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

Hydrologic Budgets for the Madison and Minnelusa Aquifers, Black Hills of South Dakota and Wyoming, Water Years 1987-96

By Janet M. Carter and Daniel G. Driscoll, U.S. Geological Survey, and Ghaith R. Hamade and Gregory J. Jarrell, South Dakota School of Mines and Technology

Water-Resources Investigations Report 01-4119

Prepared in cooperation with the South Dakota Department of Environment and Natural Resources and the West Dakota Water Development District

U.S. Department of the Interior

Gale A. Norton, Secretary

U.S. Geological Survey

Charles G. Groat, Director

Rapid City, South Dakota: 2001

For additional information write to:

District Chief
U.S. Geological Survey
1608 Mt. View Road
Rapid City, SD 57702

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Building 810
Box 25286, Federal Center
Denver, CO 80225-0286

CONTENTS

FIGURES

TABLES

Hydrologic Budgets for the Madison and Minnelusa Aquifers, Black Hills of South Dakota and Wyoming, Water Years 1987-96

By Janet M. Carter, Daniel G. Driscoll, Ghaith R. Hamade, *and* Gregory J. Jarrell

ABSTRACT

The Madison and Minnelusa aquifers are two of the most important aquifers in the Black Hills area of South Dakota and Wyoming. Quantification and evaluation of various hydrologic budget components are important for managing and understanding these aquifers.

Hydrologic budgets are developed for two scenarios, including an overall budget for the entire study area and more detailed budgets for subareas. Budgets generally are combined for the Madison and Minnelusa aquifers because most budget components cannot be quantified individually for the aquifers. An average hydrologic budget for the entire study area is computed for water years 1987-96, for which change in storage is approximately equal to zero. Annual estimates of budget components are included in detailed budgets for nine subareas, which consider periods of decreasing storage (1987-92) and increasing storage (1993-96).

Inflow components include recharge, leakage from adjacent aquifers, and ground-water inflows across the study area boundary. Outflows include springflow (headwater and artesian), well withdrawals, leakage to adjacent aquifers, and ground-water outflow across the study area boundary. Leakage, ground-water inflows, and ground-water outflows are difficult to quantify and cannot be distinguished from one another. Thus, net ground-water flow, which includes these components, is calculated as a residual, using estimates for the other budget components.

For the overall budget for water years 1987-96, net ground-water outflow from the study area is computed as 100 ft^3/s (cubic feet per second). Estimates of average combined budget components for the Madison and Minnelusa aquifers are: 395 ft^3/s for recharge, 78 ft^3/s for headwater springflow, 189 ft^3/s for artesian springflow, and 28 ft^3/s for well withdrawals.

Hydrologic budgets also are quantified for nine subareas for periods of decreasing storage (1987-92) and increasing storage (1993-96), with changes in storage assumed equal but opposite. Common subareas are identified for the Madison and Minnelusa aquifers, and previous components from the overall budget generally are distributed over the subareas. Estimates of net ground-water flow for the two aquifers are computed, with net ground-water outflow exceeding inflow for most subareas. Outflows range from 5.9 ft^3/s in the area east of Rapid City to 48.6 ft^3/s along the southwestern flanks of the Black Hills. Net groundwater inflow exceeds outflow for two subareas

where the discharge of large artesian springs exceeds estimated recharge within the subareas.

More detailed subarea budgets also are developed, which include estimates of flow components for the individual aquifers at specific flow zones. The net outflows and inflows from the preliminary subarea budgets are used to estimate transmissivity of flow across specific flow zones based on Darcy's Law. For estimation purposes, it is assumed that transmissivities of the Madison and Minnelusa aquifers are equal in any particular flow zone. The resulting transmissivity estimates range from 90 ft^2/d to about 7,400 ft^2/d, which is similar to values reported by previous investigators. The highest transmissivity estimates are for areas in the northern and southwestern parts of the study area, and the lowest transmissivity estimates are along the eastern study area boundary.

Evaluation of subarea budgets provides confidence in budget components developed for the overall budget, especially regarding precipitation recharge, which is particularly difficult to estimate. Recharge estimates are consistently compatible with other budget components, including artesian springflow, which is a dominant component in many subareas. Calculated storage changes for subareas also are consistent with other budget components, specifically artesian springflow and net ground-water flow, and also are consistent with water-level fluctuations for observation wells. Ground-water budgets and flowpaths are especially complex in the southern Black Hills area; however, budget results are consistent with geochemical interpretations by previous investigators.

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 is 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.

The Madison and Minnelusa aquifers are two of the most important aquifers in the Black Hills area and are a primary focus of the Black Hills Hydrology Study. These aquifers are utilized for domestic, municipal, agricultural, and industrial uses. The quantification and evaluation of various hydrologic budget components are important for managing and understanding the water resources in the Black Hills area.

Purpose and Scope

The purposes of this report are to: (1) present hydrologic budgets for the Madison and Minnelusa aquifers in the Black Hills area, including an overall budget for the study area and more detailed budgets for subareas; and (2) present generalized estimates of transmissivity that are based on estimates of regional flow. An average hydrologic budget is presented for the entire study area for water years 1987-96, for which change in storage is assumed to be approximately equal to zero. Annual estimates of budget components are included in detailed budgets for nine subareas, which consider periods of decreasing storage (1987-92) and increasing storage (1993-96). The overall budget is a combined budget because most of the budget components cannot be quantified individually. Estimates of well withdrawals, by aquifer, are presented, and for some budget components additional information for other periods also is presented. The detailed budgets also are combined budgets; however, estimates of ground-water flow and transmissivity for each aquifer are derived. Although the study area for the Black Hills Hydrology Study does not include Wyoming, budget components for the Black Hills of Wyoming are considered to develop realistic budgets for the aquifers.

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. Outcrop areas of the Madison Limestone and Minnelusa Formation in the Black Hills of Wyoming (just west of the study area) also are considered in this report, as described in a following section. The study area includes most of the larger communities in western South Dakota and contains about one-fifth of the State's population.

Physiography and Climate

The Black Hills uplift formed as an elongated dome about 60 to 65 million years ago (DeWitt and others, 1986). The dome trends north-northwest and is about 120 mi long and 60 mi wide. Elevations range from 7,242 ft above sea level at Harney Peak to about 3,000 ft in the adjacent plains. Most of the higher elevations 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 elevation 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 elevations. 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.

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). Local climatic conditions are affected by topography, with generally lower temperatures and higher precipitation at the higher elevations. Climatic conditions also are affected by regional climate patterns, with the northern Black Hills influenced more by moist air currents out of the northwest than the southern Black Hills.

The average annual precipitation for the study area (water years 1931-98) is 18.61 inches and has ranged from 10.22 inches for water year 1936 to 27.39 inches for water year 1995 (Driscoll and others, 2000). Annual averages for counties within the study area have ranged from 16.35 inches in Fall River County to 23.11 inches in Lawrence County. The largest precipitation amounts typically occur in the northern Black Hills near Lead, where average annual precipitation (water years 1950-98) exceeds 28 inches (fig. 2). The average annual temperature is 43.9°F (U.S. Department of Commerce, 1999) and ranges from 48.7°F at Hot Springs to approximately 37°F near Deerfield Reservoir (elevation = 6,060 ft). Average pan evaporation for April through October is about 30 inches at Pactola Reservoir and about 50 inches at Oral.

Geologic Setting

The oldest geologic units in the study area are the Precambrian metamorphic and igneous rocks (fig. 3), which underlie 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 metasediments, 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 central 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.

Surrounding the central core is a layered sequence of Paleozoic and Mesozoic sedimentary rocks including limestones, sandstones, and shales. The distribution of hydrogeologic units in the Black Hills area is shown in figure 4. The bedrock sedimentary formations 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. 5). Following are descriptions for selected bedrock units from the Deadwood Formation through the Inyan Kara Group.

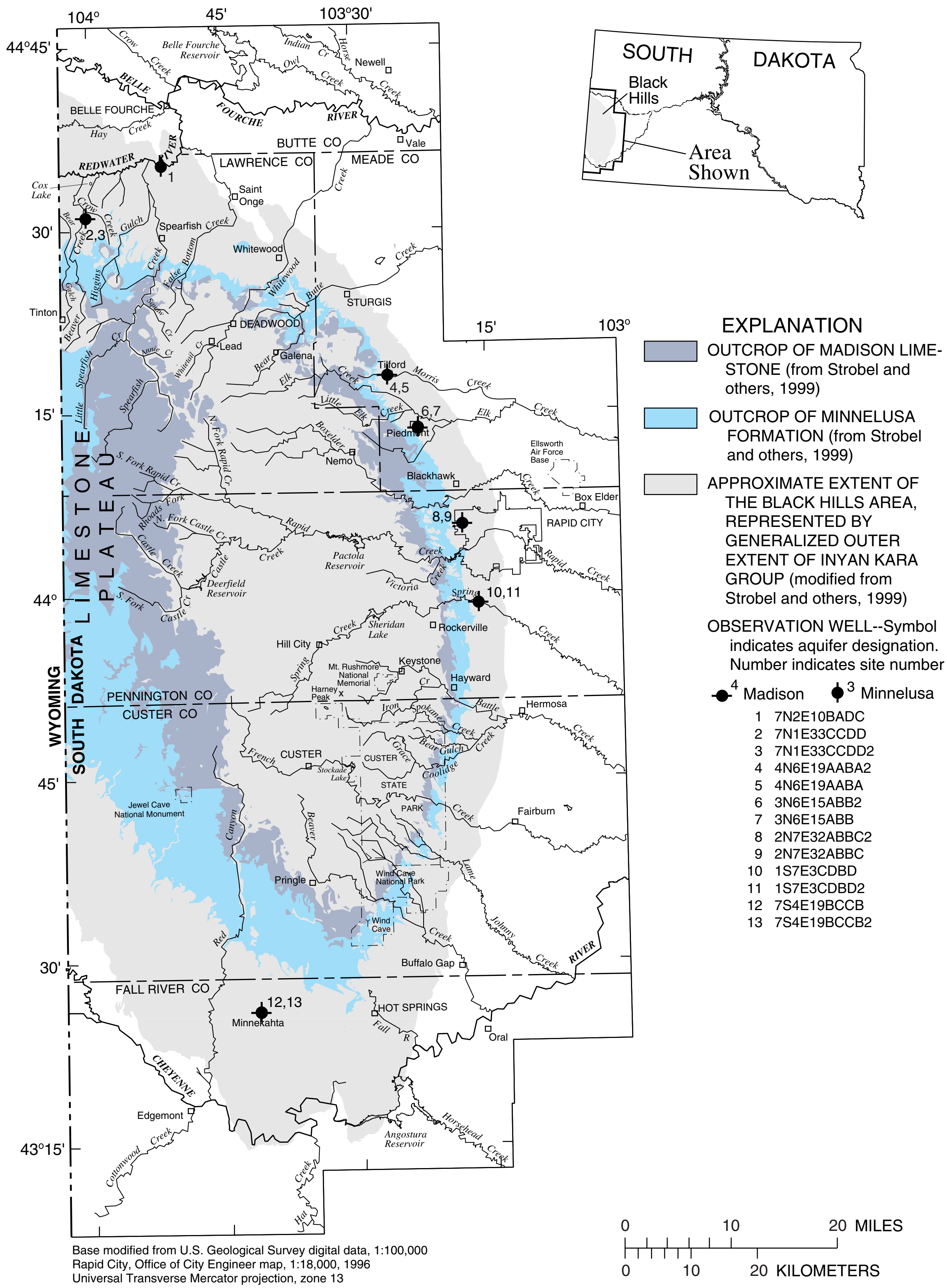
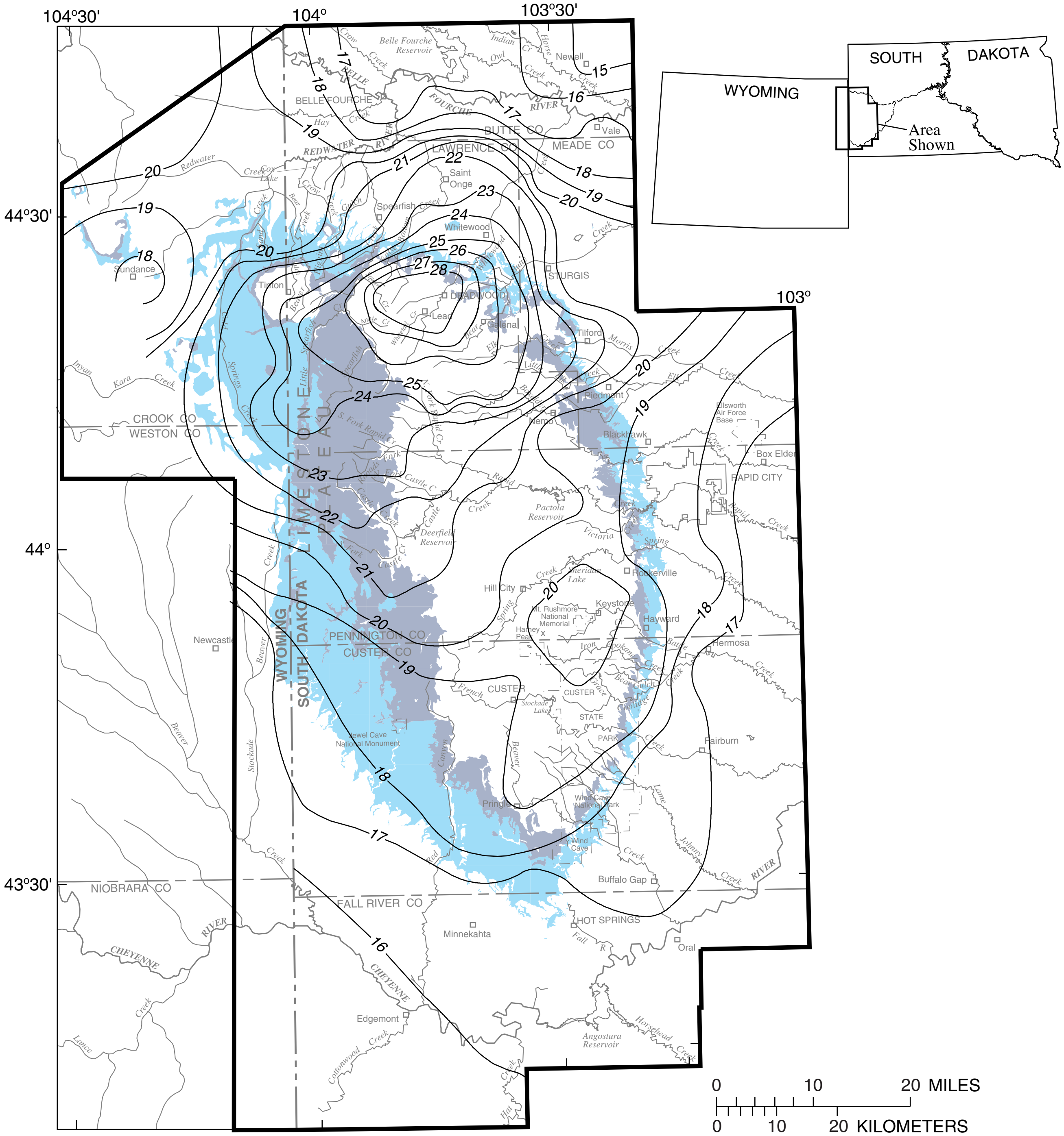


Figure 1. Area of investigation for the Black Hills Hydrology Study. Location of observation wells for which hydrographs are presented also are shown.



Base modified from U.S. Geological Survey digital data, 1:100,000 and City Engineer's map, Rapid City, 1991

EXPLANATION

- CONNECTED OUTCROP OF THE MADISON LIMESTONE (from Strobel and others, 1999; DeWitt and others, 1989)
- CONNECTED OUTCROP OF THE MINNELUSA FORMATION (from Strobel and others, 1999; DeWitt and others, 1989)
- —20— LINE OF EQUAL AVERAGE ANNUAL PRECIPITATION--Interval one inch
- AREA CONSIDERED FOR HYDROLOGIC BUDGETS

Figure 2. Isohyetal map showing distribution of average annual precipitation for the Black Hills area, water years 1950-98.

ERATHEM	SYSTEM	ABBREVIATION FOR STRATIGRAPHIC INTERVAL	GEOLOGIC UNIT	THICKNESS IN FEET	DESCRIPTION
CENOZOIC	QUATERNARY & TERTIARY (?)	QTac	UNDIFFERENTIATED SANDS AND GRAVELS	0-50	Alluvial and colluvial materials.
		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	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 slabby sandstone.
			INYAN KARA GROUP: LAKOTA FM: Fuson Shale; Minnewaste Limestone; Chilson Member	10-190 0-25 25-485	Coarse gray to buff cross-bedded conglomeratic sandstone, interbedded with buff, red, and gray clay, especially toward top. Local fine-grained limestone.
	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	TRPs	SPEARFISH FORMATION: Goose Egg Equivalent	375-800	Red sandy 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.
	PENNSYLVANIAN	PIPm	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.
	MISSISSIPPIAN	MDm	MADISON (PAHASAPA) LIMESTONE	[1]250-1,000	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	O€d	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		p€u	UNDIFFERENTIATED METAMORPHIC AND IGNEOUS 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 3. Stratigraphic section for the Black Hills.

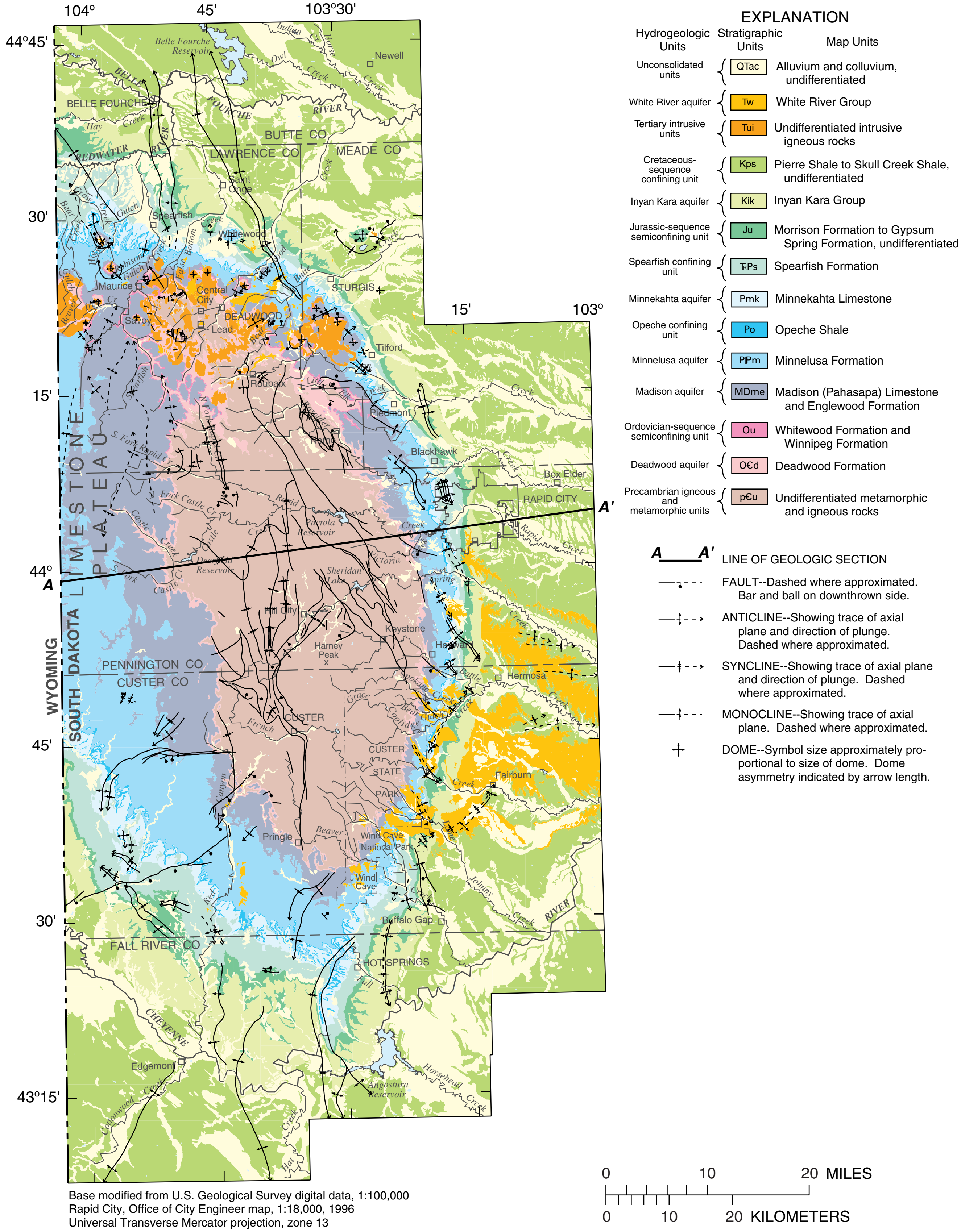


Figure 4. Distribution of hydrogeologic units in the Black Hills area (modified from Strobel and others, 1999).

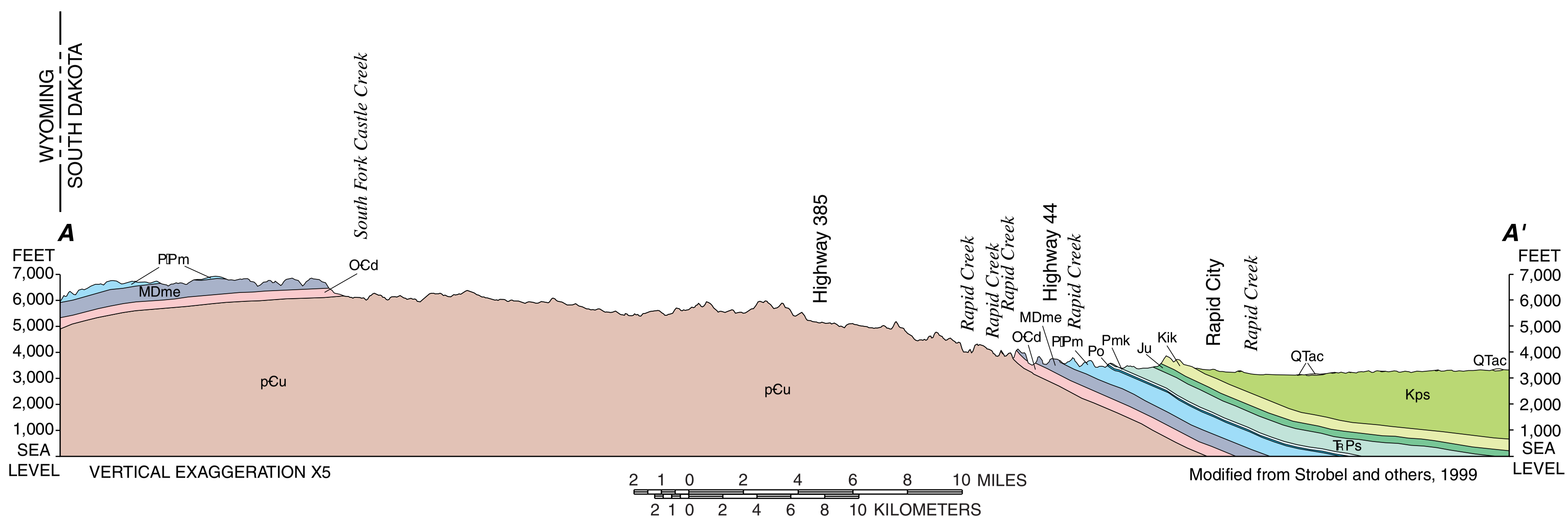


Figure 5. Generalized geologic section A-A' (Location of section is shown in figure 4. Abbreviations for stratigraphic intervals are explained in figure 3.).

The oldest sedimentary unit in the study area is the Cambrian- and Ordovician-age Deadwood Formation, which is composed primarily of brown to light-gray glauconitic sandstone, shale, limestone, and local basal conglomerate (Strobel and others, 1999). These sediments were deposited on the generally horizontal plain of Precambrian rocks in a coastal to near-shore environment (Gries, 1975). The thickness of the Deadwood Formation increases from south to north in the study area and ranges from 0 to 500 ft (Carter and Redden, 1999e). In the northern and central Black Hills, the Deadwood Formation is disconformably overlain by Ordovician rocks, which include the Whitewood and Winnipeg Formations. The Winnipeg Formation is absent in the southern Black Hills, and the Whitewood Formation has eroded to the south and is not present south of the approximate latitude of Nemo (DeWitt and others, 1986). In the southern Black Hills, the Deadwood Formation is unconformably overlain by the Devonian- and Mississippian-age Englewood Formation because of the absence of the Ordovician sequence. The Englewood Formation is overlain by the Madison Limestone.

The Mississippian-age Madison Limestone, which was deposited as a marine carbonate, is a massive, gray to buff limestone that is locally dolomitic (Strobel and others, 1999). The thickness increases from south to north in the study area and ranges from almost zero in the southeast corner of the study area (Rahn, 1985) to 1,000 ft east of Belle Fourche (Carter and Redden, 1999d). The Madison Limestone was exposed at land surface for approximately 50 million years. During this period, significant erosion, soil development, and karstification occurred (Gries, 1996). There are numerous caves and fractures within the upper part of the formation (Peter, 1985). Because the Madison Limestone was exposed to erosion and karstification for millions of years, the formation is unconformably overlain by the Minnelusa Formation.

The Pennsylvanian- and Permian-age Minnelusa Formation consists mostly of yellow to red cross-stratified sandstone, limestone, dolomite, and shale (Strobel and others, 1999). In addition to sandstone and dolomite, the lower part of the formation consists of shale and anhydrite (DeWitt and others, 1986). The upper part of the Minnelusa Formation also may contain anhydrite, which generally has been removed by dissolution near the outcrop areas, forming collapse features filled with breccia (Braddock, 1963). The thickness of the Minnelusa Formation in the study area increases from north to south and ranges from 375 ft near Belle Fourche to 1,175 ft near Edgemont (Carter and Redden, 1999c). Along the northeastern part of the central Black Hills, there is little anhydrite in the subsurface due to a change in the depositional environment (Carter and Redden, 1999c). On the south and southwest side of the study area, there is a considerable increase in thickness of clastic units as well as a thick section of anhydrite. In the southern Black Hills, the upper part of the Minnelusa Formation thins due to leaching of anhydrite. The Minnelusa Formation is disconformably overlain by the Permian-age Opeche Shale, which is overlain by the Minnekahta Limestone.

The Permian-age Minnekahta Limestone is a fine-grained, purple to gray laminated limestone (Strobel and others, 1999). The thickness of the Minnekahta Limestone ranges from about 25 to 65 ft in the study area (Strobel and others, 1999). The Minnekahta Limestone is overlain by the Triassic- and Permian-age Spearfish Formation.

The overlying Mesozoic-age units are composed primarily of shale, siltstone, and sandstone deposits, and include the Cretaceous-age Inyan Kara Group. The thickness of the Inyan Kara Group ranges from about 135 to 900 ft in the study area (Carter and Redden, 1999a).

Hydrologic Setting

The hydrologic setting of the Black Hills area is schematically illustrated in figure 6. The major aquifers in the Black Hills area are the Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara aquifers. Aquifers in the Precambrian metamorphic and igneous rocks and alluvium are used to a lesser extent. In some local areas, wells are completed in strata that generally are considered to be confining units.

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 in Precambrian rocks occur in many locations in the central core of the Black Hills, where enhanced secondary permeability results from weathering and fracturing. In these aquifers, water-table (unconfined) conditions generally prevail and land-surface topography can strongly control ground-water flow directions.

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,

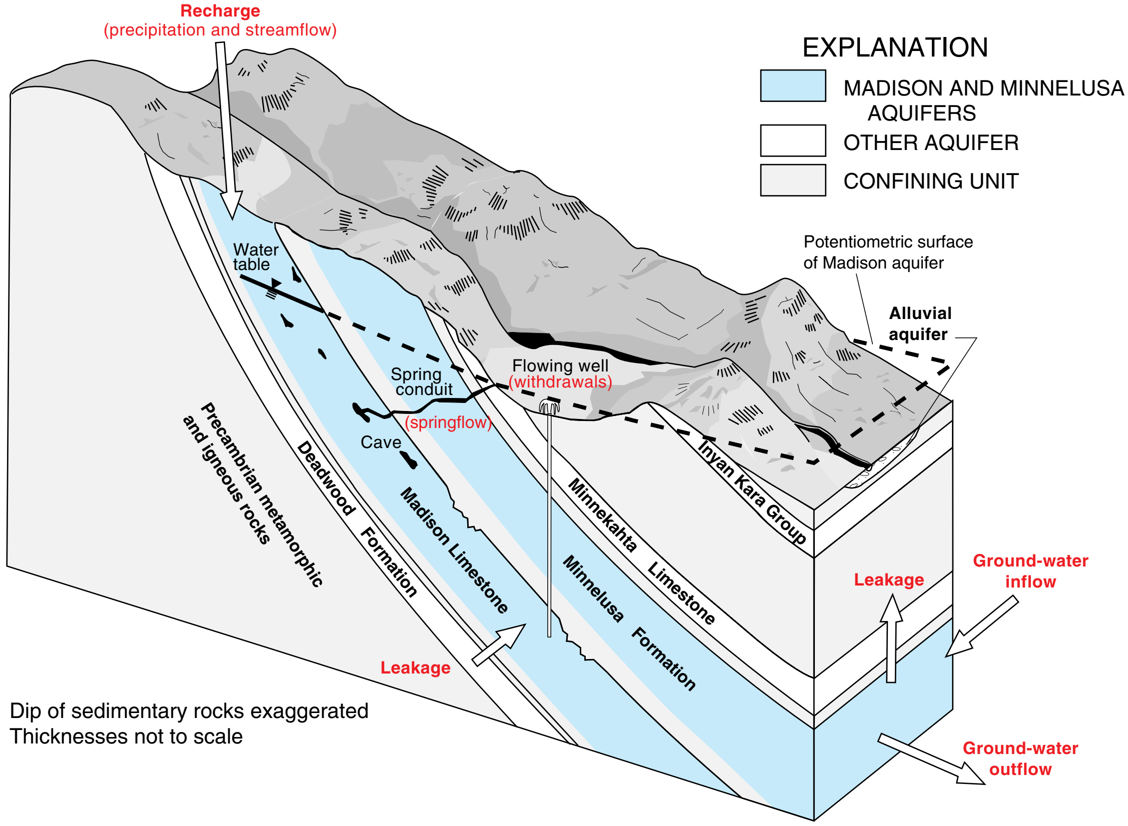


Figure 6. Schematic showing simplified hydrologic setting of the Black Hills area. Components considered for water budgets of Madison and Minnelusa aquifers also are shown.

and Minnekahta Limestone are used extensively. 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 central core of the Black Hills. Although the lateral component of flow predominates, extremely variable leakage (vertical component of flow) can occur between these aquifers (Peter, 1985; Greene, 1993).

The Deadwood Formation contains the Deadwood aquifer, which overlies the Precambrian rocks. The Deadwood aquifer, which is used mainly by domestic and municipal users near its outcrop area, receives recharge primarily from precipitation on the outcrop. There may be some hydraulic connection between the Deadwood aquifer and the underlying weathered Precambrian rocks, but regionally the Precambrian rocks act as a lower confining unit to the Deadwood aquifer. Where present, the Whitewood and Winnipeg Formations act as a semiconfining unit overlying the Deadwood aquifer (Strobel and others, 1999). These units locally may transmit water and exchange water with the Deadwood aquifer, but regionally are not considered aquifers. Where the Whitewood and Winnipeg Formations are absent, the Deadwood aquifer is in contact with the overlying Englewood Formation, which Strobel and others (1999) included as part of the Madison aquifer.

The Madison aquifer generally occurs within the karstic upper part of the Madison Limestone; however, Strobel and others (1999) included the entire Madison Limestone and the Englewood Formation in their delineation of the aquifer. Numerous fractures and solution openings in the Madison Limestone provide extensive secondary porosity to the aquifer. The Madison aquifer receives significant recharge from precipitation and streamflow losses on its outcrop. The Madison aquifer is confined by low permeability layers in the overlying Minnelusa Formation.

The Minnelusa aquifer occurs within layers of sandstone, dolomite, and anhydrite in the lower portion of the Minnelusa Formation and sandstone and anhydrite layers in the upper portion. The Minnelusa aquifer has primary porosity in the sandstone units and secondary porosity from collapse breccia associated with dissolution of interbedded evaporites and fracturing. The Minnelusa aquifer receives significant recharge from precipitation and streamflow losses on its outcrop. Streamflow recharge to the Minnelusa aquifer generally is less than to the Madison aquifer (Carter and others, 2001), which is preferentially recharged because of its upslope location. The Minnelusa aquifer is confined by the overlying Opeche Shale.

Both aquifers are potential sources for a number of large springs in the Black Hills area, and hydraulic connections are possible in other locations (Naus and others, in press). Ground-water flowpaths and velocities in both aquifers are influenced by anisotropic and heterogeneous hydraulic properties caused by secondary porosity.

The Minnekahta aquifer, which overlies the Opeche Shale, typically is very permeable, but well yields are limited by the aquifer thickness. The Minnekahta aquifer receives significant recharge from precipitation and limited recharge from streamflow losses on its outcrop. The overlying Spearfish Formation acts as a confining unit to the aquifer.

Within the Mesozoic rock interval, the Inyan Kara Group contains an aquifer that is used extensively. Aquifers in various other units are used locally to lesser degrees. The Inyan Kara aquifer receives recharge primarily from precipitation on its outcrop. The Inyan Kara aquifer also may receive recharge from leakage from the underlying Paleozoic 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 will rise above the top of the aquifer in which it is completed. Flowing wells will 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.

Numerous headwater springs originating from the Paleozoic units at high elevations on the western side of the study area provide base flow for many streams. These streams flow across the central core of the Black Hills, and most streams generally lose all or part of their flow as they cross the outcrops 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 capacity to accept recharge from streamflow. Large streamflow losses also occur in many locations within the outcrop of the Minnelusa Formation (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.

METHODS

All hydrologic budgets presented in this report are combined budgets for the Madison and Minnelusa aquifers because several of the budget components cannot be quantified individually for the aquifers. The area considered (fig. 2) includes all outcrop areas of the Madison and Minnelusa Formations in the Black Hills area. Hydrologic budgets are presented for water years 1987-96, for which change in storage is assumed to be approximately zero as discussed in a subsequent section. This section contains an overview of equation and budget components and of budget scenarios that are addressed.

Within this report, hydrologic analyses are by water year, which represents the period from October 1 through September 30. Discussions of timeframes refer to water years, rather than calender years, unless specifically noted otherwise. The most common unit used is cubic feet per second, which can be converted to acre-feet per day by multiplying by 1.9835 or to gallons per minute by multiplying by 448.83.

Equation and Budget Components

Hydrologic budgets can be represented by the following basic continuity equation, which states that for any designated volume:

$$\Sigma Inflows - \Sigma Outflows = \Delta Storage \qquad (1)$$

where:

$\Sigma Inflows$ = sum of inflows;
$\Sigma Outflows$ = sum of outflows; and
$\Delta Storage$ = change in storage.

Thus, a positive $\Delta Storage$ results when inflows exceed outflows.

Inflows, which are schematically illustrated in figure 6, may include recharge, leakage from adjacent aquifers, and ground-water inflows across the study area boundary. Recharge, which occurs at or near land surface, includes infiltration of precipitation on outcrops of the Madison Limestone and Minnelusa Formation, and streamflow recharge where streams cross the outcrops.

Outflows include springflow, well withdrawals, leakage to adjacent aquifers, and ground-water outflow across the study area boundary (fig. 6). Springflow includes headwater springs, which generally occur near the base of the Madison Limestone, and artesian springs, which constitute a form of leakage but are treated as a separate component because of magnitude and measurability.

Leakage to and from adjacent (overlying and underlying) aquifers is difficult to quantify and cannot be distinguished from ground-water inflows or outflows across the study area boundary. Thus, for budgeting purposes, leakage is included with ground-water flows. For cases when $\Delta Storage$ is assumed to be equal to zero, the sum of the inflows equals the sum of the outflows and the hydrologic budget equation can be written as:

$$\text{Ground-water}_{\text{outflow}} - \text{Ground-water}_{\text{inflow}} = \text{Recharge} - \text{Headwater springflow} - \text{Artesian springflow} - \text{Well withdrawals} \qquad (2)$$

The terms on the right side of equation 2 generally can be quantified more accurately than the terms on the left. Therefore, net ground-water flow (ground-water outflow minus ground-water inflow) can be calculated as the residual, given estimates for the other budget components.

Recharge Considerations

Recharge estimates developed by Carter and others (2001) for the Black Hills area in South Dakota and Wyoming are used in the hydrologic budgets. Recharge estimates for 1931-98 are presented in table 1. Estimates are available for two forms of recharge, including: (1) streamflow losses as streams cross outcrops of the Madison Limestone and Minnelusa Formation; and (2) infiltration of precipitation on these outcrops.

Annual recharge from infiltration of precipitation on outcrop areas was estimated by Carter and others (2001) using a "yield efficiency algorithm," which compared spatial distributions for annual precipitation, average annual precipitation, and average yield efficiency. An exponential relation between these variables was used to estimate the efficiency of basin yield, which was used as a surrogate for efficiency of precipitation recharge. Because outcrops of the Madison Limestone and Minnelusa Formation are not entirely continuous throughout the study area, identification of outcrop areas where effective recharge occurs was necessary. Precipitation recharge was specified only for the “connected” outcrops (fig. 2) and was not specified for outcrops that were considered “isolated” from the regional ground-water flow system (erosional remnants).

During periods of base flow, many streams lose all flow in crossing outcrops of the Madison Limestone and Minnelusa Formation. Until streamflow upstream from a loss zone exceeds the “threshold” loss rate, the entire flow of the stream becomes recharge to various bedrock aquifers. When streamflow upstream from the loss zone exceeds the loss threshold, some flow is sustained through the loss zone, and the loss rate (recharge) is equal to the threshold. Estimates of streamflow recharge by Carter and others (2001) were based on loss thresholds and daily streamflow records, which were available for the larger basins that constituted the majority of streamflow recharge. Other estimation techniques, including statistical regressions, were employed for basins and time periods without daily streamflow records.

Table 1. Estimated annual recharge to the Madison and Minnelusa aquifers, water years 1931-98

[From Carter and others, 2001)

Water year	Recharge, in cubic feet per second			Water year	Recharge, in cubic feet per second		
	Streamflow	Precipitation	Total		Streamflow	Precipitation	Total
1931	38.17	57.37	95.53	1967	121.00	319.45	440.45
1932	107.61	293.82	401.44	1968	82.87	246.91	329.78
1933	98.50	262.78	361.28	1969	74.24	215.90	290.14
1934	37.38	54.70	92.08	1970	105.19	293.58	398.77
1935	61.71	137.54	199.25	1971	123.68	365.41	489.09
1936	30.45	31.08	61.53	1972	126.93	418.46	545.40
1937	53.55	109.75	163.30	1973	123.78	283.41	407.18
1938	58.12	125.31	183.44	1974	54.09	127.82	181.92
1939	58.78	127.53	186.31	1975	96.06	178.43	274.49
1940	49.57	96.18	145.75	1976	113.01	366.44	479.45
1941	128.70	365.63	494.34	1977	86.23	269.50	355.73
1942	100.57	269.84	370.41	1978	108.65	333.69	442.34
1943	79.75	198.96	278.72	1979	84.96	233.26	318.22
1944	71.33	170.29	241.62	1980	60.17	112.06	172.23
1945	125.98	356.35	482.33	1981	60.88	170.50	231.38
1946	189.51	572.68	762.19	1982	89.00	514.20	603.20
1947	89.69	232.79	322.47	1983	115.39	167.59	282.97
1948	79.14	196.87	276.01	1984	122.53	262.19	384.72
1949	56.72	120.53	177.24	1985	49.88	68.91	118.79
1950	79.50	178.87	258.36	1986	92.52	356.64	449.17
1951	76.09	160.75	236.84	1987	108.41	126.33	234.73
1952	113.52	180.03	293.55	1988	38.38	102.37	140.74
1953	96.62	184.32	280.94	1989	40.36	146.66	187.01
1954	66.10	95.61	161.71	1990	76.27	190.95	267.22
1955	65.04	268.06	333.09	1991	103.11	306.66	409.77
1956	65.90	134.06	199.96	1992	66.30	199.31	265.61
1957	117.12	278.05	395.17	1993	128.83	444.35	573.18
1958	73.20	185.27	258.47	1994	120.16	203.50	323.65
1959	60.53	140.36	200.89	1995	183.57	663.81	847.38
1960	59.57	117.59	177.16	1996	179.48	522.32	701.80
1961	54.97	68.88	123.85	1997	221.55	545.83	767.38
1962	122.52	513.23	635.75	1998	174.77	458.38	633.15
1963	103.64	426.54	530.18	Minimum	30.45	31.08	61.53
1964	95.48	472.86	568.33	Maximum	221.55	663.81	847.38
1965	140.80	525.80	666.60	Average	93.18	250.90	344.08
1966	98.23	136.11	234.33	1987-96 average	104.49	290.63	395.11