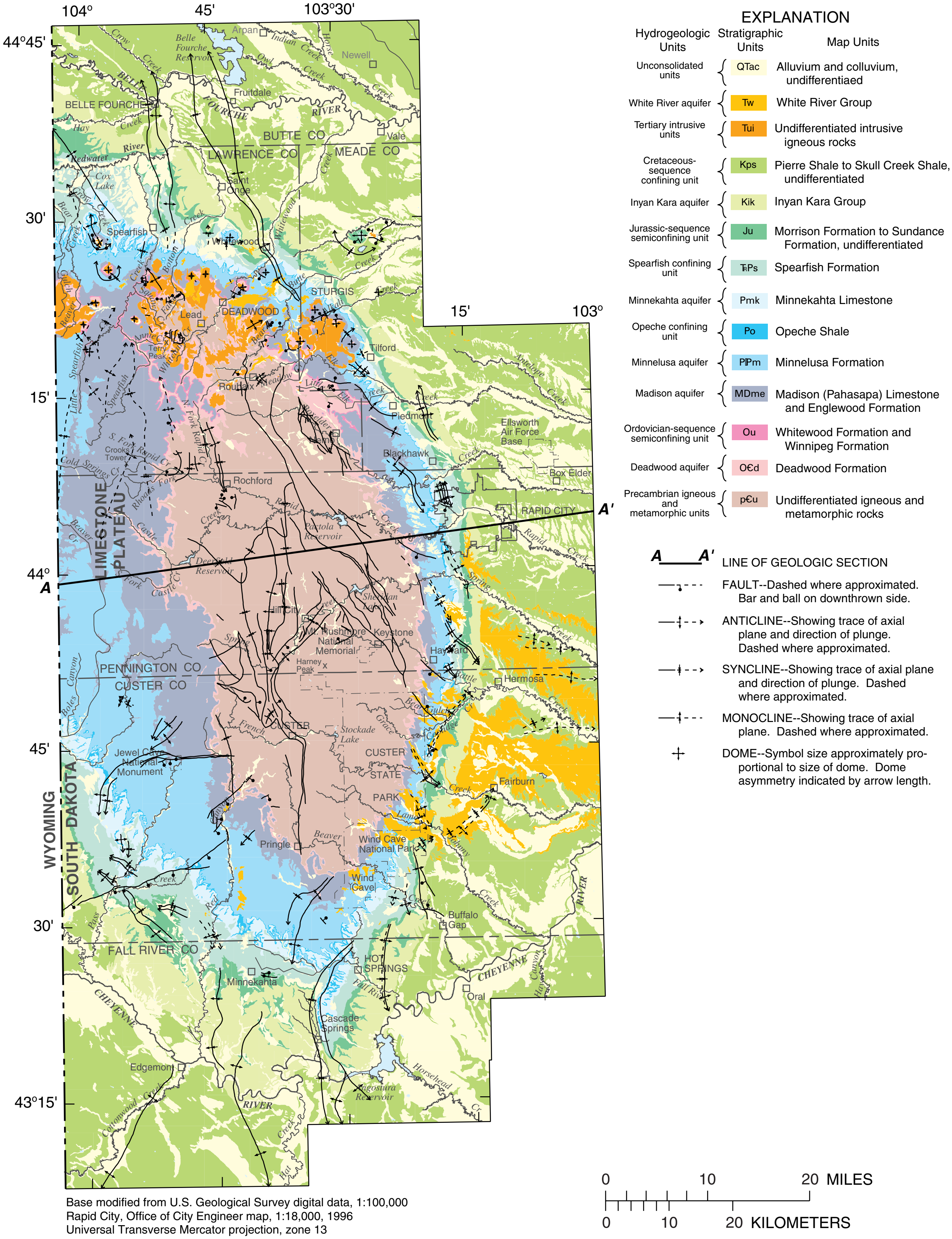

Figure 3. Distribution of hydrogeologic units in the Black Hills area (modified from Strobel and others, 1999).

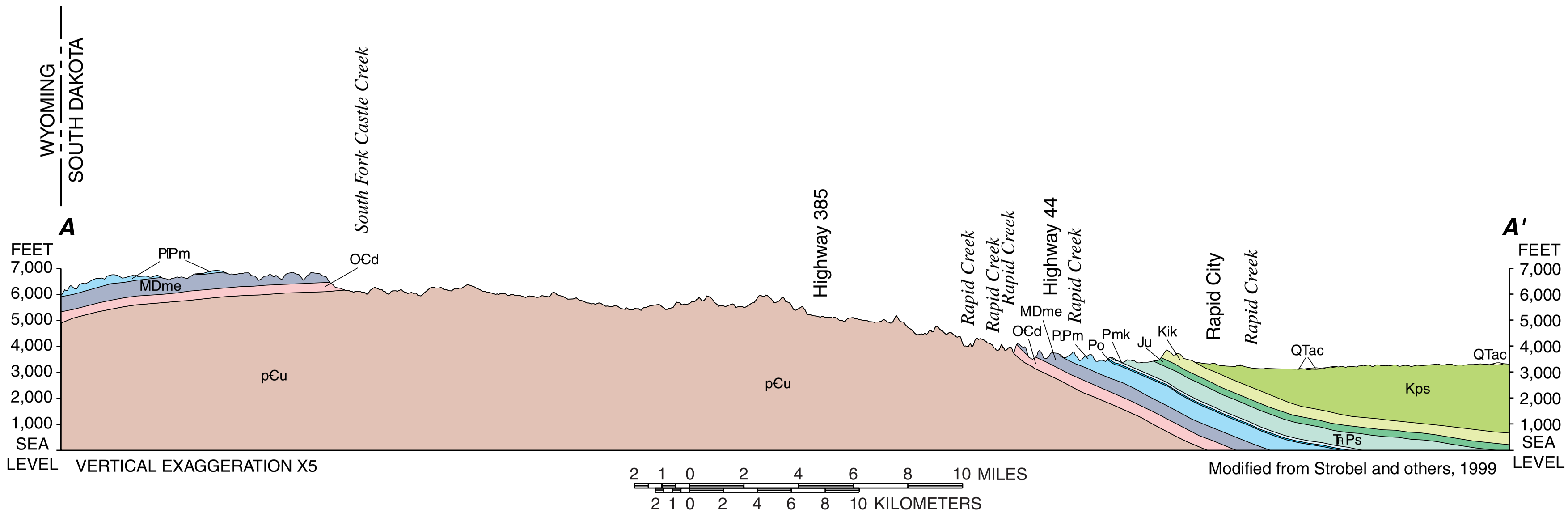

Figure 4. Geologic cross section A-A' (Location of section is shown in figure 3. Abbreviations for stratigraphic intervals are explained in figure 2.).

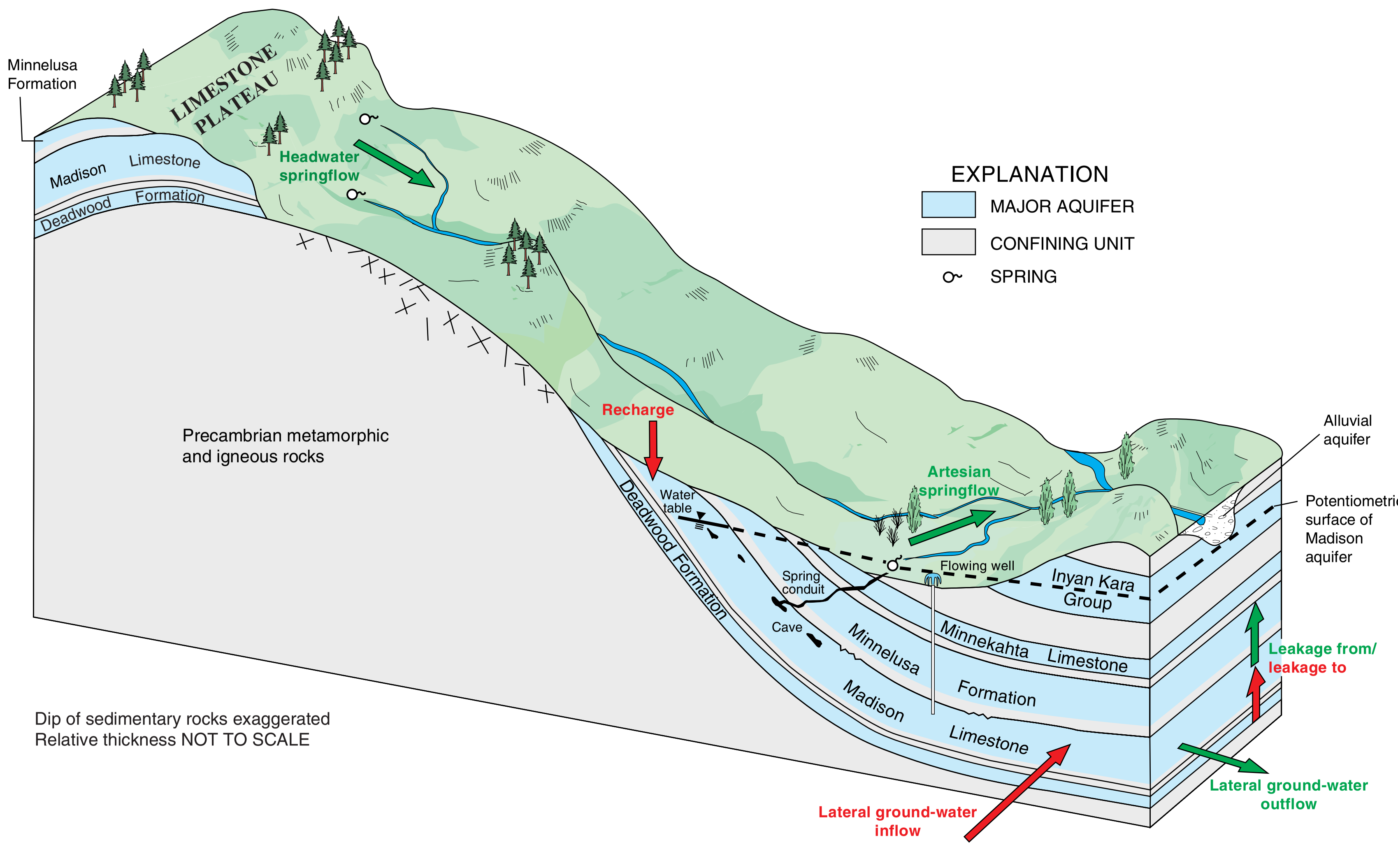

Figure 5. Schematic showing simplified hydrogeologic setting of the Black Hills area. Schematic generally corresponds with geologic cross section shown in figure 4. Components considered for hydrologic budget of the Madison aquifer also are shown with inflow components shown in red and outflow components shown in green.

Most streams generally lose all or part of their flow as they cross the outcrop of the Madison Limestone (Rahn and Gries, 1973; Hortness and Driscoll, 1998). Karst features of the Madison Limestone, including sinkholes, collapse features, solution cavities, and caves, are responsible for the Madison aquifer's large capacity to accept recharge from streamflow. Large streamflow losses also occur in many locations within the outcrop of the Minnelusa Formation, and limited losses probably also occur within the outcrop of the Minnekahta Limestone (Hortness and Driscoll, 1998). Large artesian springs occur in many locations downgradient from these loss zones, most commonly within or near the outcrop of the Spearfish Formation. These springs provide an important source of base flow in many streams beyond the periphery of the Black Hills (Rahn and Gries, 1973; Miller and Driscoll, 1998).

Acknowledgments

The authors acknowledge the efforts of the West Dakota Water Development District for helping to develop and support the Black Hills Hydrology Study. West Dakota's coordination of various local and county cooperators has been a key element in making this study possible. The authors also recognize the numerous local and county cooperators represented by West Dakota, as well as the numerous private citizens who have helped provide guidance and support for the Black Hills Hydrology Study. The South Dakota Department of Environment and Natural Resources has provided support and extensive technical assistance to the study. In addition, the authors acknowledge the technical assistance from many faculty and students at the South Dakota School of Mines and Technology.

HYDROLOGIC PROCESSES AND CONDITIONS

This section describes spatial and temporal precipitation patterns in the Black Hills area and the response of ground water and streamflow to variations in hydrologic conditions. A brief discussion of hydrologic processes also is presented for the benefit of readers with limited hydrologic backgrounds.

Hydrologic Processes

A schematic diagram illustrating hydrologic processes is presented as figure 6. Precipitation falling

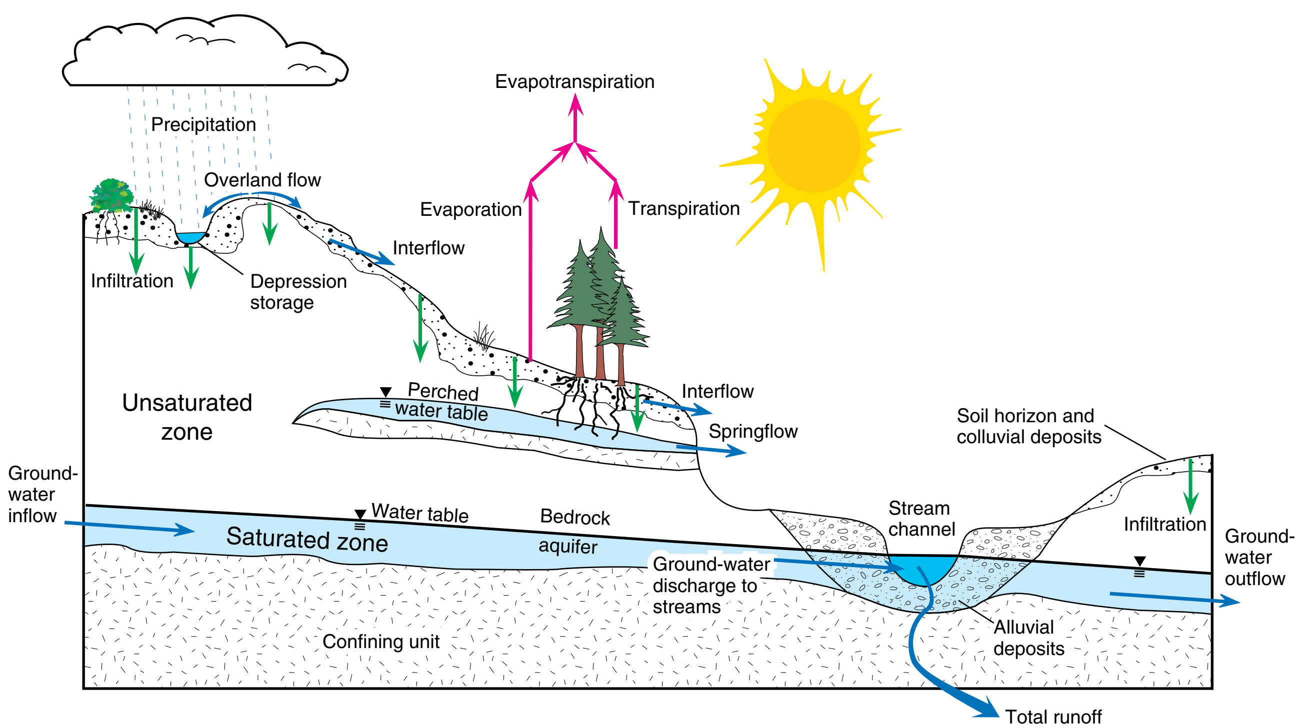

Figure 6. Schematic diagram illustrating hydrologic processes.

on the earth's surface generally infiltrates into the soil horizon, unless the soil is saturated or the infiltration capacity is exceeded, in which case overland flow or direct runoff will occur. Some water may be returned from the soil horizon to the land surface through interflow, contributing to relatively short-term increases in streamflow. In the Black Hills area, where potential evaporation generally exceeds precipitation, most water is eventually returned to the atmosphere through evapotranspiration (ET). Water infiltrating beyond the root zone may eventually recharge ground-water systems; however, ground-water discharge (in the form of springflow or seepage) also may contribute to streamflow.

For the purposes of this report, the term runoff is used to include all means by which precipitation eventually contributes to streamflow. Direct runoff includes overland flow and that portion of interflow that arrives in stream channels relatively quickly. Base flow generally includes all ground water discharging to streams and also may include some interflow. Springflow generally is considered to be ground-water discharge that occurs in somewhat discrete and identifiable locations, as opposed to more general ground-water seepage. Streamflow is inclusive of runoff and may also include water from other sources such as diversions or well discharges.

Within this report, streamflow is most commonly expressed in units of cubic feet per second, but frequently is expressed in acre-feet per year (1.0 ft^3/s = 724.46 acre-ft for a year consisting of 365.25 days). Units of acre-feet (1.0 ft over an acre, which is equivalent to 43,560 ft^3) are especially convenient for calculating annual basin yield (annual runoff per unit of drainage area), which generally is expressed in inches.

Precipitation Data and Patterns

Precipitation data sets that are used within this report generally are taken from Driscoll, Hamade, and Kenner (2000), who summarized available precipitation data for water years 1931-98 for the Black Hills area. These investigators compiled monthly precipitation records for 52 long-term precipitation gages operated by National Oceanic and Atmospheric Administration (1998) and 42 short-term precipitation gages operated by the USGS. These data sets are available at http://sd.water.usgs.gov/projects/bhhs/precip/home.htm. These investigators used a geographic information system (GIS) to generate spatial distributions of monthly precipitation data for 1,000-by-1,000-meter grid cells for the study area. Estimates of annual precipitation amounts for counties within the study area, which were reported by Driscoll, Hamade, and Kenner (2000), are used directly within this report for several purposes. This data set is presented as table 18 in the Supplemental Information section at the back of this report. Data sets and methods developed by these investigators also are used for estimating precipitation amounts over drainage areas for selected streamflow-gaging stations, using monthly precipitation distributions that are compiled by water year.

Spatial precipitation patterns in the Black Hills area are highly influenced by orography, as shown by an isohyetal map (fig. 7) for water years 1950-98, which is the period commonly used for developing hydrologic budgets in this report. The largest annual precipitation amounts typically occur in the high-altitude areas of the northern Black Hills near Lead. Orographic effects also are apparent in the high-altitude areas near Harney Peak. Consistent wintertime snowpack frequently is sustained in approximately these same areas, with snowpack potential generally increasing in a northwesterly direction from Harney Peak to near Crooks Tower.

The largest precipitation amounts typically occur during May and June, and the smallest amounts typically occur during November through February (fig. 8). The seasonal distribution of precipitation is fairly uniform throughout the study area; however, Lawrence County receives slightly larger proportions of annual precipitation during winter months than other counties (fig. 9).

Long-term precipitation trends (fig. 10) are an important consideration for hydrologic analysis for the Black Hills area. Figure 10A shows annual precipitation for water years 1931-98, relative to the long-term average of 18.61 inches (Driscoll, Hamade, and Kenner, 2000), and figure 10B shows annual departures. The cumulative trends are readily apparent from figure 10C, with the most pronounced trends identified by the longest and steepest line segments. The periods from 1931-40 and 1948-61 were sustained periods of generally deficit precipitation that were separated by a period of surplus precipitation during 1941-47. Surplus precipitation occurred during 1962-68, followed by a relatively long period of approximately average precipitation through about 1986. A short period of deficit precipitation from 1987-90 has been followed by generally average to surplus conditions through 1998.

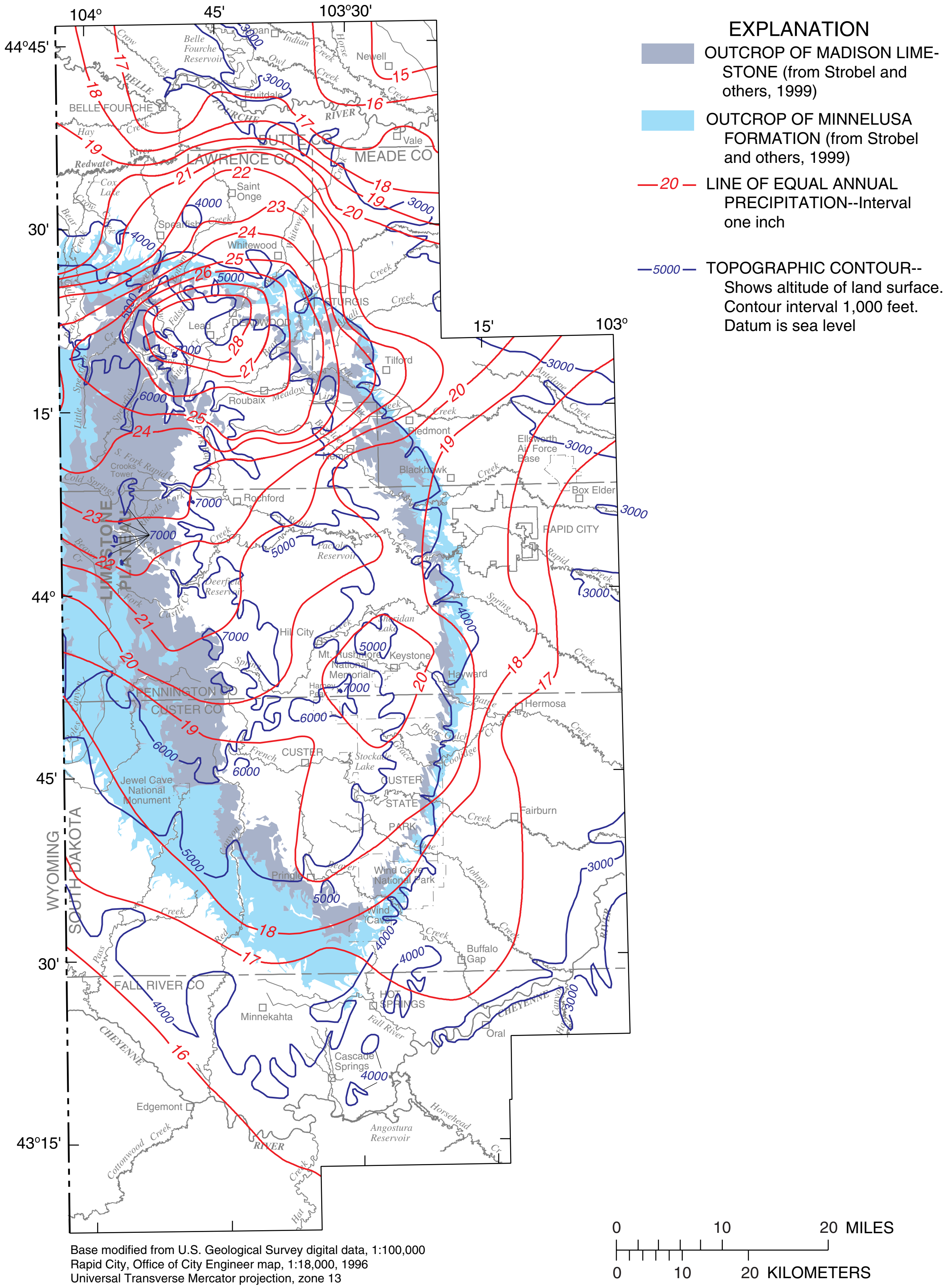

Figure 7. Isohyetal map showing distribution of average annual precipitation for Black Hills area, water years 1950-98 (from Carter, Driscoll, and Hamade, 2001).

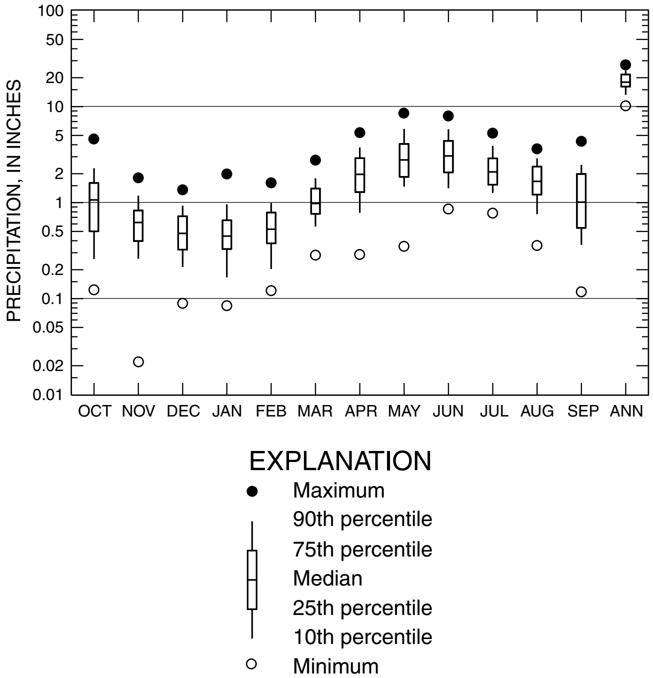

Figure 8. Distribution of monthly and annual precipitation for the study area, water years 1931-98.

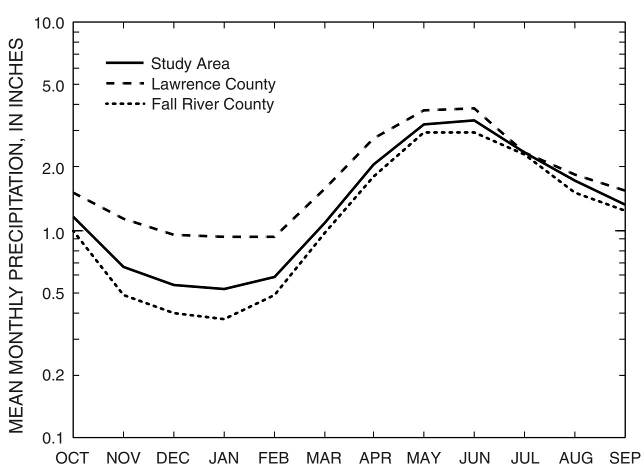

Figure 9. Mean monthly precipitation for study area and selected counties, water years 1931-98.

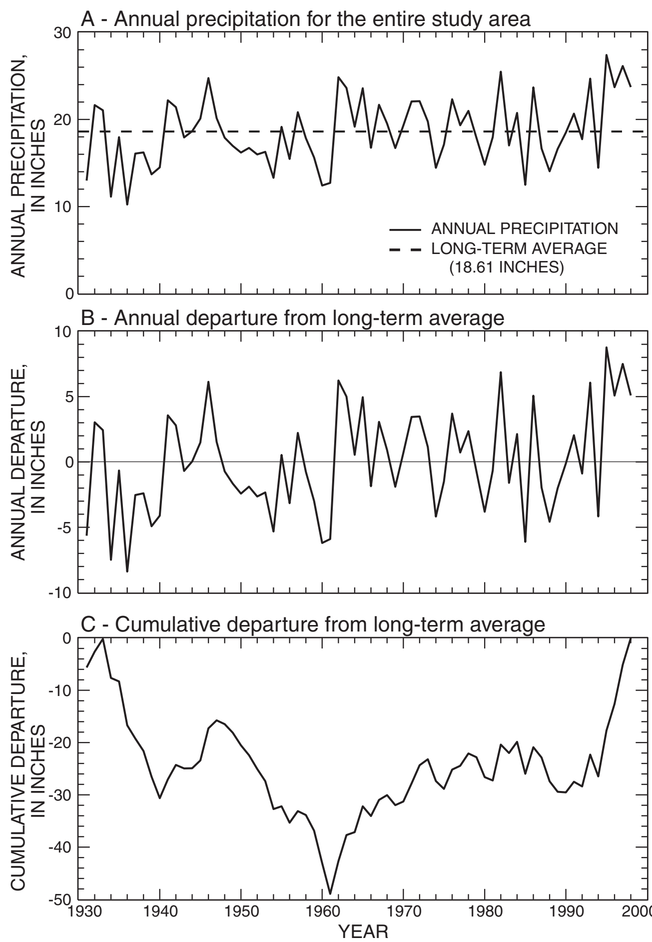

Figure 10. Long-term trends in precipitation for the Black Hills area, water years 1931-98 (from Driscoll, Hamade, and Kenner, 2000).

The long-term precipitation trends are especially important because of potential for bias in analysis and interpretation of available hydrologic data sets, which are much more abundant for the recent wet years. Water-level records are available for 71 observation wells in the Black Hills area for 1998, compared with five wells for 1965 (Driscoll, Bradford, and Moran, 2000). Miller and Driscoll (1998) reported streamflow records for 65 gages for 1993, compared with 30 gages for 1960. Thus, the potential for bias is an important consideration in analysis of hydrologic data sets for the Black Hills area.

Ground-Water Response to Precipitation

The response of ground water to precipitation patterns is shown by comparing water-level hydrographs for 52 observation wells and 1 cave site (grouped by county) to cumulative precipitation departures (figs. 39-43 in the Supplemental Information section). Observation wells for which hydrographs are shown were selected based on length of record and geographic location. On these hydrographs, solid lines indicate continuous records, and dashed lines indicate periods with discontinuous records, which may be based only on periodic manual measurements in some cases. Cumulative precipitation departures for 1961-98 for the appropriate counties are computed using precipitation data presented in table 18. Selected site information for the 53 ground-water sites is presented in table 1, and locations are shown in figure 11.

Although ground-water levels can be directly affected by recharge rates that are influenced by annual precipitation amounts, numerous other factors can affect ground-water response. The timing and intensity of precipitation, along with evaporative factors such as temperature, humidity, wind speed, and solar radiation can have a large effect on annual recharge. Streamflow losses (especially for the Madison and Minnelusa aquifers) also can contribute to recharge. Ground-water levels also can be affected by well withdrawals, spring discharges, and various hydraulic properties of aquifers. A distinct response to annual precipitation patterns is indicated by hydrographs for many wells (figs. 39-43), which indicates other influences are relatively minor for many wells.

Precipitation patterns for the five counties generally are very similar (figs. 39-43). Precipitation was below average for all counties during 1961, which is the first year considered. Thus, all of the cumulative departure graphs, which are based on 1961-98 averages, begin with a precipitation deficit. Precipitation during the next several years was above average for all counties, resulting in cumulative surpluses by the mid 1960's. For Custer and Fall River Counties, a gradual long-term deficit developed, which ended in the early 1990's (figs. 42 and 43). For Lawrence, Meade, and Pennington Counties, a slight surplus was maintained through about 1980, with general deficits then developing through the early 1990's (figs. 39-41). For all counties, annual surpluses occurred during the mid to late 1990's, bringing the cumulative departures back up to zero.

Most of the water-level records are much shorter than the precipitation records that are presented and show identifiable increases in response to the precipitation surpluses that occurred during the mid to late 1990's. Similarly, most wells with records prior to the early 1990's show short-term decreases in water levels corresponding to periods with precipitation deficits. The most notable exceptions are the four wells completed in the Inyan Kara aquifer (figs. 39B, 40B, 42C, and 42G), which show very little response to precipitation patterns. The Hermosa South Inyan Kara well (fig. 42G), with a steady decrease of about 4 ft between 1984 and 1998, is the only well of the 53 ground-water sites with a definitive long-term trend in general water levels.

Five wells have records dating back to 1965 or earlier (figs. 39C, 39L, 41B, 41K, and 41L), all of which probably are influenced by pumping of nearby wells (Driscoll, Bradford, and Moran, 2000). The Sioux Park Minnelusa well (fig. 41L) shows response to long-term production from the Minnelusa aquifer by the city of Rapid City, and the Sioux Park Madison well (fig. 41K) shows large fluctuations in response to increased production from the Madison aquifer beginning in about 1990. Thus, the responses to climatic conditions for these wells cannot necessarily be distinguished from pumping influences. The water level in the Cement Plant Minnelusa well (fig. 41B) decreased slowly during the late 1980's when a cumulative precipitation deficit was developing. A sudden decrease occurred in early 1990 when production from the Madison aquifer increased, which may indicate hydraulic connection between the Madison and Minnelusa aquifers in this area.

Table 1. Observations wells and cave site for which hydrographs are presented

[GC, Golf Course; W, West; CSP, Custer State Park. --, not applicable]

Site number (fig. 11)	Local number	Station identification number	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Other identifier		Aquifer
			Lawrence County				
1	7N 3E22DAAD	443306103434001	443310.8	1034347.2	Saint Onge	LA-90B	Inyan Kara
2	7N 2E10BADC	443515103513901	443513.1	1035143.4	Redwater	LA-62A	Minnelusa
3	7N 1E33CCDD2	443100104002002	443104.2	1040025.3	State Line Mnls	LA-87B	Minnelusa
4	7N 1E33CCDD	443100104002001	443104.2	1040025.3	State Line Mdsn	LA-87A	Madison
5	6N 3E15DDDA2	442833103434602	442834.0	1034346.2	Frawley Ranch Mdsn	LA-95A	Madison
6	6N 3E15DDDA	442833103434601	442834.5	1034346.2	Frawley Ranch Mnls	LA-88A	Minnelusa
7	6N 2E14BCCC2	442854103505602	442854.4	1035053.6	Spearfish GC Mdsn	LA-88C	Madison
8	6N 2E14BCCC	442854103505601	442854.4	1035053.6	Spearfish GC Mnls	LA-88B	Minnelusa
9	6N 2E 5BBBB2	443100103543002	443104.3	1035437.7	Spearfish W Mnkt	LA-86B	Minnekahta
10	6N 2E 5BBBB	443100103543001	443104.3	1035437.7	Spearfish W Mnls	LA-86A	Minnelusa
11	5N 4E14ADD	442344103253401	442343.6	1033525.9	Boulder Canyon Mnls	LA-63A	Minnelusa
12	5N 4E 1ABBD2	442545103343702	442544.3	1033437.1	Whitewood Mdsn	LA-90A	Madison
13	5N 4E 1ABBD	442545103343701	442544.4	1033437.5	Whitewood Mnls	LA-86C	Minnelusa
14	5N 1E11DABA	442435103571101	442434.6	1035710.8	Big Hill Trailhead	LA-95C	Madison
15	4N 2E20BBAC	441757103544601	441757.5	1035445.5	Cheyenne Xing Mdsn	LA-95B	Madison
			Meade County				
16	6N 5E16CDCC	442828103312001	442827.8	1033123.2	Bear Butte	MD-89A	Inyan Kara (Lakota)
17	5N 5E16CAAD	442335103311001	442336.7	1033111.2	Sturgis	MD-86A	Madison
18	4N 6E19AABA2	441759103261202	441759.7	1032612.2	Tilford Mdsn	MD-90A	Madison
19	4N 6E19AABA	441759103261201	441800.1	1032612.4	Tilford Mnls	MD-84B	Minnelusa
20	3N 6E15ABB2	441337103225002	441335.5	1032250.5	Piedmont Mdsn	MD-94A	Madison
21	3N 6E15ABB	441337103225001	441335.6	1032250.7	Piedmont Mnls	MD-84A	Minnelusa
			Pennington County				
22	2N 7E34BCCA	440528103161001	440530.9	1031614.2	Cement Plant	PE-64A	Minnelusa
23	2N 7E32ABBC2	440544103180002	440543.6	1031805.2	City Quarry Mdsn	PE-89C	Madison
24	2N 7E32ABBC	440544103180001	440543.6	1031805.2	City Quarry Mnls	PE-89D	Minnelusa
25	2N 7E17BAAD	440818103180801	440819.8	1031809.9	Dog Track	PE-84B	Minnelusa
26	2N 1E27ADAC	440623103583701	440626.8	1035735.9	Blind Park	PE-91A	Deadwood
27	1N 7E29CADD	440052103181201	440053.6	1031810.4	Countryside	PE-84A	Deadwood

Table 1. Observations wells and cave site for which hydrographs are presented–Continued

[GC, Golf Course; W, West; CSP, Custer State Park. --, not applicable]

Site number (fig. 11)	Local number	Station identification number	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Other identifier		Aquifer
				Pennington County—Continued			
28	1N 7E 8ADDD2	440338103173302	440337.7	1031734.9	Canyon Lake Mdsn	PE-89A	Madison
29	1N 7E 8ADDD	440338103173301	440337.6	1031735.1	Canyon Lake Mnls	PE-89B	Minnelusa
30	1N 7E 5DBCA	440423103180501	440422.6	1031806.8	West Camp Rapid 3	--	Minnelusa
31	1N 7E 3CBAA2	440430103160202	440427.2	1031605.0	Sioux Park Mdsn	PE-65A	Madison
32	1N 7E 3CBAA	440430103160201	440427.2	1031605.1	Sioux Park Mnls	PE-64B	Minnelusa
33	1N 7E 1DBBB	440427103131701	440426.6	1031318.0	Star Village	RC 7	Madison
34	1S 2E35ADCA	435517103501801	435515.6	1035018.5	Four Corners	PE-96C	Madison
35	1S 7E20CACD	435644103183801	435641.3	1031843.4	Kieffer	--	Deadwood
36	1S 7E 3CDBD	435916103161801	435915.1	1031620.6	Reptile Gardens Mdsn	PE-86A	Madison
37	1S 7E 3CDBD2	435916103161802	435915.1	1031620.6	Reptile Gardens Mnls	PE-94A	Minnelusa
				Custer County			
38	2S 7E34ABBA	435018103155801	435020.3	1031600.3	Hermosa West Mnls	CU-83A	Minnelusa
39	2S 7E36CBCB	434946103140501	434948.7	1031417.3	Hermosa West Lkot	CU-83B	Inyan Kara (Lakota)
40	3S 1E18DDDB	434700104021401	434701.7	1040215.5	Boles Canyon Mdsn	CU-93C	Madison
41	3S 1E18DDDB2	434700104021402	434701.7	1040215.5	Boles Canyon Mnls	CU-93D	Minnelusa
42	3S 4E24BCDD	434634103351801	434627.1	1033533.4	Custer Test	CU-86A	Precambrian
43	3S 8E19BBBB	434652103130501	434653.7	1031307.2	Hermosa South	CU-83C	Inyan Kara (Lakota)
44	4S 6E 1DAAA	434350103201901	434350.9	1032020.2	CSP Airport Mdsn	CU-93A	Madison
45	4S 6E 1DAAA2	434350103201902	434350.9	1032020.2	CSP Airport Mnls	CU-93B	Minnelusa
C1	6S 5E12DBAB	433302103281501	433257	1032827	Windy City Lake	--	Madison
46	6S 6E21BBBB	433115103251401	433115.4	1032516.1	7-11 Ranch Mdsn	CU-91A	Madison
47	6S 6E21BBBB2	433115103251402	433115.4	1032516.1	7-11 Ranch Mnls	CU-91B	Minnelusa
48	6S 6E21BBBB3	433115103251403	433115.3	1032516.2	7-11 Ranch Mnkt	CU-96A	Minnekahta
				Fall River County			
49	7S 4E19BCCB	432548103414801	432545.8	1034151.2	Minnekahta Junction Mdsn	FR-92A	Madison
50	7S 4E19BCCB2	432548103414802	432545.8	1034151.2	Minnekahta Junction Mnls	FR-94A	Minnelusa
51	7S 5E14CCCC	432603103295901	432602.7	1032958.7	Vets Home Mdsn	FR-95A	Madison
52	7S 5E14CCCC2	432603103295902	432602.7	1032958.7	Vets Home Mnls	FR-95B	Minnelusa