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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

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Gale A. Norton, Secretary

U.S. Geological Survey

Charles G. Groat, Director

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For additional information write to:

District Chief
U.S. Geological Survey
1608 Mt. View Road
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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 ground-water 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.

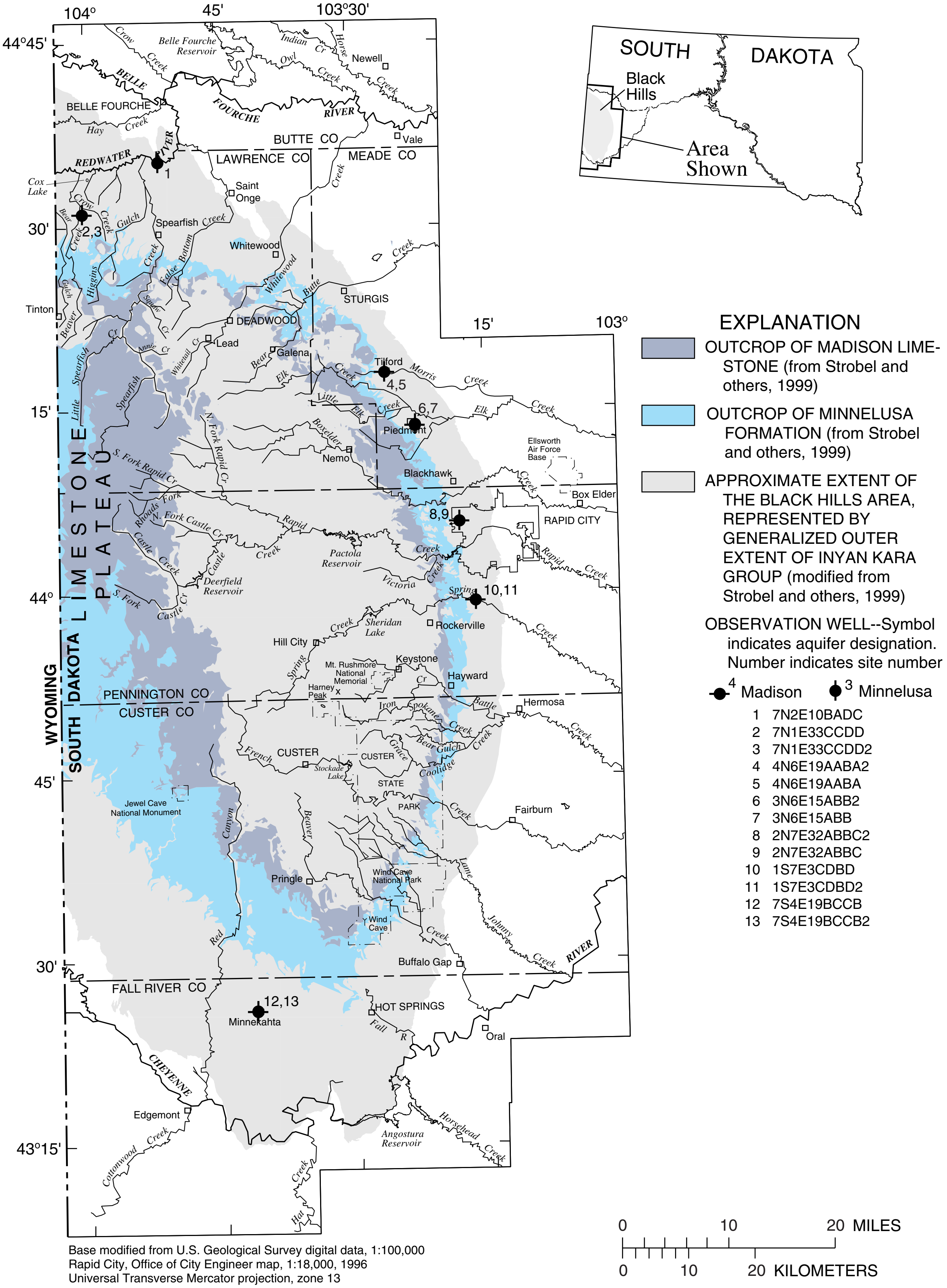
The overall climate of the study area is continental, with generally low precipitation amounts, hot summers, cold winters, and extreme variations in both precipitation and temperatures (Johnson, 1933). Local climatic conditions are affected by topography, with generally lower temperatures and higher 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

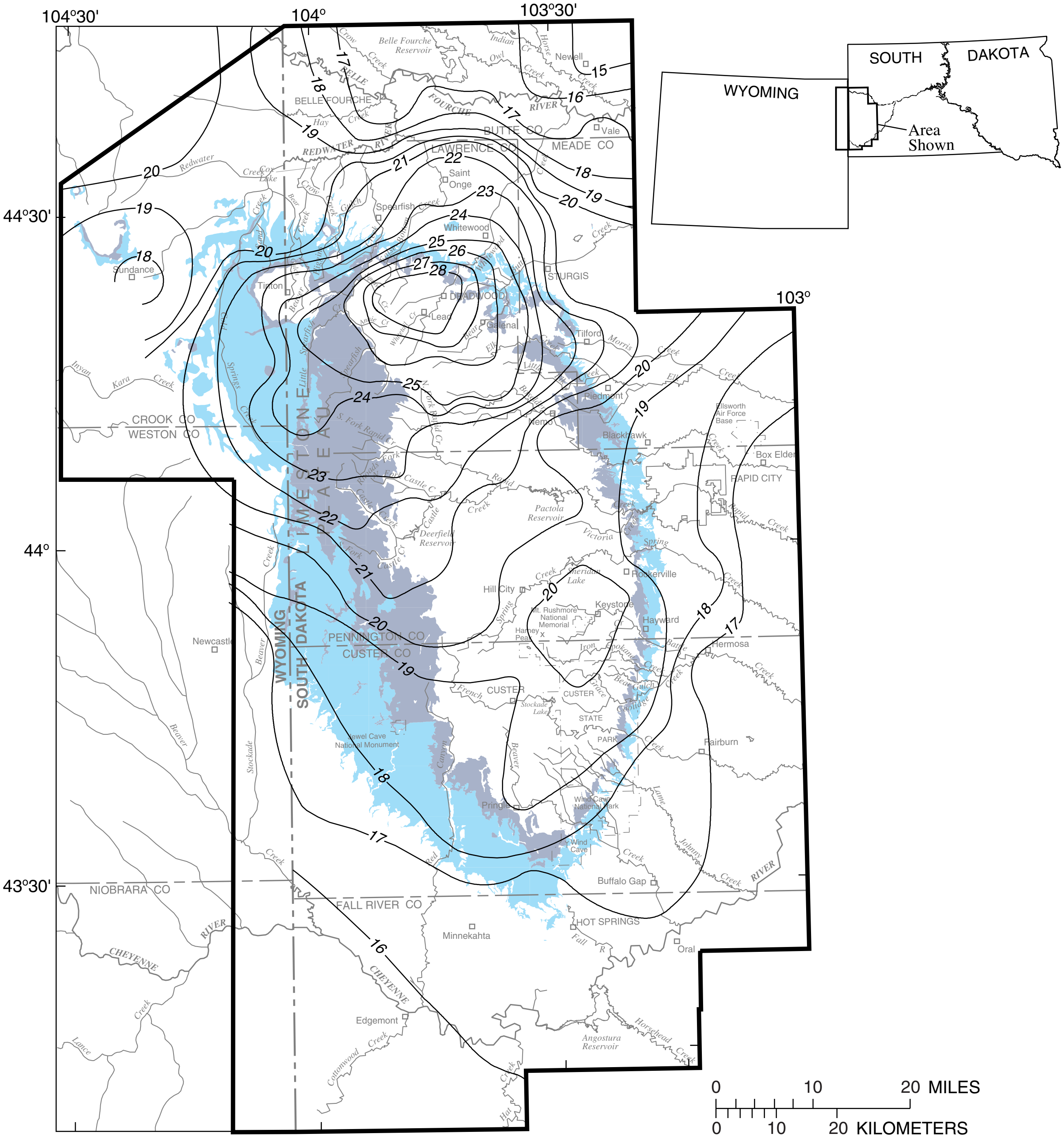
The oldest geologic units in the study area are the Precambrian metamorphic and igneous rocks (fig. 3), which underlie the Paleozoic, Mesozoic, and Cenozoic rocks and sediments. The Precambrian rocks range in age from 1.7 to about 2.5 billion years, and were eroded to a gentle undulating plain at the 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.



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

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

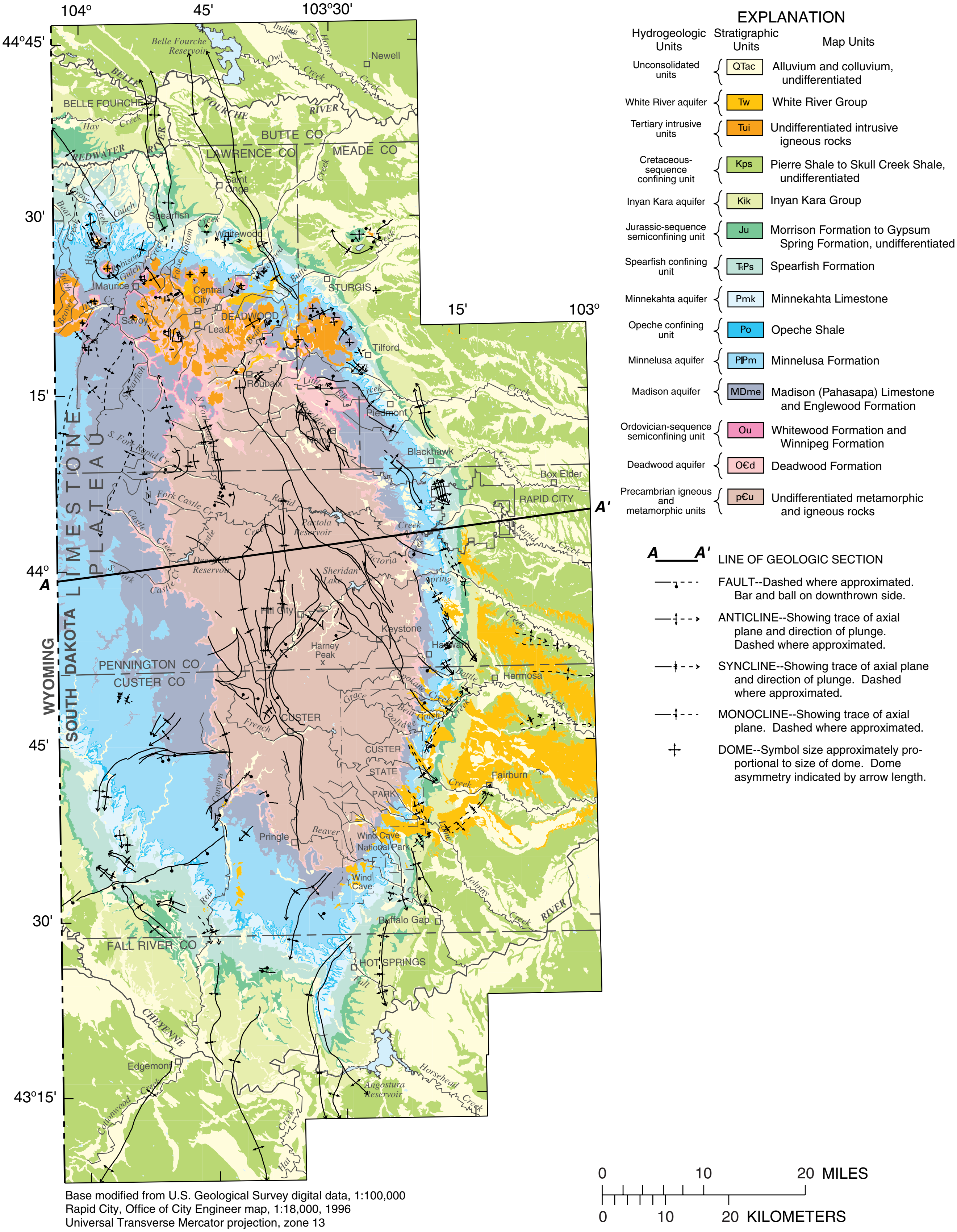
Figure 2. Isohyetal map showing distribution of average annual precipitation for the Black Hills area, water years 1950-98.

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	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 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.



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

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

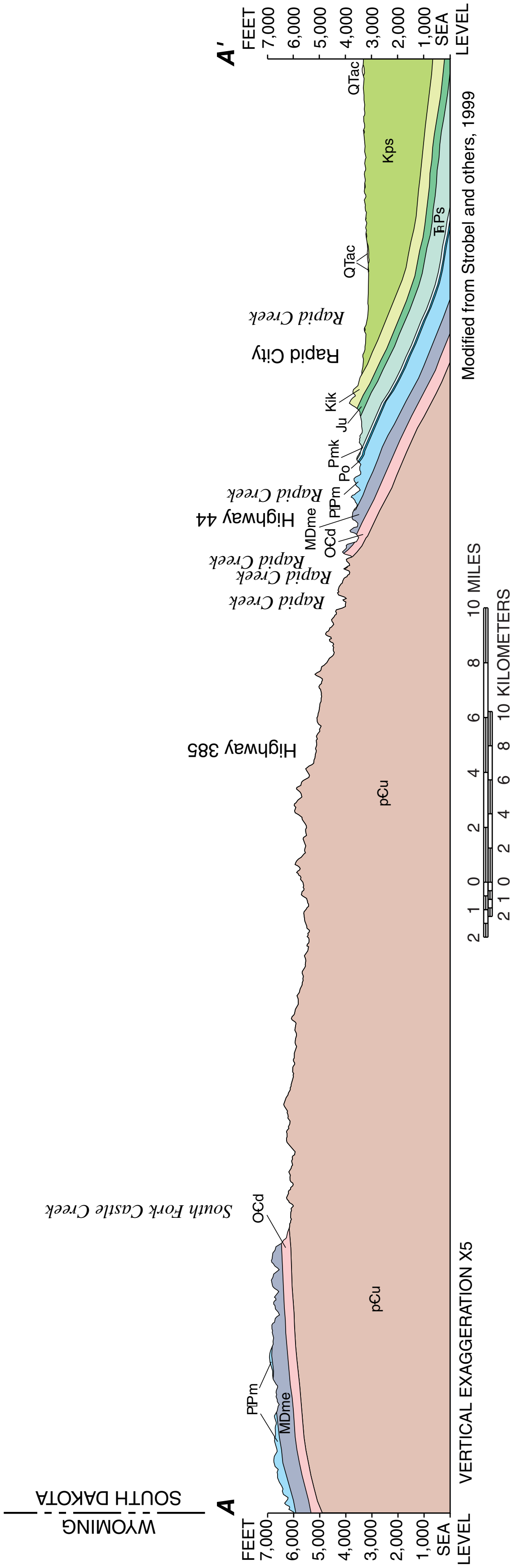


Figure 5. Generalized geologic section A-A' (Location of section is shown in figure 4. Abbreviations for stratigraphic intervals are explained in figure 3.).

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,

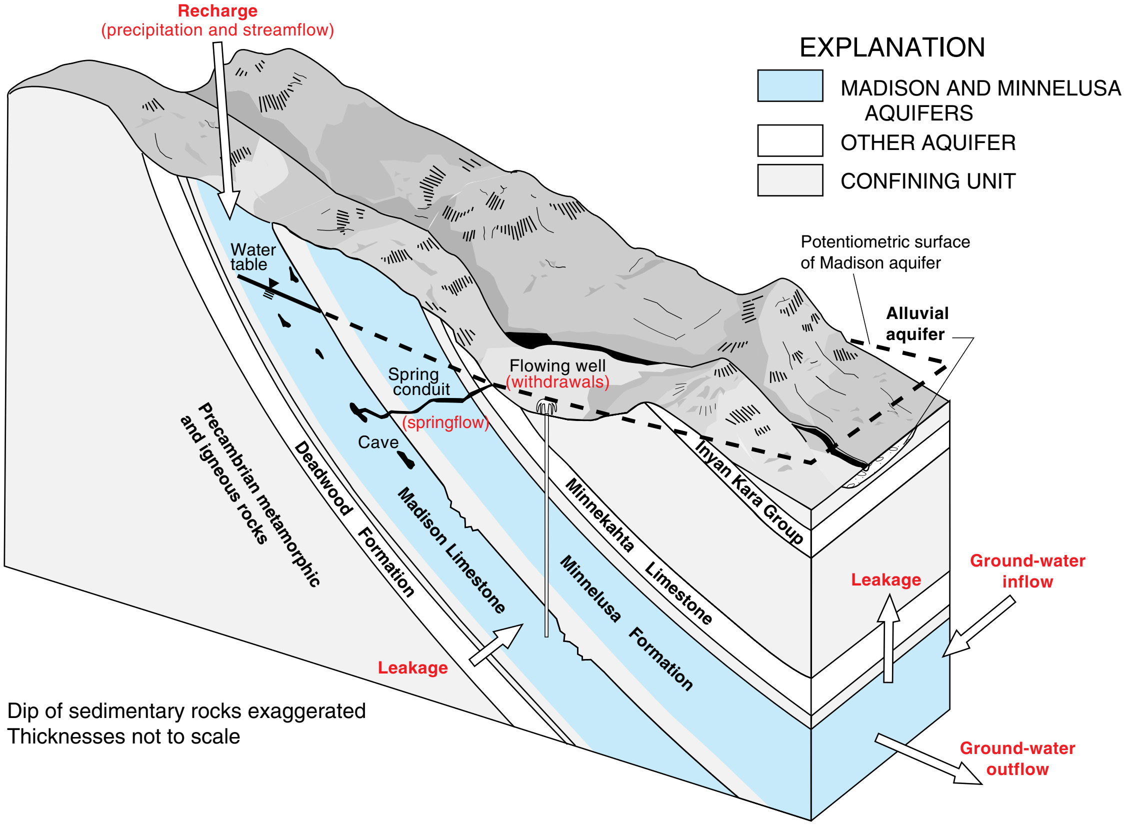


Figure 6. Schematic showing simplified hydrologic setting of the Black Hills area. Components considered for water budgets of Madison and Minnelusa aquifers also are shown.

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

Springflow and Well Withdrawals

Numerous headwater and artesian springs exist throughout the study area and both spring types are considered in the hydrologic budgets. The headwater springs originate from the Paleozoic units on the western side of the study area (Limestone Plateau area) and provide base flow to many area streams. Artesian springs that originate from the Madison and/or Minnelusa aquifers (Naus and others, in press) are common around the periphery of the Black Hills. Many artesian springs occur in locations downgradient from streamflow-loss zones, most commonly within or near the outcrop of the Spearfish Formation.

Most estimates for artesian springflow are derived from streamflow records for streams with substantial artesian springflow components. Streamflow at selected gaging stations is separated into two components—base flow and runoff. The base-flow component generally represents the amount of streamflow contributed by ground-water discharge. The base-flow component is estimated using the Base Flow Index (BFI) FORTRAN computer program (Wahl and Wahl, 1995) using coefficients of *N*=5 (5-day increments) and *f*=0.9 (90 percent minima criteria for determination of turning points).

Similar techniques were used by Jarrell (2000) to identify headwater springflow for streams with substantial headwater springflow components. However, estimates of headwater springflow used in the hydrologic budgets are based on estimates of recharge over contributing ground-water areas. Additional details are provided in a subsequent section.

Well withdrawals from the Madison and Minnelusa aquifers in the Black Hills area serve many categories of water use. These categories include municipal, self supply (domestic), irrigation, livestock, industrial, mining, thermoelectric power, and other. Estimates of well withdrawals used in the hydrologic budgets are based on water-use data from Amundson (1998).

Storage Considerations

For the period 1987-96, change in storage is approximately zero based on well hydrographs and estimated recharge. Examination of a long-term hydrograph (1962-98) for a well completed in the Minnelusa aquifer shows that although the water level has fluctuated nearly 50 ft, there is no apparent long-term trend in the water level (fig. 7; location shown in fig. 1). Hydrographs for selected well pairs (locations shown in fig. 1) completed in the Madison and

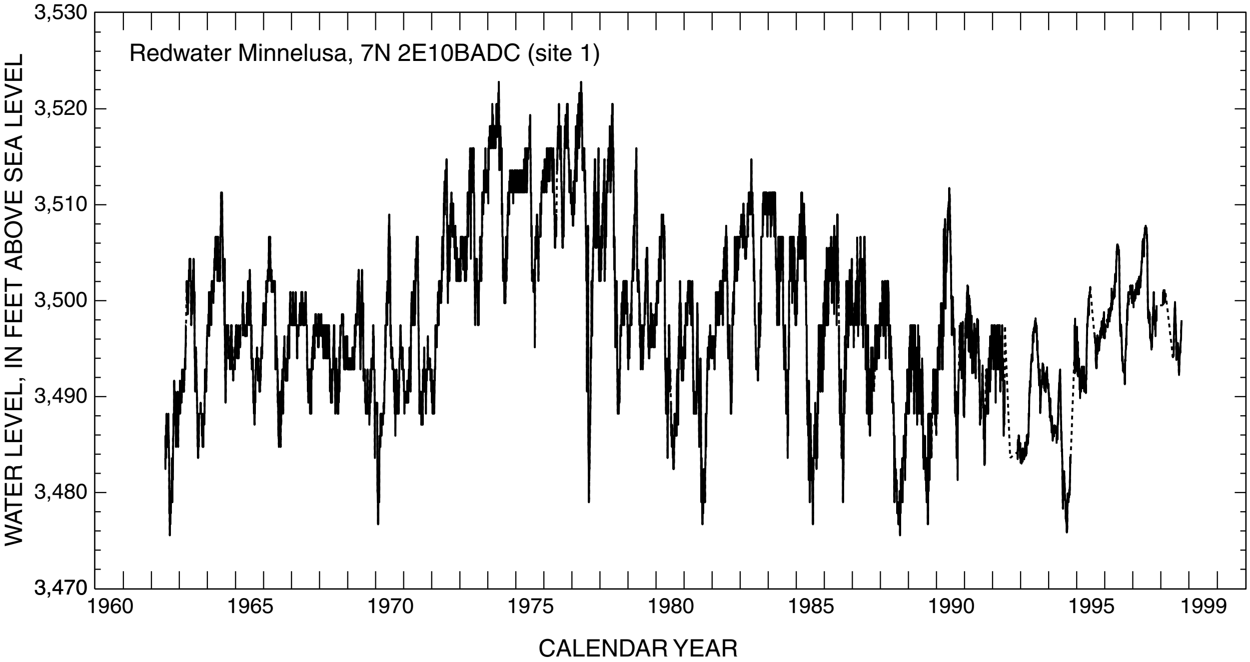


Figure 7. Hydrograph for Redwater Minnelusa well.

Minnelusa aquifers are shown in figure 8. Hydrographs that span the period 1987-96 indicate that the net change in storage during this period generally is small and can be neglected, based on water levels that were approximately equal in 1987 and 1996. Furthermore, the lowest water level during the 10-year period generally occurred during water year 1992 as indicated by most hydrographs. Thus, the 6-year period from 1987-92 generally is a period of decreasing storage (outflows exceed inflows), and the 4-year period from 1993-96 is a period of increasing storage (inflows exceed outflows).

The assumption that change in storage for 1987-96 is approximately equal to zero also is validated by recharge estimates. Average recharge for 1987-96 (395 ft^3/s) is approximately equal to average recharge for the period 1962-98 (410 ft^3/s), which was a long-term period of generally surplus precipitation, relative to generally deficit precipitation during 1931-61 (fig. 9). Thus, recharge during 1987-96 is reasonably representative of average conditions since 1962, but is considerably higher than recharge during the prolonged dry conditions of 1931-61.

Budgeting Scenarios

Two basic budgeting scenarios are considered: (1) an overall budget for the entire study area including parts of Wyoming (fig. 2); and (2) subarea budgets for selected areas within the study area. The timeframes for both budgeting scenarios are 1987-96.

For the overall budget, average values for the budget components are considered. Net ground-water flow is calculated using equation 2, assuming change in storage is zero.

For the subarea budgets, the study area is subdivided into nine subareas, and two timeframes with equal but opposite changes in storage are considered: (1) 1987-92 (generally decreasing storage); and (2) 1993-96 (generally increasing storage). For this budgeting scenario, it also is assumed that the ground-water flow terms on the left side of equation 2 do not vary on an annual basis because only large changes in hydraulic gradient could induce significant changes in ground-water flow rates. Although some error could be introduced by this assumption, the negative error introduced for years of declining water levels probably is offset by the positive error introduced for years of increasing water levels. Using annual estimates for the various budget components on the right side of equation 2, an iterative process is used to solve for the ground-water inflow and outflow components, such that the summed volumetric change in storage for the two time frames is approximately equal, but opposite.

Using Darcy's Law, the ground-water flow components determined for the subarea budgets then are used to estimate transmissivity at the study area boundaries and at any subarea flow zones that are assumed to exist. Anisotropic flow conditions are likely in the study area; however, subareas were selected so that flow boundaries could be approximated assuming isotropic and homogeneous conditions. Although anisotropic flow could not be specifically estimated, the subarea budgets and computation of average transmissivities provide useful insight on how anisotropic conditions probably are involved in the movement of water to artesian springs. Hydraulic gradients are determined using potentiometric-surface maps for the Madison and Minnelusa aquifers. The general assumption that transmissivity is equal for the Madison and Minnelusa aquifers is used, which yields estimates of transmissivity for the entire combined thicknesses of the two aquifers.

HYDROLOGIC BUDGETS

As previously discussed, two budgeting scenarios are considered—an overall budget for the entire study area and individual budgets for nine subareas. The timeframe for both budgeting scenarios is 1987-96. In the following sections, the overall budget is presented first, which includes derivations of budget components, after which subarea budgets are presented.

Overall Budget for Entire Study Area

The change in storage for the budgeting period (1987-96) is assumed to be zero, as previously discussed. Using equation 2, net ground-water flow (outflow minus inflow) is calculated as 100 ft^3/s by subtracting estimated values for headwater springflow (78 ft^3/s), artesian springflow (189 ft^3/s), and well withdrawals (28 ft^3/s) from average recharge (395 ft^3/s). Thus, artesian springflow is the single largest outflow component. Total springflow (including headwater and artesian springflow) averages 267 ft^3/s, which constitutes about 68 percent of estimated recharge.

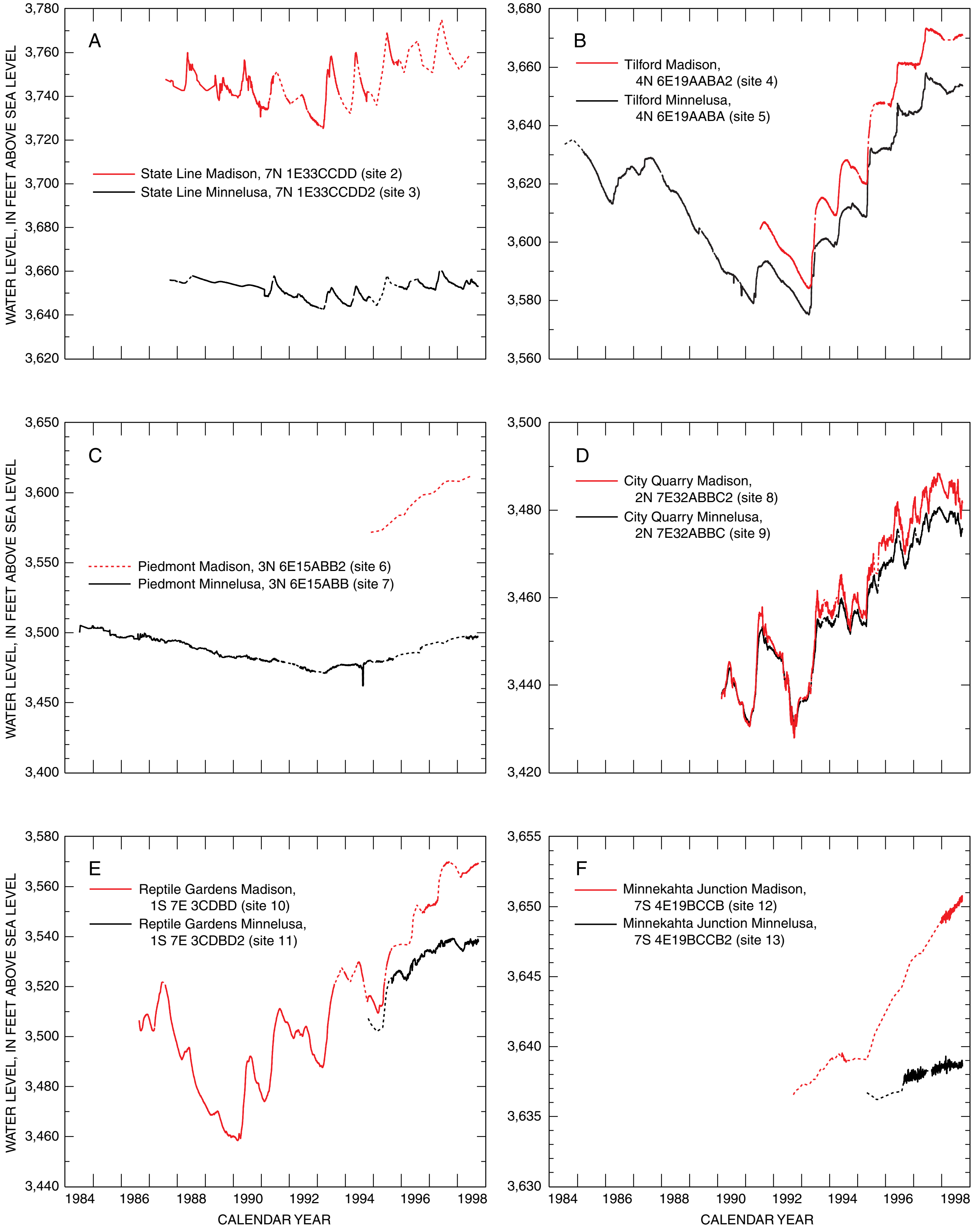


Figure 8. Hydrographs for selected well pairs.

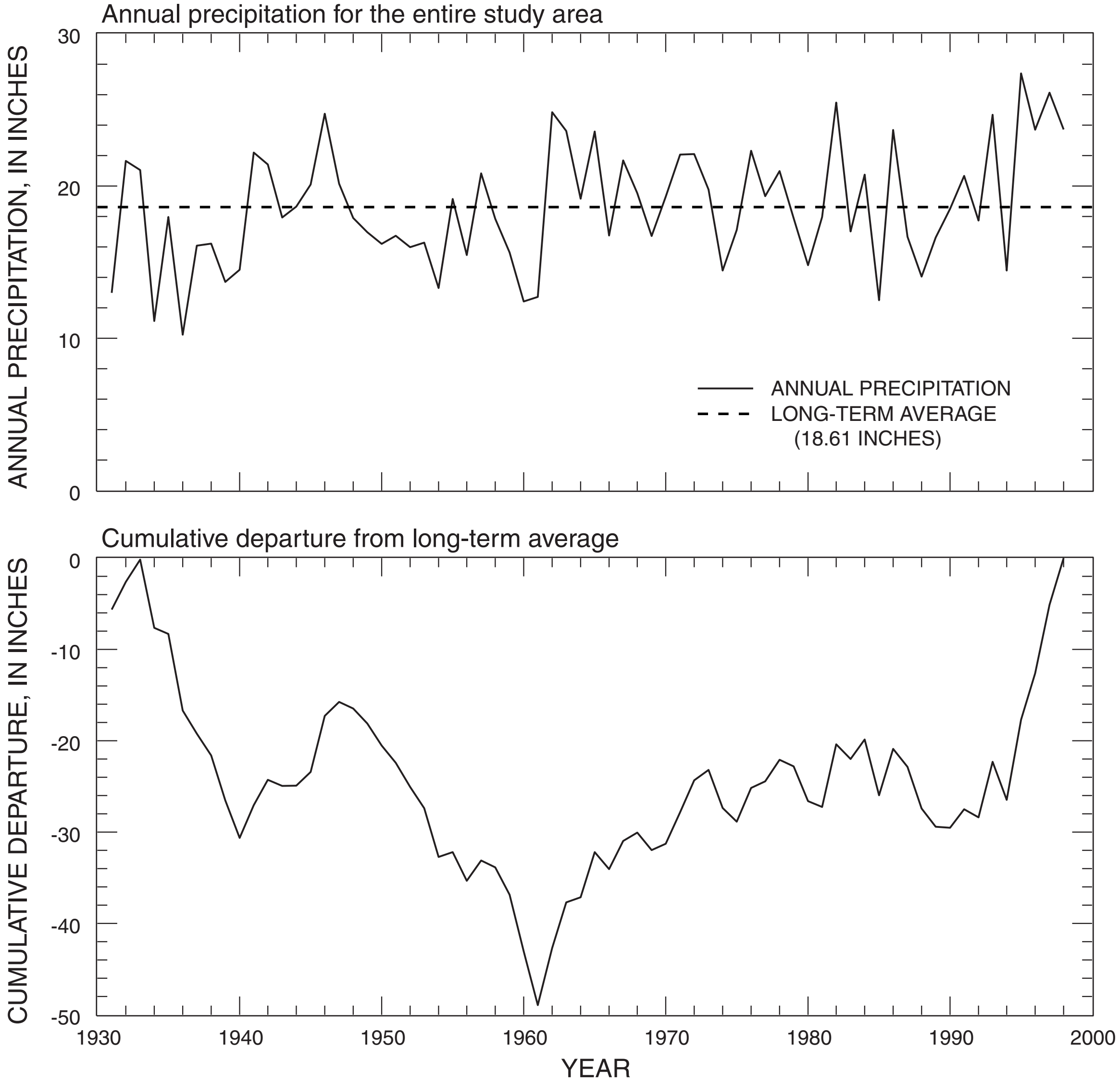


Figure 9. Long-term trends in precipitation for the Black Hills area, water years 1931-98 (from Driscoll, Hamade, and Kenner, 2000).

Because net ground-water flow (which includes leakage to and from adjacent aquifers) is positive, this solution indicates that ground-water outflow exceeds ground-water inflow by 100 ft^3/s. This solution is consistent with potentiometric-surface maps (presented in a following section), which show a gradient away from the uplifted central core of the Black Hills. Possible components of regional ground-water inflow from the west (Wyoming) cannot be evaluated using this budgeting scenario, but is addressed as part of the subarea budgets. The following sections discuss derivations of budget components that are used.

Inflow Components

Inflow components consist of recharge, ground-water inflow, and possible leakage from other aquifers. Estimates for average streamflow and precipitation recharge (table 1) for water years 1987-96 are used for the overall budget. During 1987-96, recharge estimates range from about 141 ft^3/s in 1988 to 847 ft^3/s in 1995. Because leakage to (or from) the Madison and Minnelusa aquifers cannot be evaluated, it is included with net ground-water flow (outflow minus inflow), which is calculated using equation 2. Thus, only the net difference between ground-water outflow and inflow can be evaluated using the overall budget scenario.

Outflow Components

Outflow components consist of springflow from headwater and artesian springs, well withdrawals, and ground-water outflow (including leakage to other aquifers, which is lumped with net ground-water flow). Derivations of estimates for headwater springflow, artesian springflow, and well withdrawals are presented in the following sections.

Headwater Springflow

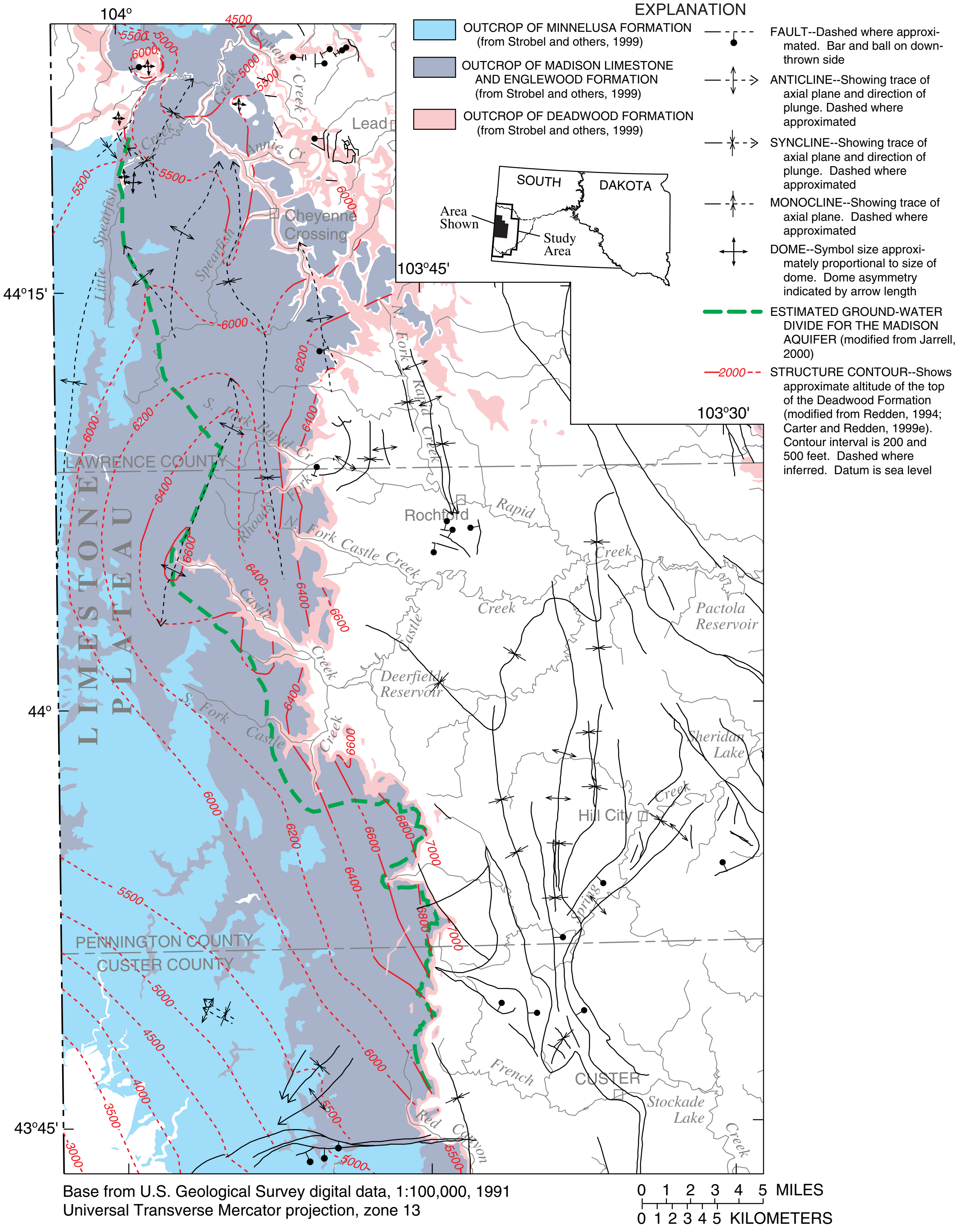
Headwater springflow is considered to be that which occurs upstream from streamflow loss zones, which primarily includes springflow in the Limestone Plateau area along the western edge of the study area (fig. 4). This area is an important recharge area for the Madison and Minnelusa aquifers and generally consists of outcrops of Paleozoic units, particularly the Minnelusa Formation, Madison Limestone, and Deadwood Formation. The largest headwater springs occur along the eastern fringe of the Limestone Plateau, near the contact between the Madison Limestone and underlying units of lower permeability, and provide substantial base flow for several area streams. Discharges from individual headwater spring areas range from minor trickles to over 30 ft^3/s. Numerous small perched springs also occur within the Limestone Plateau area (Wenker, 1997), but do not discharge to perennial streams that flow beyond the outcrop area.

Miller and Driscoll (1998) demonstrated that direct surface runoff is very uncommon in outcrops of the Madison Limestone and Minnelusa Formations, which are the dominant outcrops in the Limestone Plateau area. The general absence of direct surface runoff in this area was used by Carter and others (2001) as the basis for an assumption that the efficiency of recharge from infiltration of precipitation can be approximated by yield efficiency in nearby basins where flow characteristics are dominated by surface runoff. The resulting yield efficiency algorithm is used to estimate annual recharge, based on annual precipitation and associated relations between average precipitation and yield efficiency. Headwater springflow is estimated on the basis of a ground-water divide (fig. 10) identified by Jarrell (2000). Recharge estimates are derived by applying the yield efficiency algorithm, with recharge east of the divide assumed to result in discharge to headwater springs along the eastern fringe. West of the divide a generally westerly flow direction is assumed, with no contribution to headwater springs. Annual recharge estimates for 1987-96 (table 2) range from about 16 ft^3/s to about 215 ft^3/s and average about 78 ft^3/s. Actual variability in annual spring discharge is much smaller than this because of attenuation associated with ground-water storage.

Table 2. Estimated annual recharge to contributing areas for headwater springs, water years 1931-98

[ft^3/s, cubic feet per second]

Water year	Headwater springflow (ft^3/s)	Water year	Headwater springflow (ft^3/s)
1931	3.6	1967	83.3
1932	76.7	1968	62.2
1933	63.6	1969	50.6
1934	4.5	1970	78.7
1935	28.6	1971	101.4
1936	1.0	1972	119.9
1937	16.4	1973	69.5
1938	21.4	1974	23.3
1939	24.0	1975	37.5
1940	13.5	1976	101.1
1941	99.7	1977	69.1
1942	65.4	1978	88.7
1943	48.5	1979	54.8
1944	36.2	1980	18.0
1945	102.1	1981	32.4
1946	190.8	1982	158.7
1947	56.5	1983	37.7
1948	45.9	1984	63.2
1949	20.1	1985	8.0
1950	40.0	1986	90.8
1951	30.5	1987	21.1
1952	41.7	1988	16.2
1953	45.8	1989	26.6
1954	16.9	1990	38.7
1955	71.0	1991	74.9
1956	25.2	1992	48.5
1957	70.7	1993	127.2
1958	39.8	1994	49.3
1959	26.2	1995	214.6
1960	26.7	1996	158.2
1961	7.0	1997	192.9
1962	158.7	1998	152.8
1963	128.5	Minimum	1.0
1964	157.9	Maximum	214.6
1965	161.7	Average	65.6
1966	21.1	1987-96 average	77.5



Base from U.S. Geological Survey digital data, 1:100,000, 1991
Universal Transverse Mercator projection, zone 13

Figure 10. Major structural features and estimated ground-water divide in Limestone Plateau area.

Headwater springflow has been measured in various locations; however, the aforementioned approach is used for estimation of headwater springflow because available streamflow records are insufficient for water-budget calculations. Available streamflow records have been extremely useful, however, in quantifying recharge and discharge characteristics.

Annual yields for selected streamflow-gaging stations near the Limestone Plateau are shown in figure 11, which were used by Jarrrell (2000) to identify apparent incongruences between contributing ground- and surface-water areas for several stations. Annual yields cannot be directly compared among the gaging stations because the period of records are not identical (table 3); however, it is especially apparent for stations 06408700 (Rhoads Fork) and 06409000 (Castle Creek above Deerfield Reservoir) that large differences in yield (9.34 and 2.01 inches, respectively) are not caused by climatic differences.

A variety of information is provided in table 3 that was considered and interpreted by Jarrell (2000) in delineating the ground-water divide (fig. 10) and in delineating contributing ground-water areas for gaging locations (fig. 12). The ground-water divide corresponds with the western extent of contributing ground-water areas for most of the gaging stations shown in figure 12. The ground-water divide coincides with the surface drainage area for French Creek (station 06402995). It is assumed that there is no easterly component for ground-water flow south of French Creek, because the drainage area for Red Canyon is dominated by outcrops of the Madison and Minnelusa Formations. For French Creek, the Paleozoic units comprise only 3.0 mi^2 of the total contributing ground-water area (68.7 mi^2), which is dominated by Precambrian rocks and is delineated as congruent with the surface drainage area.

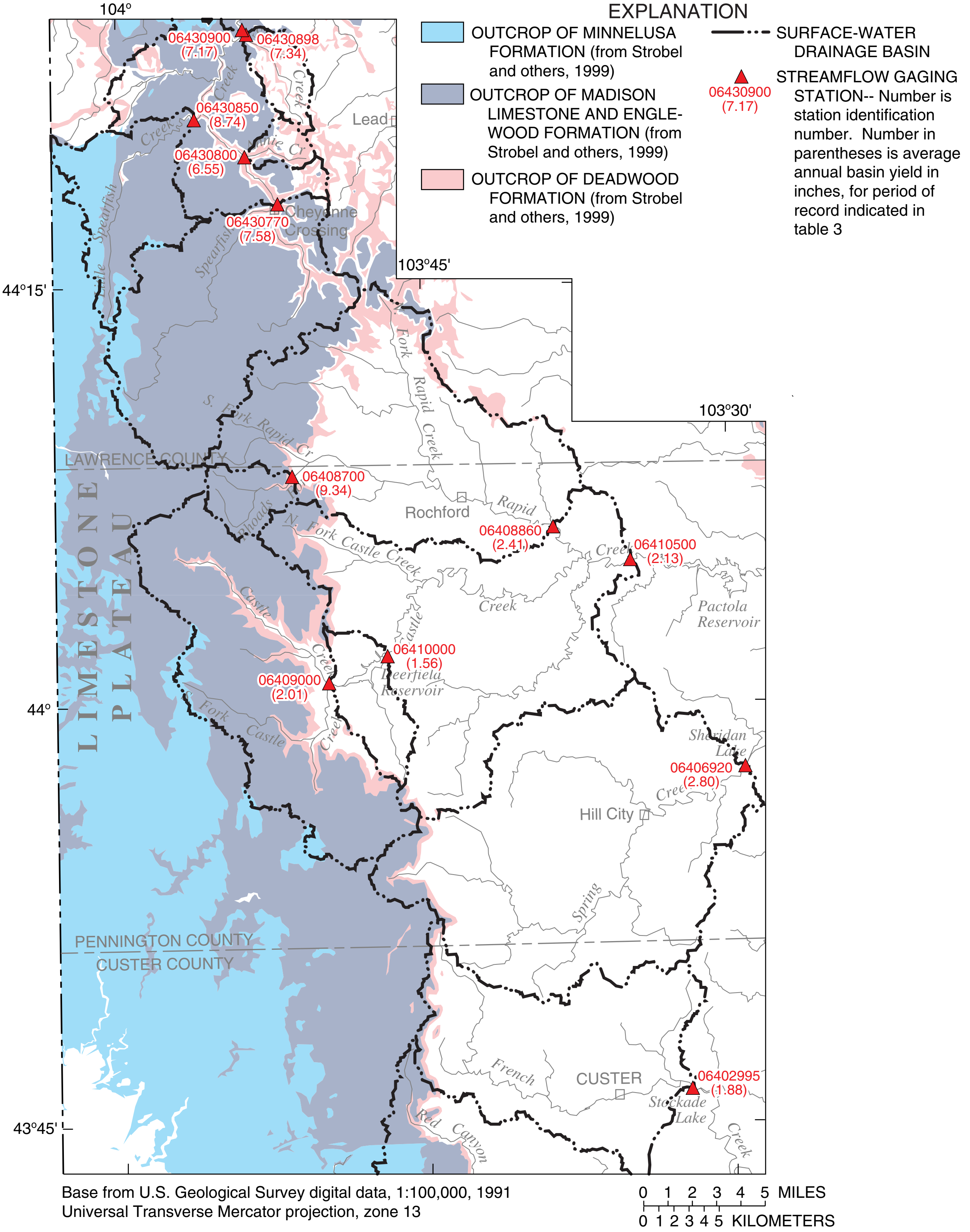
North of French Creek, the contributing ground-water area for Spring Creek (station 06406920) is delineated as slightly smaller than the surface drainage. For Castle Creek (stations 06409000 and 06410000), a large part of the surface drainage is west of the ground-water divide. For Rhoads Fork (station 06408700), the contributing ground-water area is larger than the surface drainage; however, contributing ground-water areas are smaller than surface drainages for two downstream stations on Rapid Creek (06408860 and 06410500).

For station 06430770 (Spearfish Creek near Lead), the contributing ground-water area is smaller than the surface drainage, despite inclusion of a contributing ground-water area from the Rapid Creek basin. Much of the surface drainage for this station is west of the ground-water divide, and part of the basin contributes ground-water flow to station 06438500 (Little Spearfish Creek) to the north. No westerly component of ground-water flow is identified for areas north of this basin.

Jarrell (2000) considered a variety of hydrogeologic information in postulating the location of the ground-water divide (fig. 10) and delineating contributing ground-water areas for gaging stations (fig. 12). Water-level information is too sparse for accurate potentiometric-surface mapping in the Limestone Plateau area (Strobel and others, 2000). Thus, information considered included structure contours, geologic structures, topography, spring locations, and measured spring discharges. Structural high points in the Deadwood Formation were plotted along with major geologic structures (fig. 10). Jarrell (2000) assumed: (1) the Englewood Formation is the lower confining unit of the Madison aquifer; and (2) structural features of the underlying Deadwood Formation continued upward into the lower Madison Limestone and would influence flowpaths in the Madison aquifer, which is unconfined in this area. In some cases, topography and spring locations were used to aid in the delineation of small parts of the contributing ground-water areas.

Jarrell (2000) also compared estimated springflow (based on annual precipitation and yield efficiency) to computed base flow for selected gages. The base-flow component represents the amount of streamflow that the aquifer contributes either directly (as submerged springs under the stream) or in the form of springs. The base-flow component for selected streams (table 3) was estimated using the BFI program as previously described in the “Methods” section. A summary of Jarrell’s (2000) comparisons is included in table 3.

Most estimates compare well with measured base-flow values in table 3, where shading is used to indicate comparable values within rows. Base-flow components are not identified for French Creek and Spring Creek (stations 06402995 and 06406920, respectively), which have only small areas comprised of Paleozoic rocks and for which contributing ground- and surface-water areas are roughly congruent. Correspondingly, estimated values for total basin yield (8,400 and 18,580 acre-feet, respectively) are similar to measured values (6,880 and 18,960 acre-feet).



Base from U.S. Geological Survey digital data, 1:100,000, 1991
Universal Transverse Mercator projection, zone 13

Figure 11. Locations of selected streamflow-gaging stations and associated surface-water drainage basins in Limestone Plateau area. Calculated basin yields, based on surface drainage areas, also are shown. Periods of record for calculating yield are not consistent.

Table 3. Selected information for contributing surface-water and ground-water areas in the Limestone Plateau area

[Shaded cells indicate comparable values within rows. --, not determined]

Station number	Station name	Contributing area (square miles)				Period of record (water years)	Annual values for period of record				
		Surface drainage area	Estimated ground-water area[1]				Measured			Estimated	
			Paleozoic	Other	Total		Runoff (acre-feet)	Yield (inches)	Base flow (acre-feet)	Ground-water yield (springflow) (acre-feet)	Total basin yield (acre-feet)
06402995	French Creek above Stockade Lake, near Custer	68.7	3.0	65.7	68.7	1991-97	6,880	1.88	--	--	8,400
06406920	Spring Creek above Sheridan Lake, near Keystone	127.0	2.5	120.6	123.1	1991-98	18,960	2.80	--	--	18,580
06408700	Rhoads Fork near Rochford	7.95	13.02	.05	13.07	1983-98	3,960	9.34	3,910	3,940	--
06408860	Rapid Creek near Rochford	101.0	17.3	67.0	84.3	1989-94	12,970	2.41	--	--	--
06409000	Castle Creek above Deerfield Reservoir, near Hill City	79.2	35.3	6.4	41.7	1949-98	8,500	2.01	7,400	7,700	--
06410000	Castle Creek below Deerfield Dam[2]	96.0	35.8	18.9	54.7	1947-83	8,030	1.56	--	--	--
06410500	Rapid Creek above Pactola Reservoir[3]	292.0	71.1	177.8	248.9	1954-98	33,220	2.13	--	--	--
06430770	Spearfish Creek near Lead	63.5	48.8	2.0	50.8	1989-98	[4]26,400	7.58	[4]24,020	29,400	--
06430800	Annie Creek near Lead	3.55	2.61	.94	3.55	1989-98	1,240	6.55	--	--	2,090
06430850	Little Spearfish Creek near Lead	25.8	25.3	.1	25.4	1989-98	12,020	8.74	11,660	14,140	--
06430898	Squaw Creek near Spearfish	6.95	2.58	4.37	6.95	1989-98	2,720	7.34	--	--	3,010
06430900	Spearfish Creek above Spearfish[5]	139.0	108.2	13.4	121.6	1989-97	[4]53,190	7.17	--	--	--

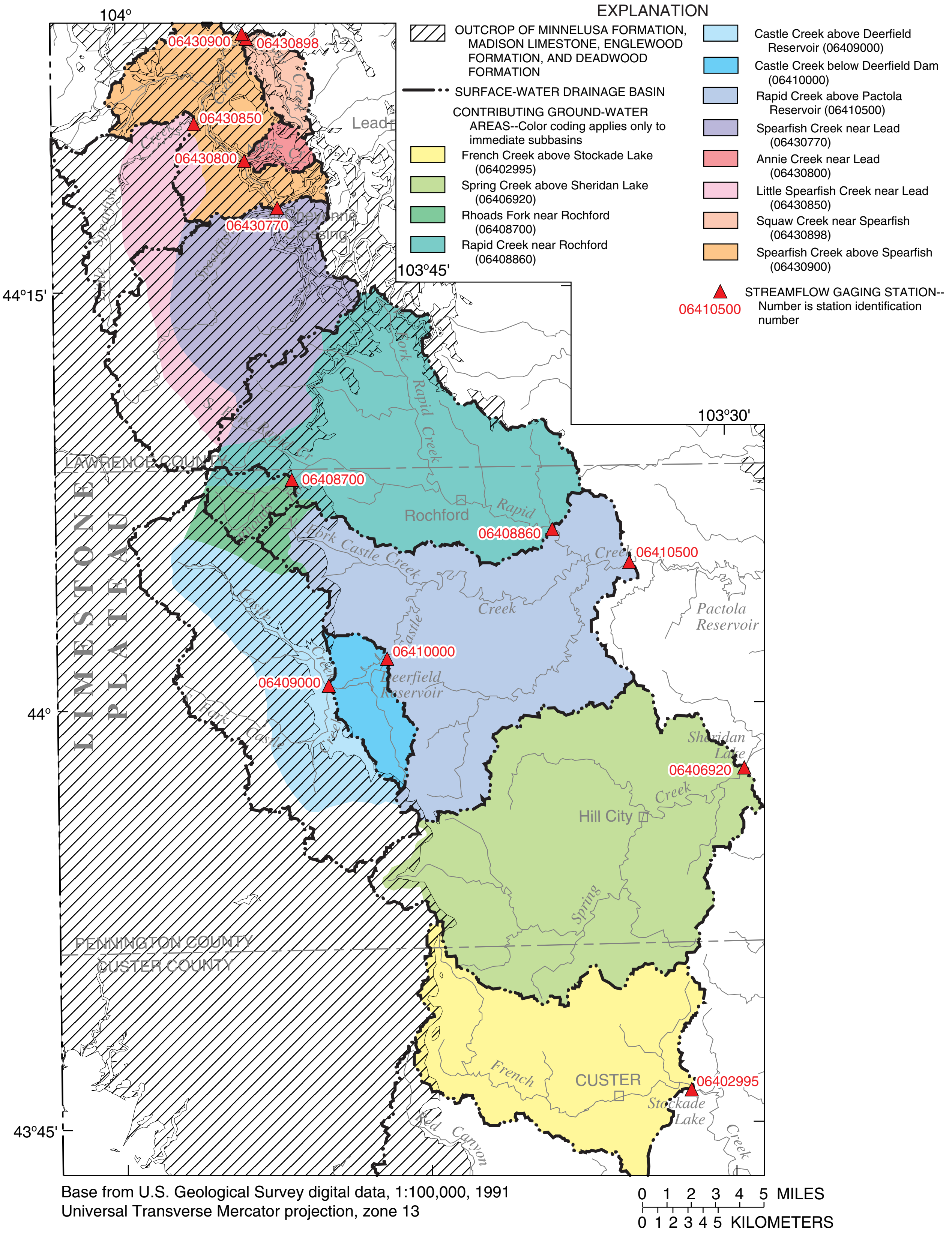
[1] Modified from Jarrell (2000).

[2] Includes flows measured at station 06409000.

[3] Includes flows measured at stations 06408700, 06408860, 06409000, and 06409000.

[4] Includes additional flow of 7,970 acre-feet (11 cubic feet per second) to account for diversions upstream from gaging station.

[5] Includes flows measured at stations 06430770, 06430800, 06430850, and 06430898.



Base from U.S. Geological Survey digital data, 1:100,000, 1991
Universal Transverse Mercator projection, zone 13

Figure 12. Comparison between contributing surface-water areas and ground-water areas for gaging stations in Limestone Plateau area (from Jarrell, 2000).

For Rhoads Fork (06408700) and Castle Creek (06409000), estimates of ground-water yield (based on recharge estimates) compare favorably with base-flow components for measured streamflow. Comparisons for Spearfish Creek (06430770) and Little Spearfish Creek (06430850) are less favorable and probably are heavily influenced by storage effects and short periods of record. The estimated yield for Squaw Creek (06430898) compares favorably with measured yield; however, values for Annie Creek (06430800) compare less favorably, which Carter and others (2001) attributed to consumptive uses for mining activities within the basin. No comparisons are made for stations 06408860, 06410000, 06410500, and 06430900, which are influenced by regulation or short periods of record.

Artesian Springflow

Artesian springflow is considered to be that which originates from confined aquifers around the periphery of the Black Hills. Artesian springs occur in locations downgradient from streamflow-loss zones, most commonly within or near the outcrop of the Spearfish Formation, and originate, at least partially, from the Madison and or Minnelusa aquifers (Naus and others, in press). Other springs, such as Cleghorn/Jackson Springs, occur within the outcrop of the Minnelusa Formation, where the Madison aquifer is confined by the Minnelusa Formation. Most estimates of artesian springflow are derived from streamflow records. Gaging sites used in estimating artesian springflow are shown in figure 13, and selected site information is presented in table 4.

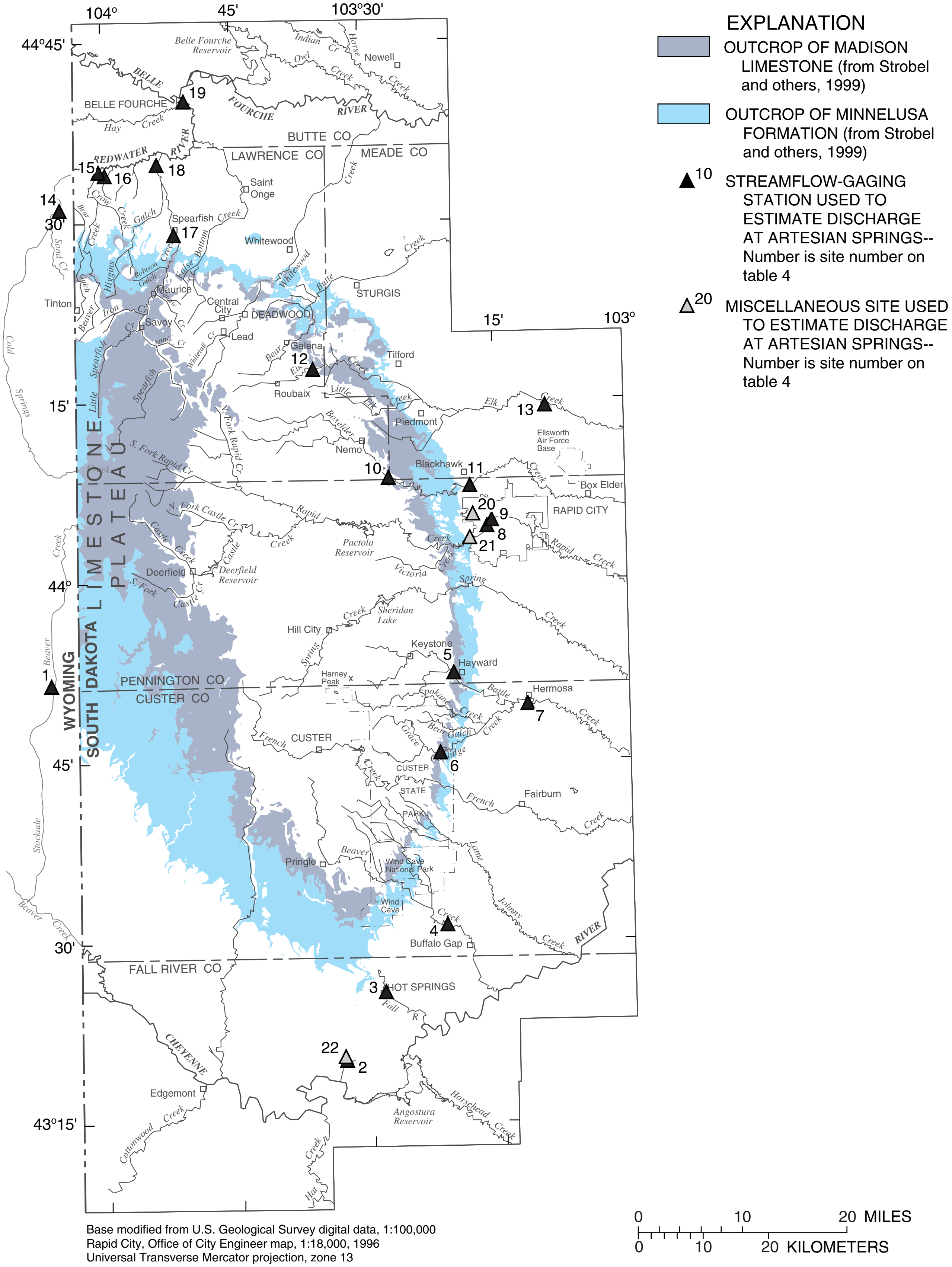
A summary of estimated annual artesian springflow for 1987-96 is presented in table 5. The sum of artesian springflow averages about 189 ft^3/s and ranges from about 163 ft^3/s in 1989 to about 246 ft^3/s in 1996. Discharges from the individual artesian springs were estimated using a variety of methods. Details regarding individual springs follow.

For some streams that are dominated by artesian springflow, the springflow component is determined by applying the BFI program to measured daily flows, as described in the "Methods" section. This was done for 1991-96 for Stockade Beaver Creek (site 1) and Beaver Creek (site 4), which is the period of record for both, and for 1987-96 for Fall River (site 3). For the period of record, spring discharges account for about 90 percent of the flow of Stockade Beaver Creek and 97 percent of the flow of both Fall River and Beaver Creek (table 5). Springflow for 1987-90 for Stockade Beaver Creek is estimated as 9.0 ft^3/s, which is similar to measured values for 1991-93. For Beaver Creek, springflow is estimated as 10.0 ft^3/s for 1987-88 and 9.0 ft^3/s for 1989-90, based on comparisons with measured flows for station 06402500, which is located several miles downstream from site 4.

Measured flows for Cascade Springs (site 2, station 06400497) for 1987-95 (table 4) were assumed to consist entirely of artesian springflow. Additional flow of 4.0 ft^3/s was estimated for Cool Spring (site 22) and other springs downstream from station 06400497 based on miscellaneous streamflow measurements (U.S. Geological Survey, 1996, 1997).

Streamflow in Battle Creek at station 06406000 (site 7) is influenced by a series of upstream springs, including springs along Grace Coolidge Creek (fig. 13). The springs along Battle Creek are located within the outcrop of the Minnelusa Formation and the springs along Grace Coolidge Creek are located downstream from the outcrop of the Minnelusa Formation. Streamflow at site 7 also is influenced by streamflow losses along Battle Creek and Grace Coolidge Creek, as well as by inflows from various other tributaries. Thus, artesian springflow for Battle Creek (site 7) was estimated by applying the BFI program only for periods when streamflows in Battle Creek at station 06404000 (site 5) and Grace Coolidge Creek at station 06404998 (site 6) were less than loss thresholds determined by Hortness and Driscoll (1998). Hence, only periods when there was no flow downgradient of stream loss zones were considered, with results extrapolated to obtain annual estimates. Estimated artesian springflow for Battle Creek averaged 7.0 ft^3/s for 1987-96 (table 5), with large variability in annual springflow.

Several artesian springs in the Rapid City area contribute to the flow of Rapid Creek. Anderson and others (1998) estimated combined springflow from Cleghorn (site 21) and Jackson Springs as 21.6 ft^3/s for 1988-89, which was assumed to be representative for 1987-96. Additional artesian springflow along Rapid Creek is estimated to average 4.3 ft^3/s. Springflow from City Springs (site 20) was measured at station 06413650 (site 8) for 1988-96. Measured flow (1988-90) of the Deadwood Avenue Drain (site 9, station 06413800) also is dominated by artesian springflow, and minor additional springflow occurs in a drainage immediately to the east. Annual springflow for all of these sites is estimated as 4.0 ft^3/s for 1987-94, with slightly higher estimates for 1995-96, based on measured flow at station 06413650 (site 8).



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

Figure 13. Locations of gaging sites used for estimation of artesian springflow.

Table 4. Selected site information for gaging stations and miscellaneous-record sites used to estimate artesian springflow

[--, not applicable]

Site number (fig. 13)	Station identification number	Local number	Name	Latitude	Longitude	Elevation (feet above sea level)	Period of record considered
			Gaging Stations				
1	06392950	45N60W19DC	Stockade Beaver Creek near Newcastle, Wyo.	435132	1040624	4,460	1991-97
2	06400497	8S5E20CDAB	Cascade Springs near Hot Springs	432010	1033307	3,440	1987-95
3	06402000	7S5E24BB	Fall River at Hot Springs	432550	1032833	3,413	1987-97
4	06402470	6S6E14CDB	Beaver Creek above Buffalo Gap	433120	1032123	3,460	1991-97
5	06404000	2S7E18CC	Battle Creek near Keystone	435221	1032010	3,800	1987-97
6	06404998	3S7E17DCDD	Grace Coolidge Creek near Game Lodge, near Custer	434540	1032149	4,100	1987-97
7	06406000	2S8E32CCA	Battle Creek at Hermosa	434941	1031144	3,290	1987-97
8	06413650	1N7E3BCD	Lime Creek at mouth, Rapid City	440430	1031600	3,286	1987-97
9	06413800	2N7E34DDC	Deadwood Avenue Drain at mouth, at Rapid City	440458	1031522	3,206	1988-90
10	06422500	2N5E12DD	Boxelder Creek near Nemo	440838	1032716	4,320	1966-97
11	06423010	2N7E17DB	Boxelder Creek near Rapid City	440754	1031754	3,450	1987-97
12	06424000	4N4E23AD	Elk Creek near Roubaix	441741	1033547	4,881	1991-97
13	06425100	3N8E9AA	Elk Creek near Rapid City	441425	1030903	2,950	1987-97
14	06429905	52N60W18C	Sand Creek near Ranch A, near Beulah, Wyo.	443107	1040457	3,580	1992-97
15	06430532	7N1E16BDB	Crow Creek near Beulah, Wyo.	443414	1040019	3,355	1992-97
16	06430540	7N1E16DADC	Cox Lake outlet near Beulah, Wyo.	443356	1035937	3,415	1991-95
17	06431500	6N2E15BD	Spearfish Creek at Spearfish	442857	1035140	3,640	1987-97
18	06432020	7N2E8DAC	Spearfish Creek below Spearfish	443448	1035337	3,280	1989-97
19	06433000	8N2E11DB	Redwater River above Belle Fourche	444002	1035020	3,000	1987-97
			Miscellaneous Sites				
20	440525103173701	2N7E32ADDA2	City Springs	440525	1031737	3,460	--
21	440327103180503	1N7E8DBBD	Cleghorn Springs	440331	1031801	3,385	--
22	432028103331601	8S5E20BDCB	Cool Spring	432028	1033316	3,450	--

Table 5. Springflow estimates for streams with artesian springs

[Base-flow indices (where applicable) given as percentage of average annual streamflow; all other values given in cubic feet per second; --, no data or not determined; e, estimated; POR, period of record]

Water year	Stockade Beaver Creek (06392950)		Cascade Springs (06400497)	Other springs near Cascade	Fall River (06402000)		Beaver Creek (06402470)	
	Stream-flow	Spring-flow	Spring-flow	Spring-flow	Stream-flow	Spring-flow	Stream-flow	Spring-flow
1987	--	9.0e	21.3	4.0e	21.8	20.1	--	10.0e
1988	--	9.0e	19.6	4.0e	21.3	20.5	--	10.0e
1989	--	9.0e	18.3	4.0e	21.5	20.8	--	9.0e
1990	--	9.0e	18.8	4.0e	21.9	21.3	--	9.0e
1991	9.8	8.8	18.4	4.0e	21.2	20.7	8.2	8.1
1992	9.8	8.9	17.8	4.0e	21.7	21.1	8.1	8.0
1993	10.4	9.1	16.3	4.0e	22.3	21.8	9.2	9.1
1994	10.4	9.7	18.4	4.0e	21.8	21.6	9.7	9.5
1995	12.2	11.8	19.0	4.0e	23.7	23.3	13.7	12.5
1996	13.4	11.3	19.3e	4.0e	24.5	24.2	11.3	11.1
Mean (1987-96)	--	9.6	18.7	4.0e	--	21.5	--	9.6
Base-flow index (POR)	.90	--	--		.97	--	.97	--

Water year	Battle Creek (06406000)		Jackson and Cleghorn Springs	Other Rapid Creek springs	Boxelder Creek (06422500 and 06423010)	Elk Creek (06424000 and 06425100)	Redwater River (06433000)		Sum of artesian spring-flow
	Stream-flow	Spring-flow	Spring-flow	Spring-flow	Spring-flow	Spring-flow	Stream-flow	Spring-flow	
1987	7.8	6.2	21.6e	4.0e	0.0	1.6	123	101.8	199.6
1988	2.7	2.4	21.6	4.0e	.0	.3	93.9	94.8	186.2
1989	1.6	1.2	21.6	4.0e	.0	.0	95.1	75.5	163.4
1990	6.9	1.6	21.6e	4.0e	.0	.0	93.3	78.8	168.1
1991	23.0	3.5	21.6e	4.0e	.0	.1	91.8	81.4	170.6
1992	5.2	4.5	21.6e	4.0e	.0	.0	79.1	76.0	165.9
1993	26.1	7.1	21.6e	4.0e	.2	.1	127	80.6	173.9
1994	11.7	10.8	21.6e	4.0e	.0	.4	124	93.6	193.6
1995	52.6	11.3	21.6e	5.0e	.5	8.6	240	103.9	221.5
1996	32.2	21.0	21.6e	6.0e	2.5	8.2	222	116.7	245.9
Mean (1987-96)	--	7.0	21.6	4.3	.3	1.9	--	90.3	188.9
Base-flow index (POR)	--	--	--	--	--	--	--	--	--

Several springs are located within outcrops of the Madison Limestone and Minnelusa Formation along Boxelder Creek (Rahn and Gries, 1973) between sites 10 and 11 (fig. 13). Artesian conditions probably do not occur in most of this reach, where streamflow losses typically occur. Artesian springflow probably occurs occasionally at the lower end of the reach, however, just upstream from site 11. Artesian springflow for Boxelder Creek (site 11) was estimated by applying the BFI program for periods when streamflow at site 10 was less than the loss threshold determined by Hortness and Driscoll (1998).

Highly variable artesian springflow occurs along Elk Creek, primarily in a short reach just upstream from the confluence with Little Elk Creek (fig. 13). Artesian springflow during 1991-96 was estimated by applying the BFI program for site 13 for periods when streamflow at site 12 was less than the loss threshold determined by Hortness and Driscoll (1998). Streamflow records for site 12 are not available prior to 1991 (table 4); thus, the BFI program was used directly for 1987-90.

The Redwater River, which is measured at site 19 (fig. 13), often consists primarily of flow from a number of large artesian springs. Streamflow in the Redwater River also is influenced by surface runoff, as well as extensive diversions during the irrigation season. Continuous flow records are available for several spring areas contributing to the Redwater River; however, available records are insufficient to quantify all contributing artesian springflow. Thus, combined springflow of all artesian springs contributing to the Redwater River is estimated. Monthly differences in streamflow between sites 17 and 19 are presented in table 6. Artesian springflow for each year is assumed equal to the median of values for November through February, when effects of irrigation diversions and surface runoff generally are minimal. Thus, mean artesian springflow contributing to Redwater River for 1987-96 is estimated as 90.3 ft^3/s, which includes springflow that occurs along Spearfish Creek, downstream from site 17.

Estimated artesian springflow that occurs along Spearfish Creek in the reach between sites 17 and 18 also is shown in table 6. Extensive irrigation diversions also occur in this reach; thus, an approach similar to that for the Redwater River was used to estimate springflow. Artesian springflow for each year is assumed equal to the median of monthly differences in streamflow between sites 17 and 18 for November through February.

Springflow for several other individual artesian spring reaches contributing to Redwater River are quantified for years for which streamflow records are available (table 7). Measured annual streamflow values for Sand Creek (site 14), Crow Creek (site 15), and Cox Lake (site 16) are shown in table 7, along with estimated springflow derived using the BFI program.

Springflow from individual spring reaches contributing to Redwater River is summed in table 7 for 1992-96. Springflow for Cox Lake has little variability; thus, springflow for 1996 was assumed equal to previous years. Variability for the other sites generally is similar to that of Redwater River. For 1992-96, total artesian springflow for Redwater River is estimated as 94.2 ft^3/s, of which 69.2 ft^3/s (about 73 percent) can be attributed to the individual sources listed in table 7. Estimates of unmeasured springflow contributing to the flow of Redwater River for these years range from about 16 to 34 ft^3/s.

Well Withdrawals

Withdrawals from the Madison and Minnelusa aquifers in the Black Hills area serve many categories of water use including municipal, self supply (domestic), irrigation, livestock, industrial, mining, thermoelectric power, and unaccounted withdrawals. Estimated withdrawals for these categories of water use are presented in table 8, with total withdrawals from the Madison and Minnelusa aquifers for 1987-96 estimated as about 18.3 Mgal/d, which is equivalent to about 28 ft^3/s. Municipal use, with combined withdrawals of about 6.5 Mgal/d, is the largest use category (fig. 14). The largest use occurs within Pennington County, which averages about 3.1 Mgal/d and is dominated by municipal usage.

Most estimates in table 8 are based on 1995 water-use data (Amundson, 1998) compiled for the entire counties included in the study area. Therefore, well withdrawals probably are slightly overestimated; however, most of the demand within these counties does occur within the study area. Withdrawals in Wyoming are small and are not estimated. Annual estimates for Rapid City municipal withdrawals in Pennington County and for irrigation withdrawals are used in developing the 1987-96 estimates, as discussed in the following paragraphs.

Table 6. Streamflow analysis and estimated artesian springflow for Redwater River and Spearfish Creek

[All values in cubic feet per second. Shaded cells show months for which median flow is used as estimate of annual springflow. --, not computed]

Water year	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	Estimated springflow[1]
Monthly difference in streamflow between Redwater River (06433000) and Spearfish Creek at Spearfish (06431500)													
1987	109.3	127.9	112.3	91.2	88.4	107.4	122.8	113.0	40.1	-20.5	27.8	77.5	101.8
1988	91.9	114.0	97.7	81.1	91.9	115.5	91.0	53.6	-35.4	-32.6	-25.7	-.9	94.8
1989	83.0	95.1	82.6	67.5	68.4	90.6	95.0	99.5	3.3	-31.5	-31.0	21.7	75.5
1990	95.8	86.3	73.2	76.1	81.5	85.9	77.2	94.7	10.9	-30.1	-25.5	-7.5	78.8
1991	63.5	95.5	86.0	73.2	76.7	90.2	84.4	40.2	53.7	-34.6	-29.5	19.1	81.4
1992	60.9	85.2	75.4	76.5	70.8	69.0	75.5	-28.7	-13.9	-3.6	-15.3	32.6	76.0
1993	87.9	104.8	96.3	64.8	60.3	119.5	90.9	115.0	128.3	81.9	12.1	33.6	80.6
1994	59.2	85.3	104.6	88.9	98.2	138.6	126.1	151.1	4.1	-18.5	-18.0	14.0	93.6
1995	101.7	101.9	84.3	105.8	124.2	99.6	94.3	719.0	299.0	92.1	19.7	51.0	103.9
1996	131.7	115.2	106.2	118.2	214.4	207.5	187.8	251.0	232.0	21.4	26.9	93.2	116.7
Mean (1987-96)	--	--	--	--	--	--	--	--	--	--	--	--	90.3
Monthly difference in streamflow between Spearfish Creek at Spearfish (06431500) and Spearfish Creek below Spearfish (06432020)													
1989	9.5	16.6	11.1	11.9	4.5	14.8	11.9	-9.5	-12.9	-29.6	-33.4	-8.8	11.5
1990	11.4	11.2	2.5	12.8	10.7	8.2	-1.1	-0.7	-13.6	-30.7	-28.6	-14.1	11.0
1991	2.2	10.4	2.5	-2.8	10.4	8.7	8.5	11.8	3.9	-31.3	-25.6	-5.1	6.5
1992	1.8	12.8	6.9	2.1	2.3	10.2	1.7	-27.3	-21.8	-16.9	-18.7	-0.5	4.6
1993	6.8	14.6	7.1	4.2	9.6	13.9	7.3	5.0	6.2	8.4	-1.5	0.7	8.4
1994	7.9	9.2	13.6	15.2	12.7	10.6	-4.1	-3.4	-27.4	-29.4	-26.3	-14.5	13.2
1995	12.6	17.6	13.5	5.4	6.7	9.9	18.0	25.0	51.0	14.4	-10.2	-4.2	10.1
1996	14.9	14.5	8.0	14.2	16.6	14.7	22.8	20.0	19.0	-5.2	-15.6	3.1	14.4
Mean (1989-96)	--	--	--	--	--	--	--	--	--	--	--	--	8.0

[1] Estimated using median difference for months of November through February.

Table 7. Springflow for artesian springs or spring reaches along tributaries to Redwater River

[Base-flow indices (where applicable) given as a percentage of average annual streamflow, all other values given in cubic feet per second; --, no data or not determined; e, estimated]

Water year	Sand Creek (06429905)		Crow Creek (06430532)		Cox Lake (06430540)		Spearfish Creek (06431500 and 06432020)	Sub-total	Redwater River[1] (06433000)	Un-measured spring-flow[2]
	Stream-flow	Spring-flow	Stream-flow	Spring-flow	Stream-flow	Spring-flow	Spring-flow	Spring-flow	Spring-flow	
1987	--	--	--	--	--	--	--	--	101.8	--
1988	--	--	--	--	--	--	--	--	94.8	--
1989	--	--	--	--	--	--	11.5	--	75.5	--
1990	--	--	--	--	--	--	11.0	--	78.8	--
1991	--	--	--	--	4.3	4.2	6.5	--	81.4	--
1992	15.7	15.0	33.3	32.8	4.2	4.2	4.6	56.6	76.0	19.4
1993	16.4	15.6	37.4	36.0	4.2	4.2	8.4	64.2	80.6	16.4
1994	17.2	16.4	37.8	36.0	4.2	4.2	13.2	69.8	93.6	23.8
1995	23.2	22.1	42.9	36.1	4.3	4.2	10.1	72.5	103.9	31.4
1996	24.3	23.1	44.5	41.3	--	4.2e	14.4	83.0	116.7	33.7
Mean (1992-96)	--	18.4	--	36.4	--	4.2	10.1	69.2	94.2	24.9
Base-flow index (period of record)	.95	--	.93	--	.99	--	--	--	--	--

[1] From table 6.

[2] Calculated as Redwater River springflow minus subtotal.

Table 8. Estimated well withdrawals from the Madison and Minnelusa aquifers in the Black Hills area, water years 1987-96

Aquifer	Average annual water use, in thousands of gallons per day						
	County						Total
	Butte	Custer	Fall River	Lawrence	Meade	Pennington	
Municipal							
Madison	723.0	0.0	666.0	1,436.0	284.0	2,537.6	5,646.6
Minnelusa	.0	.0	.0	.0	284.0	575.7	859.7
Total	723.0	.0	666.0	1,436.0	568.0	3,113.3	6,506.3
Self-supply Domestic							
Madison	2.1	5.2	2.9	45.9	54.1	98.6	208.8
Minnelusa	8.4	24.1	38.5	109.8	353.0	186.9	720.7
Total	10.5	29.3	41.4	155.7	407.1	285.5	929.5
Irrigation							
Madison	480.2	.0	2.8	107.9	12.7	51.3	654.9
Minnelusa	610.5	9.3	48.1	1,573.5	31.4	10.7	2,283.5
Total	1,090.7	9.3	50.9	1,681.4	44.1	62.0	2,938.4
Livestock Watering							
Madison	9.6	6.2	1.2	7.3	2.4	11.9	38.6
Minnelusa	33.9	20.1	8.4	51.0	13.4	16.2	143.0
Total	43.5	26.3	9.6	58.3	15.8	28.1	181.6
Industrial							
Madison	.0	.0	.0	52.0	.0	.0	52.0
Minnelusa	.0	4.0	.0	.0	19.0	901.0	924.0
Total	.0	4.0	.0	52.0	19.0	901.0	976.0
Mining							
Madison	.0	.0	210.0	25.0	.0	.0	235.0
Minnelusa	.0	.0	.0	107.0	.0	941.0	1,048.0
Total	.0	.0	210.0	132.0	.0	941.0	1,283.0
Thermoelectric							
Madison	.0	.0	.0	.0	.0	320.0	320.0
Minnelusa	.0	.0	.0	.0	.0	120.0	120.0
Total	.0	.0	.0	.0	.0	440.0	440.0
Subtotal							
Madison	1,214.9	11.4	882.9	1,674.1	637.2	3,019.4	7,439.9
Minnelusa	652.8	57.5	95.0	1,841.3	416.8	2,751.5	5,814.9
Total	1,867.7	68.9	977.9	3,515.4	1,054.0	5,770.9	13,254.8
Unaccounted Withdrawals							
Madison	2,000.0	2.9	220.7	418.5	159.3	754.9	3,556.3
Minnelusa	163.2	14.4	23.8	460.3	104.2	687.9	1,453.7
Total	2,163.2	17.3	244.5	878.9	263.5	1,442.7	5,010.0
Total							
Madison	3,214.9	14.3	1,103.6	2,092.6	796.5	3,774.3	10,990.2
Minnelusa	816.0	71.9	118.8	2,301.6	521.0	3,439.4	7,268.6
Total	4,030.9	86.1	1,222.4	4,394.3	1,317.5	7,213.6	18,264.8

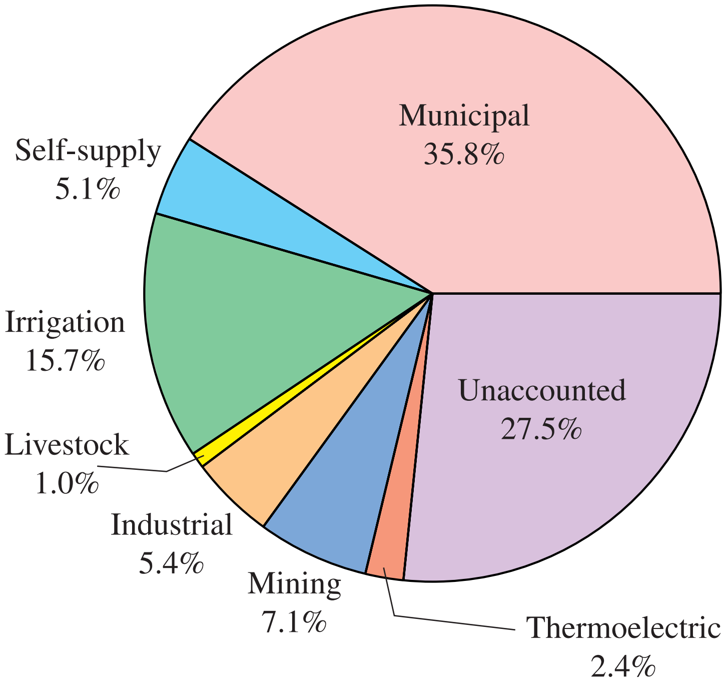


Figure 14. Pie chart showing percentages of use from the Madison and Minnelusa aquifers, by category, for South Dakota counties in the Black Hills area.

Municipalities that use the Madison and Minnelusa aquifers to some degree to supply water for their customers include Belle Fourche, Box Elder, Edgemont, Hot Springs, Rapid City, Spearfish, Sturgis, and Whitewood (table 9). Rapid City, which used an average of about 2.9 Mgal/d from the Madison and Minnelusa aquifers during 1987-96, is the largest user.

Withdrawals for municipal purposes in Rapid City have increased steadily since increased development of the Madison aquifer began in the early 1990's. Thus, the average withdrawal for 1987-96 (table 8) is calculated from annual withdrawals, which are used in the subsequent budgets for subareas. In table 8, it was assumed that 80 percent of the municipal withdrawals in Rapid City are from the Madison aquifer and 20 percent are from the Minnelusa aquifer. Municipal withdrawals from the Madison and Minnelusa aquifers in other communities also may have been less than the 1995 withdrawals used for budgeting purposes; however, the difference is assumed to be small in comparison to the difference for Rapid City. The average municipal water use rate (1987-96) from the Madison and Minnelusa aquifers is about 6,506,300 gal/d (10.07 ft^3/s).

Self-supply water use includes all withdrawals for domestic use that are not supplied by municipalities. Total self-supply ground-water withdrawals are available for 1995 by county, but not by aquifer. To estimate the percent of total ground-water withdrawals from the Madison and Minnelusa aquifers, data on domestic wells in the six-county area were compiled from the USGS Ground-Water Site Inventory (GWSI) database. The percentages of wells completed in the Madison and Minnelusa aquifers were applied to the total ground-water withdrawals to apportion self-supply use (table 10). The estimated total withdrawal from the Madison and Minnelusa aquifers for domestic purposes from self-supply wells is 929,500 gal/d (1.44 ft^3/s).

Irrigation water use includes all water artificially applied to farms, orchards, and horticultural crops. Data on irrigation withdrawals from the Madison and Minnelusa aquifers were compiled from the USGS Site-Specific Water-Use Data System (SWUDS) for the period of record (1981-98) for counties in the study area (table 11). Over three times as much water is used from the Minnelusa aquifer than the Madison aquifer for irrigation. Irrigation water use varies from year to year depending on precipitation conditions, and averaged 2,938,400 gal/d (4.48 ft^3/s) from 1987-96. The largest irrigation withdrawals occur in Lawrence and Butte Counties for the Minnelusa aquifer, and in Butte County for the Madison aquifer (table 11).

Table 9. Estimated water use from the Madison and Minnelusa aquifers by incorporated municipalities in the Black Hills area, 1995

Municipality	Population	Aquifer	Annual use (million gallons)	Average daily use (thousand gallons)
Belle Fourche	5,168	Madison	263.895	[1]723.0
Box Elder	3,133	Madison	85.775	[1]235.0
Edgemont	907	Madison	46.355	[1]127.0
Hot Springs	4,277	Madison	196.735	[1]539.0
Rapid City	59,373	Madison/Minnelusa	[2]1,050.598	2,878.3
Spearfish	7,747	Madison	469.380	[1]1,286.0
Sturgis	5,570	Madison/Minnelusa	207.320	[1]568.0
Whitewood	987	Madison	[3]54.750	150.0
Total	87,162	Madison/Minnelusa	2,374.800	6,506.3

[1] Joe Lyons, U.S. Bureau of Reclamation, written commun., 1999.

[2] John Wagner, Rapid City Water Department, written commun, 2000. Annual and daily use are averages for 1987-96.

[3] Dave Mikkelson, City of Whitewood, oral commun., 2000.

Table 10. Percentages of wells, by aquifer, used to estimate domestic and livestock uses

[--, not applicable]

County	Population	Total ground-water use (thousand gallons per day)	Percentage of wells, by aquifer		
			Madison	Minnelusa	Other
		Self-supplied Domestic			
Butte	1,120	90	2.3	9.3	88.4
Custer	4,100	290	1.8	8.3	89.9
Fall River	1,950	140	2.1	27.5	70.4
Lawrence	7,940	560	8.2	19.6	72.2
Meade	16,400	1,230	4.4	28.7	66.9
Pennington	16,050	1,280	7.7	14.6	77.7
Totals	47,560	3,590	--	--	--
		Livestock Watering			
Butte	--	320	3.0	10.6	86.4
Custer	--	110	5.6	18.3	76.1
Fall River	--	240	0.5	3.5	96.0
Lawrence	--	170	4.3	30.0	65.7
Meade	--	480	0.5	2.8	96.7
Pennington	--	270	4.4	6.0	89.6
Totals	--	1,590	--	--	--

Table 11. Estimated irrigation withdrawals from the Madison and Minnelusa aquifers in the Black Hills area, water years 1981-98

[All values in acre-feet, unless otherwise indicated. acre-ft, acre-feet; gal/d, gallons per day]

Water year		Madison aquifer							Minnelusa aquifer							Combined Minnelusa and Madison aquifers						
		Butte	Custer	Fall River	Law-rence	Meade	Pen-nington	Total	Butte	Custer	Fall River	Law-rence	Meade	Pen-nington	Total	Butte	Custer	Fall River	Law-rence	Meade	Pen-nington	Total
1981		972.9	0.0	0.0	121.1	0.0	0.0	1,093.9	837.5	2.6	20.4	2,047.6	0.0	49.3	2,957.3	1,810.3	2.6	20.4	2,168.6	0.0	49.3	4,051.2
1982		473.6	.0	.0	72.9	.0	.0	546.5	749.0	.0	50.9	782.1	2.9	20.0	1,604.9	1,222.6	.0	50.9	855.0	2.9	20.0	2,151.4
1983		543.0	.0	.0	.0	.0	.0	543.0	832.7	.5	65.1	3,508.2	.0	48.8	4,455.3	1,375.7	.5	65.1	3,508.2	.0	48.8	4,998.3
1984		626.0	.0	.0	.0	.0	.0	626.0	956.0	111.0	76.0	2,575.1	63.0	.0	3,781.1	1,582.0	111.0	76.0	2,575.1	63.0	.0	4,407.1
1985		859.6	.0	.0	.0	.0	.0	859.6	1,152.0	17.7	86.7	2,840.2	66.0	.0	4,162.6	2,011.6	17.7	86.7	2,840.2	66.0	.0	5,022.2
1986		300.6	.0	.0	.0	.0	.0	300.6	490.0	21.0	32.0	2,117.8	59.0	.3	2,720.1	790.6	21.0	32.0	2,117.8	59.0	.3	3,020.6
1987		272.9	.0	31.0	119.0	.0	.0	422.9	1,006.0	20.1	20.6	1,825.0	67.0	7.1	2,945.8	1,278.9	20.1	51.6	1,944.0	67.0	7.1	3,368.7
1988		860.9	.0	.0	182.4	.0	.0	1,043.3	1,204.7	17.8	43.4	2,591.1	48.8	12.7	3,918.5	2,065.6	17.8	43.4	2,773.5	48.8	12.7	4,961.8
1989		858.4	.0	.0	152.0	.0	.0	1,010.4	1,021.0	13.0	47.8	1,850.9	39.5	13.3	2,985.5	1,879.4	13.0	47.8	2,002.9	39.5	13.3	3,995.9
1990		809.0	.0	.0	193.0	10.0	.0	1,012.0	711.0	11.3	21.8	2,497.0	44.6	5.1	3,290.8	1,520.0	11.3	21.8	2,690.0	54.6	5.1	4,302.8
1991		602.8	.0	.0	92.0	8.2	1.3	704.3	487.2	4.4	37.1	2,076.7	41.2	5.6	2,652.2	1,090.0	4.4	37.1	2,168.7	49.4	6.9	3,356.5
1992		699.5	.0	.0	149.6	7.3	1.0	857.4	451.6	3.1	39.4	2,459.3	43.2	5.8	3,002.3	1,151.1	3.1	39.4	2,608.9	50.5	6.8	3,859.7
1993		356.0	.0	.0	52.9	4.2	.7	413.8	355.0	1.2	38.9	589.5	18.0	1.0	1,003.6	711.0	1.2	38.9	642.4	22.2	1.7	1,417.4
1994		77.9	.0	.0	112.7	6.5	332.5	529.5	820.4	9.3	87.0	2,018.7	2.0	12.9	2,950.3	898.3	9.3	87.0	2,131.4	8.5	345.4	3,479.8
1995		565.8	.0	.0	83.7	58.7	105.1	813.3	392.1	3.1	133.0	578.8	14.1	5.7	1,126.9	957.9	3.1	133.0	662.5	72.9	110.8	1,940.2
1996		275.2	.0	.0	70.9	47.1	134.6	527.7	389.7	21.3	69.7	1,138.5	33.9	51.2	1,704.3	664.9	21.3	69.7	1,209.3	81.0	185.8	2,232.0
1997		498.7	.0	11.0	56.6	25.1	240.5	831.8	433.5	5.8	71.3	1,455.3	10.7	11.0	1,987.6	932.3	5.8	82.3	1,511.9	35.8	251.5	2,819.5
1998		337.7	.0	.0	81.9	144.2	377.2	941.0	1,022.4	107.4	61.4	1,614.3	45.1	16.2	2,866.8	1,360.1	107.4	61.4	1,696.2	189.3	393.4	3,807.8
Mean 1987-96	Acre-ft	537.8	.0	3.1	120.8	14.2	57.5	733.5	683.9	10.5	53.9	1,762.5	35.2	12.0	2,558.0	1,221.7	10.5	57.0	1,883.4	49.4	69.6	3,291.5
	1,000 gal/d	480.2	.0	2.8	107.9	12.7	51.3	654.9	610.5	9.3	48.1	1,573.5	31.4	10.7	2,283.5	1,090.7	9.3	50.9	1,681.4	44.1	62.1	2,938.4
Mean 1981-98	Acre-ft	555.0		2.3	85.6	17.3	66.3	726.5	739.5	20.6	55.7	1,920.3	33.3	14.8	2,784.2	1,294.6	20.6	58.0	2,005.9	50.6	81.0	3,510.7
	1,000 gal/d	495.5		2.1	76.4	15.4	59.2	648.6	660.2	18.4	49.7	1,714.4	29.7	13.2	2,485.6	1,155.7	18.4	51.8	1,790.8	45.1	72.4	3,134.1

Livestock water use includes water used in the production of meat, poultry, eggs, milk, and wool. Like the self-supply domestic use, total ground-water withdrawals for livestock watering are available for 1995 by county, but not by aquifer. To estimate the percent of total ground-water withdrawals from the Madison and Minnelusa aquifers, data on livestock wells in the six-county area were compiled from the GWSI database. The percentages of wells completed in the Madison and Minnelusa aquifers were applied to the total ground-water withdrawals to apportion livestock use (table 10). The estimated total withdrawal from the Madison and Minnelusa aquifers for livestock-watering purposes is 181,600 gal/d (0.28 ft^3/s).

Estimates for industrial, mining, and thermoelectric uses were determined using withdrawal data from the Madison and Minnelusa aquifers compiled from the SWUDS database for 1995. Industrial water use represents water used to manufacture products; mining water use represents water withdrawn for the extraction of minerals; and thermoelectric water use represents water used in the production of electric power generated with fossil-fuel, geothermal, or nuclear energy (Amundson, 1998). The estimated total withdrawal from the Madison and Minnelusa aquifers is 976,000 gal/d (1.51 ft^3/s) for industrial use, 1,283,000 gal/d (1.99 ft^3/s) for mining use, and 440,000 gal/d (0.68 ft^3/s) for thermoelectric use.

The category of unaccountable withdrawals includes all flowing wells discharging water continuously from the Madison and Minnelusa aquifers (wild wells) and other withdrawals that are not accounted for by other use categories. The unaccountable withdrawals, 5,010,000 gal/d (7.75 ft^3/s), are estimated as being 25 percent of the subtotal of all other water use categories, with the exception of the withdrawal from the Madison aquifer in Butte County, which was estimated as 2,000,000 gal/d based on known wild wells completed in the Madison aquifer (Jim Goodman, South Dakota Department of Environment and Natural Resources, oral commun., 2000).

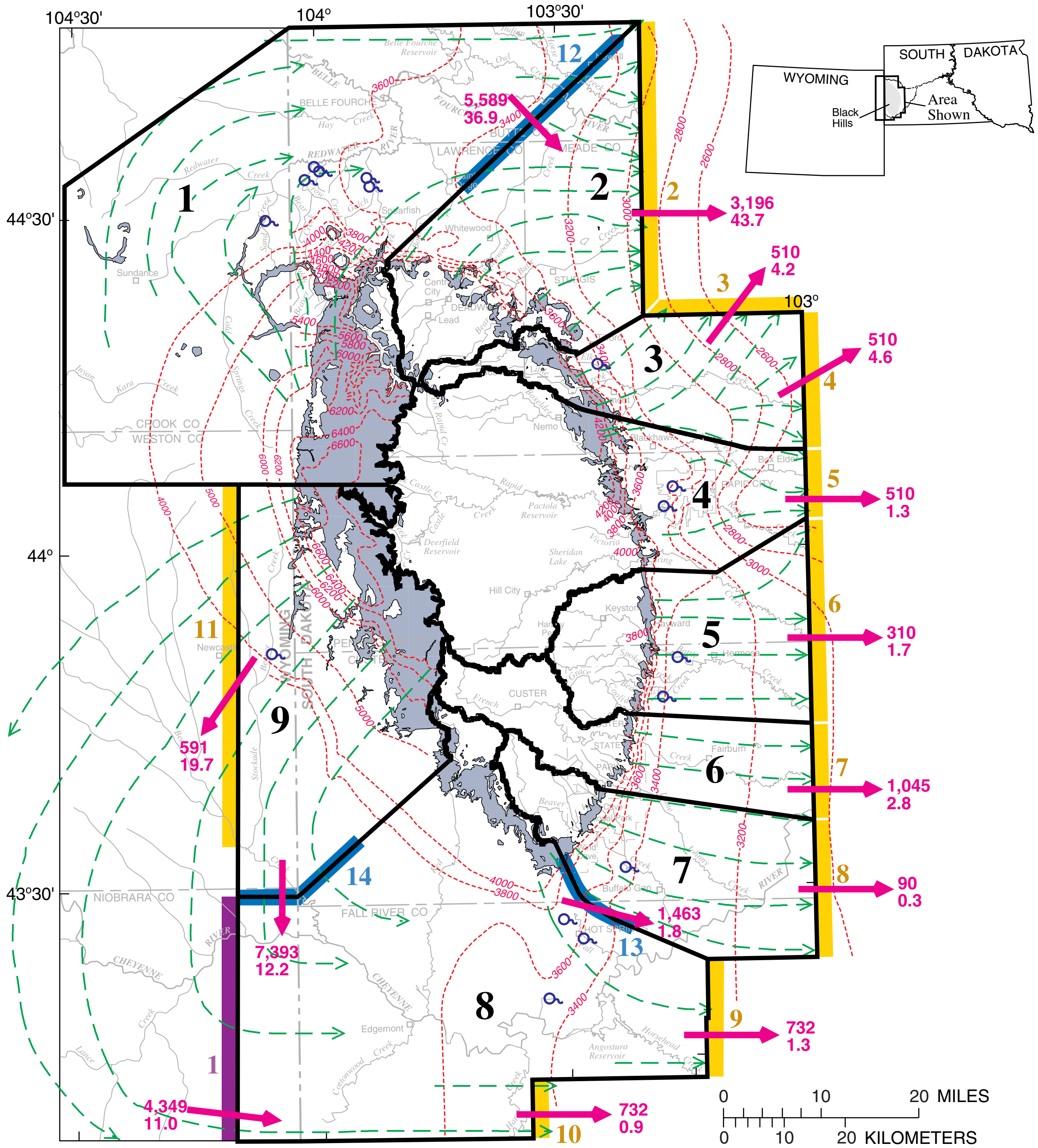
Subarea Budgets

Within this section, individual budgets are quantified for nine subareas within the overall study area. Preliminary budgets quantifying only combined, net ground-water inflows or outflows for the Madison and Minnelusa aquifers are developed first for each subarea. Detailed budgets also are developed, which include estimates of flow components and transmissivity for the individual aquifers at specific flow zones. An evaluation of budget components also is provided.

Preliminary Budgets

Separate budgets are developed for nine subareas within the study area (figs. 15 and 16). The subarea budgets are developed as combined budgets for the Madison and Minnelusa aquifers, using common subareas for both aquifers. Subareas were identified on the basis of hypothetical flowpaths that were constructed roughly orthogonal to mapped hydraulic heads in the Madison and Minnelusa aquifers. For unconfined settings near outcrop areas, flowpaths probably are heavily influenced by bedding dips, which generally are radially away from the central part of the uplift. For confined settings, anisotropic and heterogeneous hydraulic properties can result in flowpaths that are strongly nonorthogonal to hydraulic heads (Long, 2000). Regional ground-water flow from the west also may influence potentiometric surfaces in the northern and southwestern parts of the study area.

Subarea boundaries were selected with the intent of minimizing apparent flow across the boundaries (referred to as interior subarea flow zones in figs. 15 and 16); however, in a number of cases, zero-flow boundaries that respect mapped hydraulic heads could not be established for both aquifers. Various other factors such as locations of major artesian springs, streamflow loss zones, and areas dominated by precipitation recharge also were considered in selecting subarea boundaries. These factors are useful in evaluating various budget components. For example, subarea 6, which has no artesian springflow, is located between subareas 5 and 7, both of which have large artesian springs.

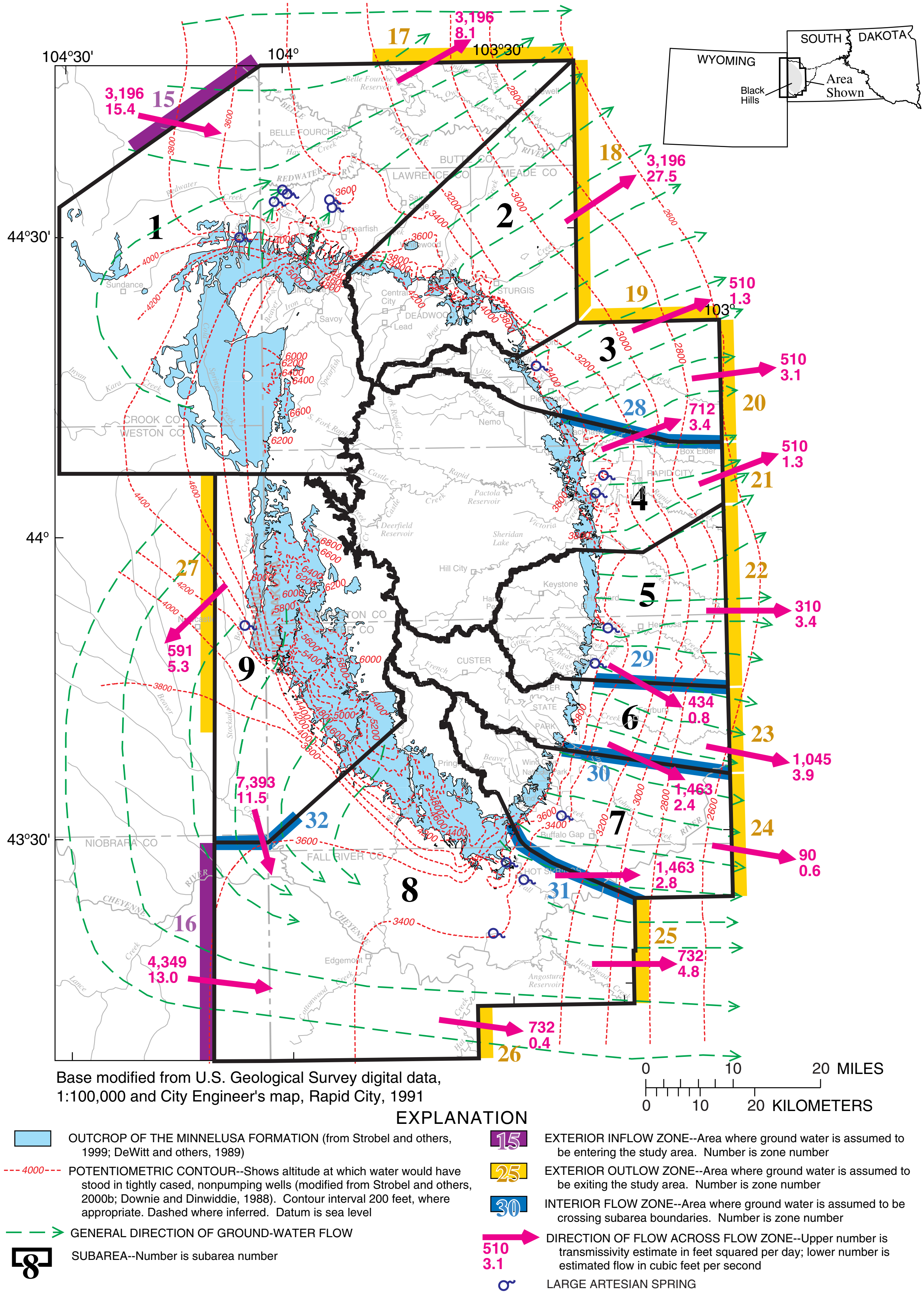


Base modified from U.S. Geological Survey digital data,
1:100,000 and City Engineer's map, Rapid City, 1991

EXPLANATION

▨	OUTCROP OF MADISON LIMESTONE AND ENGLEWOOD FORMATION (from Strobel and others, 1999; DeWitt and others, 1989)
---4000---	POTENTIOMETRIC CONTOUR--Shows altitude at which water would have stood in tightly cased, nonpumping wells (modified from Strobel and others, 2000a; Greene and Rahn, 1995). Contour interval 200 feet. Dashed where inferred. Datum is sea level
— — >	GENERAL DIRECTION OF GROUND-WATER FLOW
8	SUBAREA--Number is subarea number
1	EXTERIOR INFLOW ZONE--Area where ground water is assumed to be entering the study area. Number is zone number
10	EXTERIOR OUTLOW ZONE--Area where ground water is assumed to be exiting the study area. Number is zone number
12	INTERIOR SUBAREA FLOW ZONE--Area where ground water is assumed to be crossing subarea boundaries. Number is zone number
→ 732 1.3	DIRECTION OF FLOW ACROSS FLOW ZONE--Upper number is transmissivity estimate in feet squared per day; lower number is estimated flow in cubic feet per second
♂	LARGE ARTESIAN SPRING

Figure 15. Subareas, generalized ground-water flow directions, and flow zones for the Madison aquifer. Estimated transmissivities and flow components for flow zones also are shown.



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

Figure 16. Subareas, generalized ground-water flow directions, and flow zones for the Minnelusa aquifer. Estimated transmissivities and flow components for flow zones also are shown.

Subarea budgets are developed for 1987-92 (decreasing storage) and 1993-96 (increasing storage). Change in storage is assumed to be equal in magnitude but opposite for the two periods. Consideration of these two different time periods and numerous subareas provides various opportunities to evaluate ground-water flow components.

Precipitation recharge estimates for each subarea were distributed using the yield efficiency algorithm and excluded areas east of the ground-water divide in the Limestone Plateau area (fig. 10), which would contribute to headwater springflow. With this exception, the sum of budget components for the subareas is equal to the components for the overall budget. Other budget components are distributed by the following methods: (1) percent of each subarea relative to ungaged drainage basins for streamflow recharge presented in Carter and others (2001); (2) percent of each subarea relative to counties for all water-use categories except municipal; and (3) discrete locations within subareas for streamflow recharge estimates for gaged streams, artesian springflow, and municipal water use.

Subarea budgets are presented in table 12. Net ground-water flow (either net inflow or net outflow in equation 2) for each subarea is calculated using an iterative process until the volumetric change in storage for the period 1987-92 is approximately equal, but opposite to the change in storage for the period 1993-96. Results also are presented in figures 15 and 16, which collectively show balances that are identical to table 12, but also include estimated flow components for the individual aquifers at specific flow zones, as described in a subsequent section. Using subarea 1 as an example, inflows are identified only for the Minnelusa aquifer (15.4 ft^3/s); however, outflows are identified for both the Madison (36.9 ft^3/s) and Minnelusa (8.1 ft^3/s) aquifers, which results in a combined net outflow of 29.6 ft^3/s (table 12).

For most subareas, net ground-water outflow exceeds inflow. Net ground-water outflow for these subareas ranges from 5.9 ft^3/s in subarea 4 to 48.6 ft^3/s in subarea 9. The large net ground-water outflow component in subarea 9 results from large precipitation recharge (table 12) on the expansive outcrops of Madison Limestone and Minnelusa Formation in this area.

Net ground-water inflow exceeds ground-water outflow for subareas 7 and 8 because discharge of large artesian springs exceeds estimated recharge within these subareas. Outflows from subarea 8 probably contribute to subarea 7, and outflows from subarea 9 probably contribute to subarea 8 (figs. 15 and 16).

Detailed Budgets

Within this section, detailed subarea budgets are developed, which include estimates of flow components for the individual aquifers at specific flow zones. Estimates of transmissivity also are derived using the preliminary subarea budgets, which are required for development of the detailed subarea budgets, as described in the following sections.

General Methods and Considerations for Estimating Transmissivity

The net ground-water outflows and inflows determined using the subarea budgets are used to estimate transmissivity and flow across subarea boundaries at various locations based on Darcy's Law:

$$Q = KiA \tag{1}$$

where:

Q = flow, in cubic feet per day;
K = hydraulic conductivity, in feet per day;
i = hydraulic gradient; and
A = cross-sectional area, in square feet.

Flow through any vertical section of an aquifer can be expressed using transmissivity, as follows:

$$Q = TiL \tag{2}$$

where:

Q = flow, in cubic feet per day;
T = transmissivity, in feet squared per day;
i = hydraulic gradient; and
L = length of boundary, in feet.

Table 12. Hydrologic budgets, by subareas, for the Madison and Minnelusa aquifers in the Black Hills area, water years 1987-96

[ft^3/s, cubic feet per second; acre-ft, acre-feet]

	Inflows (ft^3/s)			Outflows (ft^3/s)			Sum (ft^3/s)		Change in storage	
Water year	**Streamflow recharge**	**Precipitation recharge**	**Net ground-water inflow**	**Artesian springflow**	**Wells**	**Net ground-water outflow**	**Inflows**	**Outflows**	**ft^3/s**	**acre-ft**
					Subarea 1					
1987	8.6	64.8	0.0	101.8	11.0	29.6	73.4	142.4	-69.0	-49,961
1988	5.9	53.9	.0	94.8	12.6	29.6	59.8	137.0	-77.2	-55,898
1989	6.1	65.5	.0	75.5	11.7	29.6	71.6	116.8	-45.2	-32,728
1990	7.5	83.9	.0	78.8	12.2	29.6	91.4	120.6	-29.2	-21,143
1991	8.5	122.7	.0	81.4	10.9	29.6	131.2	121.9	9.3	6,734
1992	6.6	86.5	.0	76.0	11.3	29.6	93.1	116.9	-23.8	-17,233
Average/sum[1] 1987-92	7.2	79.6	.0	84.7	11.6	29.6	86.8	125.9	-39.2	[1]-170,228
1993	9.8	170.2	.0	80.6	9.1	29.6	180.0	119.3	60.7	43,951
1994	11.3	100.7	.0	93.6	10.6	29.6	112.0	133.8	-21.8	-15,785
1995	15.9	260.0	.0	103.9	9.4	29.6	275.9	142.9	133.0	96,301
1996	16.1	202.9	.0	116.7	9.6	29.6	219.0	155.9	63.1	45,689
Average/sum[1] 1993-96	13.3	183.5	.0	98.7	9.7	29.6	196.7	138.0	58.8	[1]170,156
Average/sum[1] 1987-96	9.6	121.1	.0	90.3	10.8	29.6	130.7	130.8	.0	[1]-72
					Subarea 2					
1987	27.5	6.1	.0	.0	3.7	34.2	33.6	37.9	-4.3	-3,113
1988	5.8	5.9	.0	.0	4.2	34.2	11.7	38.4	-26.7	-19,333
1989	9.2	6.2	.0	.0	3.8	34.2	15.4	38.0	-22.6	-16,364
1990	15.5	5.8	.0	.0	4.1	34.2	21.3	38.3	-17.0	-12,309
1991	23.8	8.9	.0	.0	3.7	34.2	32.7	37.9	-5.2	-3,765
1992	12.3	5.7	.0	.0	3.8	34.2	18.0	38.0	-20.0	-14,481
Average/sum[1] 1987-92	15.7	6.4	.0	.0	3.9	34.2	22.1	38.1	-16.0	[1]-69,366
1993	32.9	16.0	.0	.0	3.1	34.2	48.9	37.3	11.6	8,399
1994	35.4	5.9	.0	.0	3.6	34.2	41.3	37.8	3.5	2,534
1995	58.5	31.7	.0	.0	3.2	34.2	90.2	37.4	52.8	38,231
1996	49.7	16.0	.0	.0	3.3	34.2	65.7	37.5	28.2	20,419
Average/sum[1] 1993-96	44.1	17.4	.0	.0	3.3	34.2	61.5	37.5	24.0	[1]69,583
Average/sum[1] 1987-96	27.1	10.8	.0	.0	3.7	34.2	37.9	37.9	.0	[1]217

Table 12. Hydrologic budgets, by subareas, for the Madison and Minnelusa aquifers in the Black Hills area, water years 1987-96–Continued

[ft^3/s, cubic feet per second; acre-ft, acre-feet]

Water year	Inflows (ft^3/s)			Outflows (ft^3/s)			Sum (ft^3/s)		Change in storage	
	Stream-flow recharge	Precipita-tion recharge	Net ground-water inflow	Artesian spring-flow	Wells	Net ground-water outflow	Inflows	Outflows	ft^3/s	acre-ft
					Subarea 3					
1987	10.6	1.6	0.0	1.6	0.6	9.8	12.2	12.0	0.2	145
1988	2.5	1.3	.0	.3	.6	9.8	3.8	10.7	-6.9	-4,996
1989	2.7	2.1	.0	.0	.6	9.8	4.8	10.4	-5.6	-4,055
1990	8.6	2.1	.0	.0	.6	9.8	10.7	10.4	.3	217
1991	9.1	4.6	.0	.1	.6	9.8	13.7	10.5	3.2	2,317
1992	5.6	1.8	.0	.0	.6	9.8	7.4	10.4	-3.0	-2,172
Average/sum[1] 1987-92	6.5	2.3	.0	.3	.6	9.8	8.8	10.7	-2.0	[1]-8,544
1993	10.0	5.3	.0	.1	.6	9.8	15.3	10.5	4.8	3,476
1994	10.9	1.7	.0	.4	.6	9.8	12.6	10.8	1.8	1,303
1995	12.0	10.3	.0	8.6	.6	9.8	22.3	19.0	3.3	2,389
1996	13.9	6.3	.0	8.2	.6	9.8	20.2	18.6	1.6	1,159
Average/sum[1] 1993-96	11.7	5.9	.0	4.3	.6	9.8	17.6	14.7	2.9	[1]8,327
Average/sum[1] 1987-96	8.6	3.7	.0	1.9	.6	9.8	12.3	12.3	.0	[1]-217
					Subarea 4					
1987	33.3	2.7	.0	25.6	4.3	5.9	36.0	35.8	.2	145
1988	17.3	1.0	.0	25.6	4.2	5.9	18.3	35.7	-17.4	-12,599
1989	15.6	3.9	.0	25.6	3.4	5.9	19.5	34.9	-15.4	-11,151
1990	24.1	3.7	.0	25.6	5.0	5.9	27.8	36.5	-8.7	-6,299
1991	33.7	10.3	.0	25.6	6.7	5.9	44.0	38.2	5.8	4,200
1992	25.9	3.2	.0	25.6	10.5	5.9	29.1	42.0	-12.9	-9,340
Average/sum[1] 1987-92	25.0	4.1	.0	25.6	5.7	5.9	29.1	37.2	-8.1	[1]-35,045
1993	43.3	8.4	.0	25.8	10.2	5.9	51.7	41.9	9.8	7,096
1994	40.3	1.4	.0	25.6	11.1	5.9	41.7	42.6	-0.9	-652
1995	47.5	12.3	.0	27.1	9.1	5.9	59.8	42.1	17.7	12,816
1996	55.8	9.6	.0	30.1	7.6	5.9	65.4	43.6	21.8	15,785
Average/sum[1] 1993-96	46.7	7.9	.0	27.2	9.5	5.9	54.7	42.6	12.1	[1]35,045
Average/sum[1] 1987-96	33.7	5.7	.0	26.2	7.2	5.9	39.3	39.3	.0	[1]0

Table 12. Hydrologic budgets, by subareas, for the Madison and Minnelusa aquifers in the Black Hills area, water years 1987-96–Continued

[ft^3/s, cubic feet per second; acre-ft, acre-feet]

Water year	Inflows (ft^3/s)			Outflows (ft^3/s)			Sum (ft^3/s)		Change in storage	
	Streamflow recharge	Precipitation recharge	Net ground-water inflow	Artesian springflow	Wells	Net ground-water outflow	Inflows	Outflows	ft^3/s	acre-ft
Subarea 5										
1987	12.8	1.3	0.0	6.2	1.6	6.0	14.1	13.8	0.3	217
1988	2.4	.6	.0	2.4	1.6	6.0	3.0	10.0	-7.0	-5,068
1989	3.1	2.2	.0	1.2	1.6	6.0	5.3	8.8	-3.5	-2,534
1990	10.6	3.6	.0	1.6	1.6	6.0	14.2	9.2	5.0	3,620
1991	12.9	4.5	.0	3.5	1.6	6.0	17.4	11.1	6.3	4,562
1992	7.9	2.0	.0	4.5	1.6	6.0	9.9	12.1	-2.2	-1,593
Average/sum[1] 1987-92	8.3	2.4	.0	3.2	1.6	6.0	10.7	10.8	-0.2	[1]-796
1993	17.3	4.9	.0	7.1	1.6	6.0	22.2	14.7	7.5	5,430
1994	10.2	1.3	.0	10.8	1.7	6.0	11.5	18.5	-7.0	-5,068
1995	18.7	7.2	.0	11.3	1.6	6.0	25.9	18.9	7.0	5,068
1996	18.0	4.7	.0	21.0	1.7	6.0	22.7	28.7	-6.0	-4,344
Average/sum[1] 1993-96	16.1	4.5	.0	12.6	1.7	6.0	20.6	20.2	.4	[1]1,086
Average/sum[1] 1987-96	11.4	3.2	.0	7.0	1.6	6.0	14.6	14.6	.0	[1]290
Subarea 6										
1987	7.8	.3	.0	.0	.0	8.3	8.1	8.3	-0.2	-145
1988	2.7	.2	.0	.0	.0	8.3	2.9	8.3	-5.4	-3,910
1989	1.6	.6	.0	.0	.0	8.3	2.2	8.3	-6.1	-4,417
1990	5.1	.8	.0	.0	.0	8.3	5.9	8.3	-2.4	-1,738
1991	7.8	.9	.0	.0	.0	8.3	8.7	8.3	.4	290
1992	5.5	.7	.0	.0	.0	8.3	6.2	8.3	-2.1	-1,521
Average/sum[1] 1987-92	5.1	.6	.0	.0	.0	8.3	5.7	8.3	-2.6	[1]-11,440
1993	9.2	1.3	.0	.0	.0	8.3	10.5	8.3	2.2	1,593
1994	7.4	.3	.0	.0	.0	8.3	7.7	8.3	-0.6	-434
1995	13.0	2.5	.0	.0	.0	8.3	15.5	8.3	7.2	5,213
1996	13.9	1.5	.0	.0	.0	8.3	15.4	8.3	7.1	5,141
Average/sum[1] 1993-96	10.9	1.4	.0	.0	.0	8.3	12.3	8.3	4.0	[1]11,513
Average/sum[1] 1987-96	7.4	.9	.0	.0	.0	8.3	8.3	8.3	.0	[1]72

Table 12. Hydrologic budgets, by subareas, for the Madison and Minnelusa aquifers in the Black Hills area, water years 1987-96–Continued

[ft^3/s, cubic feet per second; acre-ft, acre-feet]

Water year	Inflows (ft^3/s)			Outflows (ft^3/s)			Sum (ft^3/s)		Change in storage	
	Stream-flow recharge	Precipita-tion recharge	Net ground-water inflow	Artesian spring-flow	Wells	Net ground-water outflow	Inflows	Outflows	ft^3/s	acre-ft
				Subarea 7						
1987	2.0	0.6	6.1	10.0	0.1	0.0	8.7	10.1	-1.4	-1,014
1988	.4	.4	6.1	10.0	.1	.0	6.9	10.1	-3.2	-2,317
1989	.4	.6	6.1	9.0	.1	.0	7.1	9.1	-2.0	-1,448
1990	1.0	.9	6.1	9.0	.1	.0	8.0	9.1	-1.1	-796
1991	1.6	1.1	6.1	8.1	.1	.0	8.8	8.2	.6	434
1992	1.0	1.2	6.1	8.0	.1	.0	8.3	8.1	.2	145
Average/sum[1] 1987-92	1.1	.8	6.1	9.0	.1	.0	8.0	9.1	-1.2	[1]-4,996
1993	2.2	2.1	6.1	9.1	.1	.0	10.4	9.2	1.2	869
1994	2.3	.6	6.1	9.5	.1	.0	9.0	9.6	-0.6	-434
1995	6.1	4.2	6.1	12.5	.1	.0	16.4	12.6	3.8	2,751
1996	6.1	1.2	6.1	11.1	.1	.0	13.4	11.2	2.2	1,593
Average/sum[1] 1993-96	4.2	2.0	6.1	10.6	.1	.0	12.3	10.7	1.7	[1]4,779
Average/sum[1] 1987-96	2.3	1.3	6.1	9.6	.1	.0	9.7	9.7	.0	[1]-217
				Subarea 8						
1987	5.9	3.2	35.6	45.4	1.8	.0	44.7	47.2	-2.5	-1,810
1988	1.5	2.2	35.6	44.1	1.8	.0	39.3	45.9	-6.6	-4,779
1989	1.6	3.8	35.6	43.1	1.8	.0	41.0	44.9	-3.9	-2,824
1990	3.9	5.4	35.6	44.1	1.9	.0	44.9	46.0	-1.1	-796
1991	5.5	5.7	35.6	43.1	1.8	.0	46.8	44.9	1.9	1,376
1992	1.6	5.2	35.6	42.9	1.8	.0	42.4	44.7	-2.3	-1,665
Average/sum[1] 1987-92	3.3	4.3	35.6	43.8	1.8	.0	43.2	45.6	-2.4	[1]-10,499
1993	4.1	10.8	35.6	42.1	1.8	.0	50.5	43.9	6.6	4,779
1994	2.4	2.3	35.6	44.0	1.9	.0	40.3	45.9	-5.6	-4,055
1995	11.9	14.6	35.6	46.3	1.9	.0	62.1	48.2	13.9	10,065
1996	6.0	7.5	35.6	47.5	1.8	.0	49.1	49.3	-0.2	-145
Average/sum[1] 1993-96	6.1	8.8	35.6	45.0	1.9	.0	50.5	46.8	3.7	[1]10,644
Average/sum[1] 1987-96	4.4	6.1	35.6	44.3	1.8	.0	46.1	46.1	.0	[1]145

Table 12. Hydrologic budgets, by subareas, for the Madison and Minnelusa aquifers in the Black Hills area, water years 1987-96–Continued

[ft^3/s, cubic feet per second; acre-ft, acre-feet]

Water year	Inflows (ft^3/s)			Outflows (ft^3/s)			Sum (ft^3/s)		Change in storage	
	Streamflow recharge	Precipitation recharge	Net ground-water inflow	Artesian springflow	Wells	Net ground-water outflow	Inflows	Outflows	ft^3/s	acre-ft
Subarea 9										
1987	0.0	24.6	0.0	9.0	2.2	48.6	24.6	59.8	-35.2	-25,487
1988	.0	20.7	.0	9.0	2.2	48.6	20.7	59.8	-39.1	-28,311
1989	.0	35.3	.0	9.0	2.2	48.6	35.3	59.8	-24.5	-17,740
1990	.0	46.1	.0	9.0	2.2	48.6	46.1	59.8	-13.7	-9,920
1991	.0	73.1	.0	8.8	2.2	48.6	73.1	59.6	13.5	9,775
1992	.0	44.6	.0	8.9	2.2	48.6	44.6	59.7	-15.1	-10,933
Average/sum[1] 1987-92	.0	40.7	.0	9.0	2.2	48.6	40.7	59.8	-19.0	[1]-82,616
1993	.0	98.2	.0	9.1	2.2	48.6	98.2	59.9	38.3	27,732
1994	.0	40.2	.0	9.7	2.3	48.6	40.2	60.6	-20.4	-14,771
1995	.0	106.4	.0	11.8	2.2	48.6	106.4	62.6	43.8	31,714
1996	.0	114.3	.0	11.3	2.3	48.6	114.3	62.2	52.1	37,724
Average/sum[1] 1993-96	.0	89.8	.0	10.5	2.3	48.6	89.8	61.3	28.5	[1]82,399
Average/sum[1] 1987-96	.0	60.4	.0	9.6	2.2	48.6	60.4	60.4	.0	[1]-217

[1] Sum used for change in storage in acre-feet.

Where flowpaths cross study area or subarea boundaries, flow zones were identified to represent ground-water flow areas along individual boundary segments for the Madison and Minnelusa aquifers (figs. 15 and 16). The flow zones consist of: (1) exterior inflow zones, where ground water is assumed to be entering the study area; (2) exterior outflow zones, where ground water is assumed to be exiting the study area; and (3) interior flow zones, where ground water is assumed to be crossing subarea boundaries. For the Madison aquifer, 14 flow zones are identified (fig. 15), and for the Minnelusa aquifer, 18 flow zones are identified (fig. 16).

For purposes of this report, an estimate of average transmissivity for individual flow zones can be obtained by rearranging equation 4 and using the hydraulic gradient perpendicular to the flow zone to yield the following equation:

$$T = \frac{Q}{i_p L} \qquad (3)$$

where:

T = transmissivity, in feet squared per day;
Q = flow, in cubic feet per day;
i_p = hydraulic gradient perpendicular to the boundary; and
L = length of flow zone, in feet.

For each flow zone, the average hydraulic gradient perpendicular to the flow zone was determined. Hydraulic gradients and the lengths of flow zones are presented in table 13.

Table 13. Flow-zone information used in estimating transmissivity

Flow zone number	Subarea number	Flow direction	Hydraulic gradient[1]	Length of flow zone (miles)
		Madison Aquifer		
1	8	Inflow	0.0017	15.2
2	2	Outflow	.0076	29.4
3	3	Outflow	.0089	15.2
4	3	Outflow	.0125	11.9
5	4	Outflow	.0051	8.1
6	5	Outflow	.0046	19.7
7	6	Outflow	.0046	9.6
8	7	Outflow	.0039	14.4
9	8	Outflow	.0025	12.0
10	8	Outflow	.0034	6.0
11	9	Outflow	.0147	37.1
12	1,2	Interior boundary[2]	.0047	22.8
13	7,8	Interior boundary[2]	.0019	10.4
14	8,9	Interior boundary[2]	.0017	15.9
		Minnelusa Aquifer		
15	1	Inflow	.0046	17.2
16	8	Inflow	.0020	24.9
17	1	Outflow	.0019	22.0
18	2	Outflow	.0048	29.4
19	3	Outflow	.0027	15.2
20	3	Outflow	.0083	11.9
21	4	Outflow	.0050	8.1
22	5	Outflow	.0092	19.7
23	6	Outflow	.0064	9.6
24	7	Outflow	.0072	14.4
25	8	Outflow	.0089	12.0
26	8	Outflow	.0016	6.0
27	9	Outflow	.0050	29.3
28	3,4	Interior boundary[2]	.0045	17.0
29	5,6	Interior boundary[2]	.0025	12.9
30	6,7	Interior boundary[2]	.0016	16.7
31	7,8	Interior boundary[2]	.0018	17.0
32	8,9	Interior boundary[2]	.0025	10.7

[1] Hydraulic gradient determined perpendicular to flow zones.

[2] Indicates flow across interior subarea boundary.

Equations 3 through 5 assume homogeneous and isotropic conditions in the aquifers, which generally is not the case for the Madison and Minnelusa aquifers. However, it is assumed that these conditions are averaged over the length of the flow zones, which approximates isotropic conditions resulting in an average transmissivity. For estimation purposes, it is assumed that the transmissivity of the Madison and Minnelusa aquifers are equal in any particular flow zone. It is assumed that hypothetical flowpaths are approximately perpendicular to the potentiometric-surface contours (figs. 15 and 16); however, ground-water flow can be nearly parallel to potentiometric-surface contours in some areas (Long, 2000), especially in the Madison aquifer due to heterogeneity and anisotropy.

Transmissivity of the Madison and Minnelusa aquifers in the Black Hills area varies greatly. Estimates of hydraulic conductivity and transmissivity are available from previous investigations (table 14). In the Madison aquifer, transmissivity estimates range from less than 1 to 56,000 ft^2/d, and in the Minnelusa aquifer, transmissivity estimates range from less than 1 to 12,000 ft^2/d. Some of the transmissivity estimates from previous investigations were for small areas near large-discharge wells and are not necessarily representative of average transmissivity over large areas. Although transmissivity values from previous investigations were not used in determining ground-water flow components, they provide a basis against which estimated transmissivities (using flows from subarea budgets) can be compared.

Because all subareas have multiple flow zones, transmissivity generally is calculated in equation 5 by dividing the net ground-water inflow or outflow given in table 12 for each respective subarea (Q) by the sum of the product of hydraulic gradient (i) times length (L), for the flow zones included in each particular calculation. This calculation yields equal values of transmissivity for all flow zones involved in a calculation, which is used as an initial assumption, when possible. Ground-water flow for individual flow zones is calculated using equation 5 to solve for Q using the estimated transmissivity for each flow zone. More specific methods and assumptions that have been applied in estimating transmissivity for the flow zones, by subarea, are presented in the following section.

Table 14. Estimates of hydraulic conductivity and transmissivity from previous investigations

[ft/d, feet per day; ft^2/d, feet squared per day; <, less than]

Source	Hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)	Area represented
		Madison Aquifer	
Konikow, 1976	--	860 - 2,200	Mont., N. Dak., S. Dak., Wyo.
Miller, 1976	--	0.01 - 5,400	Southeastern Mont.
Blankennagel and others, 1977	2.4×10^{-5} - 1.9	--	Crook County, Wyo.
Woodward-Clyde Consultants, 1980	--	3,000	Eastern Wyo., western S. Dak.
Blankennagel and others, 1981	--	5,090	Crook County, Wyo.
Downey, 1982	--	250 - 1,500	Mont., N. Dak., S. Dak., Wyo.
Back and others, 1983	2.93×10^{-5}	--	Eastern Wyo., western S. Dak.
Cooley and others, 1986	1.04	--	Mont., N. Dak., S. Dak., Wyo., Nebr.
Kyllonen and Peter, 1987	--	4.3 - 8,600	Northern Black Hills
Imam,1991	9.0×10^{-6}	--	Black Hills area
Greene, 1993	--	1,300 - 56,000	Rapid City area
Tan, 1994	5 -1,300	--	Rapid City area
Greene and others, 1999	--	2,900 - 41,700	Spearfish area
		Minnelusa Aquifer	
Blankennagel and others, 1977	$<2.4 \times 10^{-5}$ - 1.4	--	Crook County, Wyo.
Pakkong, 1979	--	880	Boulder Park area, S. Dak.
Woodward-Clyde Consultants, 1980	--	30 - 300	Eastern Wyo., western S. Dak.
Kyllonen and Peter, 1987	--	0.86 - 8,600	Northern Black Hills
Greene, 1993	--	12,000	Rapid City area
Tan, 1994	32	--	Rapid City area
Greene and others, 1999	--	267 - 9,600	Spearfish area

Budget Components and Transmissivity Estimates

Estimates of transmissivity and ground-water flow are obtained from equation 5 using the general methods previously described. The resulting estimates for individual flow zones are presented in table 15, and are shown in figure 15 for the Madison aquifer and in figure 16 for the Minnelusa aquifer. Although transmissivity estimates are calculated to the nearest integer so that calculations balance, the estimates should be considered valid only within an order of magnitude. Numerous limitations exist for subdividing flow in the Madison and Minnelusa aquifers due to: (1) numerous assumptions associated with transmissivity estimates; and (2) potential errors resulting from presumed flowpaths and hydraulic gradients. Thus, the overall budget estimate of 100 ft^3/s for net outflow is the most reliable estimate, and estimates of net outflows and inflows associated with individual subareas are more reliable than estimates of flow for individual flow zones.

Because of an interior boundary flow component from subarea 1 into subarea 2 for the Madison aquifer (interior flow zone 12, fig. 15), transmissivities for exterior flow zones 15 and 17 in subarea 1 and zones 2 and 18 in subarea 2 are calculated first, assuming equal transmissivities for these exterior flow zones. Summing net outflows of 29.6 ft^3/s in subarea 1 and 34.2 ft^3/s in subarea 2 (table 12) yields a combined outflow of 63.8 ft^3/s, which is independent of the calculated value for interior zone 12. Equation 5 is solved by dividing the combined outflow (63.8 ft^3/s) by the sum of the products i and L for the four flow zones, which results in equal transmissivity estimates of 3,196 ft^2/d (table 15). Substituting this transmissivity into equation 4 yields flow estimates for the four exterior flow zones. Balancing with net outflow for either subarea indicates an interior flow component of 36.9 ft^3/s from subarea 1 to subarea 2. Then transmissivity for interior flow zone 12 is calculated as 5,589 ft^2/d. The transmissivity of interior flow zone 12 is about 1.7 times higher than transmissivity for the exterior flow zones for subareas 1 and 2. This is consistent with a general hypothesis of decreasing basinward transmissivity (Hamade, 2000).

Table 15. Estimates of transmissivity and flow for flow zones

[ft^3/s, cubic feet per second; ft^2/d, feet squared per day]

Ground-water flow[1] total for subarea (ft^3/s)	Flow zone number	Flow direction	Aquifer	Hydraulic gradient	Length of flow zone (miles)	Transmissivity (ft^2/d)	Ground-water flow[2] for flow zone (ft^3/s)
			Subarea 1				
29.6	12	Interior boundary (out)	Madison	0.0047	22.8	5,589	36.9
29.6	15	Inflow	Minnelusa	.0046	17.2	3,196	-15.4
29.6	17	Outflow	Minnelusa	.0019	22.0	3,196	8.1
			Subarea 2				
34.2	12	Interior boundary (in)	Madison	.0047	22.8	5,589	-36.9
34.2	2	Outflow	Madison	.0076	29.4	3,196	43.7
34.2	18	Outflow	Minnelusa	.0048	29.4	3,196	27.5
			Subarea 3				
9.8	28	Interior boundary (in)	Minnelusa	.0045	17.0	712	-3.4
9.8	3	Outflow	Madison	.0089	15.2	510	4.2
9.8	4	Outflow	Madison	.0125	11.9	510	4.6
9.8	19	Outflow	Minnelusa	.0027	15.2	510	1.3
9.8	20	Outflow	Minnelusa	.0083	11.9	510	3.1
			Subarea 4				
5.9	28	Interior boundary (out)	Minnelusa	.0045	17.0	712	3.4
5.9	5	Outflow	Madison	.0051	8.1	510	1.3
5.9	21	Outflow	Minnelusa	.0050	8.1	510	1.3
			Subarea 5				
6.0	29	Interior boundary (out)	Minnelusa	.0025	12.9	434	0.8
6.0	6	Outflow	Madison	.0046	19.7	310	1.7
6.0	22	Outflow	Minnelusa	.0092	19.7	310	3.4
			Subarea 6				
8.3	29	Interior boundary (in)	Minnelusa	.0025	12.9	434	-0.8
8.3	30	Interior boundary (out)	Minnelusa	.00016	16.7	1,463	2.4
8.3	7	Outflow	Madison	.0046	9.6	1,045	2.8
8.3	23	Outflow	Minnelusa	.0064	9.6	1,045	3.9
			Subarea 7				
-6.1	30	Interior boundary (in)	Minnelusa	.0016	16.7	1,463	-2.4
-6.1	13	Interior boundary (in)	Madison	.0019	10.4	1,463	-1.8
-6.1	31	Interior boundary (in)	Minnelusa	.0018	17.0	1,463	-2.8
-6.1	8	Outflow	Madison	.0039	14.4	90	.3
-6.1	24	Outflow	Minnelusa	.0072	14.4	90	.6

Table 15. Estimates of transmissivity and flow for flow zones–Continued

[ft^3/s, cubic feet per second; ft^2/d, feet squared per day]

Ground-water flow[1] total for subarea (ft^3/s)	Flow zone number	Flow direction	Aquifer	Hydraulic gradient	Length of flow zone (miles)	Transmissivity (ft^2/d)	Ground-water flow[2] for flow zone (ft^3/s)
			Subarea 8				
-35.6	13	Interior boundary (out)	Madison	0.0019	10.4	1,463	1.8
-35.6	31	Interior boundary (out)	Minnelusa	.0018	17.0	1,463	2.8
-35.6	14	Interior boundary (in)	Madison	.0017	15.2	7,393	-12.2
-35.6	32	Interior boundary (in)	Minnelusa	.0025	10.0	7,393	-11.5
-35.6	1	Inflow	Madison	.0017	15.2	4,349	-11.0
-35.6	9	Outflow	Madison	.0025	12.0	732	1.3
-35.6	10	Outflow	Madison	.0034	6.0	732	.9
-35.6	16	Inflow	Minnelusa	.0020	24.9	4,349	-13.0
-35.6	25	Outflow	Minnelusa	.0089	12.0	732	4.8
-35.6	26	Outflow	Minnelusa	.0016	6.0	732	.4
			Subarea 9				
48.6	14	Interior boundary (out)	Madison	.0017	15.2	7,393	12.2
48.6	32	Interior boundary (out)	Minnelusa	.0025	10.0	7,393	11.5
48.6	11	Outflow	Madison	.0147	37.1	591	19.7
48.6	27	Outflow	Minnelusa	.0050	29.3	591	5.3

[1] A positive flow indicates net outflow, and a negative flow indicates net inflow.

[2] Flows may not sum exactly to flow total for zone due to independent rounding; a positive flow indicates outflow, and a negative flow indicates inflow.

Subareas 3 and 4 also share a common interior flow zone; thus, transmissivities are calculated using the same approach as subareas 1 and 2. Assuming equal transmissivity for exterior outflow zones 3, 4, 5, 19, 20, and 21 in subareas 3 and 4 yields values of 510 ft^2/d, which then can be used to solve for other flow components. Transmissivity for interior flow zone 28 is calculated as 712 ft^2/d, which is about 1.4 times higher than the estimated transmissivity for the exterior outflow zones.

In the Minnelusa aquifer, some flow from subarea 5 into subarea 6 is indicated by interior flow zone 29 in figure 16. A viable solution to equation 5 for subareas 5 and 6 does not exist using the same approach as used for subareas 1-4. Therefore, transmissivity for subarea 5 is solved by using only the net outflow of 6.0 ft^3/s (table 12) for that subarea. Transmissivities of exterior outflow zones 6 and 22 are assumed to be equal, while the transmissivity for interior flow zone 29 is assumed to be 1.4 times the transmissivity of the exterior outflow zones, which is the resulting factor in subareas 3 and 4. This yields transmissivity estimates of 310 ft^2/d for the two exterior outflow zones and 434 ft^2/d for the interior flow zone.

The previous calculation yielded a transmissivity estimate for interior flow zone 29. A similar approach to subarea 5 is used to calculate transmissivity for interior flow zone 30 and the exterior outflow zones 7 and 23. The transmissivity of interior flow zone 30 is assumed to be 1.4 times the transmissivity of exterior outflow zones 7 and 23, which is the resulting factor used in previous calculations. This yields transmissivity estimates of 1,463 ft^2/d for interior flow zone 30 and 1,045 ft^2/d for exterior outflow zones 7 and 23.

A similar approach is used in subarea 7, where the transmissivity estimate for interior flow zone 30 is known from a previous calculation. However, in this case, the transmissivities in interior flow zones 13 (Madison aquifer) and 31 (Minnelusa aquifer) are assumed to be equal to the transmissivity for interior flow zone 30. This assumption is made on the basis that the transmissivity must be sufficiently high along this interior boundary to supply flow from subarea 8 to large artesian springs in subarea 7. Transmissivities should be much higher for interior flow zones 13 and 31 than for the exterior outflow zones 8 and 24 due to: (1) decreasing saturated thickness in the Madison aquifer at distance from the outcrop as the thickness of the Madison Limestone approaches zero in this area (Rahn, 1986); and (2) major structural features that are present in the vicinity of interior flow zones 13 and 31 (fig. 4). Equation 5 is solved for exterior outflow zones 8 and 24 using the estimated transmissivity of 1,463 ft^2/d for all three interior flow zones. This yields a transmissivity estimate of 90 ft^2/d for exterior outflow zones 8 and 24.

In subarea 8, transmissivity calculations are complicated by the numerous flow zones. Transmissivities for interior flow zones 13 and 31 were estimated in previous calculations, but transmissivities have not been estimated for the remaining eight flow zones. First, it is assumed that the transmissivities for exterior outflow zones 9, 10, 25, and 26 are equal to each other, and are equal to one-half the transmissivity for interior flow zones 13 and 31 due to thinning of the Madison Limestone. This yields a transmissivity estimate of 732 ft^2/d for the exterior outflow zones. Next, it is assumed that the transmissivity for interior flow zones 14 and 32 in the southwestern part of the study area is equal to 1.7 times the transmissivity for exterior inflow zones 1 and 16, which is the resulting factor determined in subareas 1 and 2. Then, equation 5 is solved, which yields transmissivity estimates of 7,393 ft^2/d for interior flow zones 14 and 13 and 4,349 ft^3/d for exterior inflow zones 1 and 16. Although the transmissivity estimates for the flow zones in the southwestern part of the study area are within ranges determined by previous investigations (table 14), they are higher than for any other flow zones in the study area. This is consistent with very low hydraulic gradients in the vicinity of these flow zones, which generally indicates high transmissivity.

For subarea 9, transmissivities for interior flow zones 14 and 32 were determined by previous calculations. Equation 5 is solved for exterior outflow zones 11 and 27, which yields a transmissivity estimate of 591 ft^2/d. It is expected that the transmissivity for exterior outflow zones 11 and 27 would be much less than for flow zones further south in subarea 8 because neither the Madison nor Minnelusa aquifer is fully saturated along the entire length of the exterior outflow zones in subarea 9. In addition, exterior outflow zones 11 and 27 have a higher hydraulic gradient, especially in the Madison aquifer, than flow zones to the south, indicating lower transmissivity.

Evaluation of Budget Components

As discussed, development of subarea budgets allows evaluation of various budget components. Transmissivity estimates range from 90 ft^2/d to about 7,400 ft^2/d, which are similar to values reported by previous investigators (table 14). The highest transmissivity values are for areas in the northern and southwestern parts of the study area, and the lowest values are along the eastern study area boundary (figs. 15 and 16). It is emphasized that the transmissivity estimates are averages over larger areas than can be obtained using aquifer test data, and large spatial variability in actual transmissivities can be expected. The potential for large errors exists in estimates of transmissivity and flow components because calculations are based on net outflow estimates and assumptions of equal transmissivity.

Most of the transmissivity estimates are derived for flow zones located considerable distances from the outcrops. Transmissivities probably are higher nearer the outcrop areas due to structural deformation and dissolution activity. Extremely high transmissivity probably occurs in the immediate vicinity of artesian springs, where large, focused discharge occurs. Transmissivities probably decrease downgradient from large artesian springs due to reduced dissolution activity. Basinward decreases in transmissivity were hypothesized by Huntoon (1985) as a major factor in artesian spring development, which is consistent with transmissivity calculations for subareas 1, 2, 3, and 4 that resulted in lower estimates for the exterior flow zones than for interior flow zones. In other subareas, lower transmissivities were assumed in exterior flow zones than in interior flow zones.

Uncertainties associated with estimates of streamflow recharge probably are small, relative to uncertainties associated with estimates of precipitation recharge (Carter and others, 2001). Evaluation of subarea budgets provides confidence that the yield efficiency algorithm systematically provides realistic estimates for precipitation recharge. A good example for evaluating precipitation recharge is subarea 1, which has a large component of artesian springflow that averages about 90 ft^3/s for 1987-96 (table 12). Streamflow recharge, which averages 9.6 ft^3/s, is especially small for this subarea, which is dominated by precipitation recharge of about 121 ft^3/s. Net outflow of 29.6 ft^3/s is consistent with a conclusion by Naus and others (in press) from geochemical evidence that flow in this area is dominated by areal recharge, with minor or negligible influence from regional flowpaths from the west. The collective evidence provides confidence that the methods used for estimating precipitation recharge perform well for this area, which has the highest rates for precipitation recharge in the study area.

The large change in storage (table 12) for subarea 2 (about 69,000 acre-ft) results primarily from a large net outflow rate and a large differential in streamflow recharge rates between the dry and wet periods. The large storage change is consistent with large water-level fluctuations (figs. 1 and 8) for the Tilford wells (sites 4 and 5) and for another pair of observation wells (not shown) located northwest of Sturgis, where fluctuations of about 50 ft have occurred during 1987-96 (Driscoll, Bradford, and Moran, 2000).

In comparison, changes in storage are much smaller for subareas 3 and 5, both of which have much smaller differentials in both streamflow and precipitation recharge rates. Both of these subareas are influenced by artesian springs with highly variable discharge rates, relative to most other artesian springs (table 12). Water-level data for subarea 5 are sparse; however, the Piedmont wells in subarea 3 (sites 6 and 7) show relatively small water-level fluctuations (figs. 1 and 8).

Budgets for subareas in the southern Black Hills are consistent with geochemical interpretations (Naus and others, in press), which indicated long flowpaths along the western and southwestern flanks contributing to large artesian springs in the area. The average discharge of Beaver Creek Spring (tables 5 and 12) exceeds estimated recharge in subarea 7 and probably is influenced by outflow from subarea 8, which is consistent with the geochemical information. Similarly, discharges of artesian springs in subarea 8 are much larger than recharge in this subarea. Outflow from subarea 9 is a probable source for inflow to subarea 8, which again is substantiated by geochemical information (Naus and others, in press).

Consideration of combined budgets for subareas 7, 8, and 9 provides useful insights. Combined streamflow and precipitation recharge of 74.5 ft^3/s exceeds discharge of springs and wells (67.6 ft^3/s) for these subareas, indicating net ground-water outflow of 6.9 ft^3/s. This combined budget is again consistent with a geochemical interpretation by Naus and others (in press) that the large springs in this area are recharged primarily within the uplift area, and the influence of regional flow from the west probably is minor or negligible.

Although regional flow from the west probably does not contribute substantially to ground-water flow in the southern part of the study area, the complex potentiometric surfaces and ground-water flowpaths in this area may be affected by regional influences such as flowpaths and pinching out of the Madison Limestone to the southeast. Because of sparsity of data points (Strobel and others, 2000), large uncertainties exist for the potentiometric-surface maps, which affects both postulated flowpaths and gradients used for calculation of transmissivity and subdivided flow for the Madison and Minnelusa aquifers.

The aforementioned factors probably contribute to possible inconsistencies in estimated flow components and associated transmissivity values along the southwestern boundary of the study area, where estimates should be used with caution. The assumption of orthogonal flowpaths necessitates westerly flow components out of subarea 9 and back into subarea 8, which may not be entirely realistic. The small transmissivity estimates for exterior outflow zones 11 and 27 result from steep hydraulic gradients and may be heavily influenced by unconfined conditions. Conversely, the hydraulic gradients are very low for flow zones 1, 14, 16, and 32, which results in large transmissivity estimates for these zones. Despite uncertainties in accurate mapping of hydraulic heads, there is certainty that hydraulic gradients are very low in the southwest corner of the study area and that large flow components out of subarea 9 exist. Thus, high transmissivities must occur somewhere in the vicinity of subarea 9 to allow large flow components with low hydraulic gradients.

SUMMARY AND CONCLUSIONS

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

The basic continuity equation (Sum of inflows - Sum of outflows = Change in storage) is used to develop hydrologic budgets for two scenarios, including an overall budget for the entire study area and more detailed budgets for subareas. The overall budget is a combined budget for the Madison and Minnelusa aquifers because most budget components cannot be quantified individually for the aquifers. This average budget is computed for water years 1987-96, for which change in storage is approximately equal to zero, based on well hydrographs and recharge estimates. Estimates of well withdrawals are presented by aquifer, and for some budget components additional information for other time periods also is presented. 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 detailed budgets also are combined budgets; however, estimates of ground-water flow for each aquifer are derived.

Inflows considered 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 (headwater and artesian), well withdrawals, leakage to adjacent aquifers, and ground-water outflow across the study area boundary.

Leakage to and from adjacent aquifers, which is difficult to quantify and cannot be distinguished from ground-water inflows or outflows, is included with these components. Similarly, ground-water inflows and outflows are difficult to quantify individually; thus, for cases when change in storage is assumed equal to zero, net ground-water flow (outflow minus inflow) can be calculated, given 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. Thus, artesian springflow is the single largest outflow component. Total springflow (including headwater and artesian springflow) averages 267 ft^3/s, which constitutes about 68 percent of estimated recharge.

Estimates of recharge to the Madison and Minnelusa aquifers used in the hydrologic budgets are from a previous investigation. During 1987-96, recharge ranged from about 141 to 847 ft^3/s and averaged about 395 ft^3/s. Of this amount, about 104 ft^3/s (26 percent) was contributed by streamflow recharge and 291 ft^3/s (74 percent) was from infiltration of precipitation on outcrop areas.

Headwater springflow is considered to be that which occurs upstream from streamflow loss zones, primarily within the Limestone Plateau area, which is an important recharge area for the Madison and Minnelusa aquifers on the western flanks of the Black Hills. A ground-water divide has been identified in the Limestone Plateau area, with recharge to the east of the divide assumed to discharge to headwater springs along the eastern fringe of the plateau. Incongruences between contributing surface- and ground-water areas also are identified for various drainage basins in this area. Estimates of headwater springflow are derived from estimates of precipitation recharge for contributing ground-water areas east of the divide. Precipitation recharge is estimated using a "yield efficiency algorithm" developed by previous investigators that compares spatial distributions for annual precipitation, average annual precipitation, and average efficiency of basin yield, which is used as a surrogate for efficiency of precipitation recharge. Average headwater springflow for 1987-96 is estimated as 78 ft^3/s, based on estimates of annual recharge that ranged from about 16 to 215 ft^3/s. Variability in annual springflow is much smaller because of attenuation associated with ground-water storage.

Artesian springflow is considered to be that which originates from confined aquifers in locations downgradient from streamflow loss zones. Estimates of artesian springflow for 1987-96 ranged from about 163 to 246 ft^3/s and averaged 189 ft^3/s.

Well withdrawals serve many categories of water use including municipal, self supply (domestic), irrigation, livestock, industrial, mining, thermoelectric power, and unaccountable withdrawals. Total well withdrawals from the Madison and Minnelusa aquifers are about 18.3 million gallons per day (28 ft^3/s), with about 60 percent of overall withdrawals from the Madison aquifer. Municipal use, with combined withdrawals of about 6.5 million gallons per day, is the largest use category.

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 are distributed over the subareas, excluding headwater springflow and recharge for areas contributing to headwater springflow. An estimate of net ground-water flow for the two aquifers is computed for each subarea using an iterative process until the volumetric change in storage for the two periods are approximately equal, but opposite. For most subareas, net ground-water outflow exceeds inflow, and ranges 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 ground-water 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 and flow across exterior flow zones corresponding with parts of the study area boundary and interior flow zones between subareas based on Darcy's Law. For estimation purposes, it is assumed that transmissivities of the Madison and Minnelusa aquifers are equal in corresponding flow zones. Equal transmissivities also are assumed, when possible, for exterior flow zones within an individual subarea. Calculated transmissivities for several interior flow zones are larger than for nearby exterior flow zones, which is consistent with general basinward decreases in transmissivity.

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. Because the transmissivity estimates are averages over large areas, much larger spatial variability in actual transmissivities can be expected.

Evaluation of subarea budgets provides confidence in budget components developed for the overall budget. 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.

The overall results are particularly beneficial in corroborating a systematic method for estimation of precipitation recharge developed by previous investigators. Uncertainties associated with estimates of precipitation recharge are inherently larger than for streamflow recharge, which, in many cases, can be based on discrete measurements. Although uncertainties cannot be specifically evaluated, the hydrologic budgets do provide confidence that realistic estimates for precipitation recharge are obtained for a wide variety of recharge conditions.

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