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Estimated Recharge to the Madison and Minnelusa Aquifers in the Black Hills Area, South Dakota and Wyoming, Water Years 1931-98

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Metric	
acre	4,047	square meter
acre	0.4047	hectare
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
gallon per minute (gal/min)	0.06309	liter per second
inch	2.54	centimeter
inch	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer
	Other	
cubic foot per second (ft^3/s)	1.9835	acre-foot per day

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

$$°C = (°F - 32) / 1.8$$

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

Water year: Water year is the 12-month period, October 1 through September 30, and is designated by the calendar year in which it ends. Thus, the water year ending September 30, 1998, is called the "1998 water year."

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ABSTRACT

The Madison and Minnelusa aquifers are two of the most important aquifers in the Black Hills area. Long-term estimates of recharge to the Madison and Minnelusa aquifers are important for managing the water resources in the Black Hills area. Thus, annual recharge from streamflow losses and infiltration of precipitation on outcrop areas is estimated for water years 1931-98. All estimates are for recharge that contributes to regional ground-water flow patterns and that occurs in outcrop areas connected to the regional flow system. Estimates exclude recharge to outcrop areas that are isolated from the regional flow system, which generally results in ground-water discharge to area streams.

Streamflow recharge is calculated directly for 11 streams in the Black Hills area that have continuous-record gaging stations located upstream from loss zones, using available records of daily streamflow, against which estimated loss thresholds (from previous investigations) are applied. Daily streamflow records are extrapolated, when necessary, using correlations with long-term gages, to develop annual estimates of streamflow recharge for 1950-98.

Streamflow recharge is estimated for a number of smaller basins using loss thresholds for miscellaneous-record sites. Annual recharge estimates are derived from synthetic records of daily streamflow for 1992-98, which are based on drainage-area ratios applied to continuous-record gaging stations. Recharge estimates are further extrapolated for 1950-91, based on the average percentage of streamflow recharge contributed by these basins during 1992-98, relative to overall streamflow recharge.

Streamflow recharge also is estimated for small drainage areas with undetermined loss thresholds that are situated between larger basins with known thresholds. Estimates for 1992-98 are based on estimates of annual streamflow derived using drainage-area ratios, with assumed losses equal to 90 percent of annual streamflow. Recharge estimates also are extrapolated for 1950-91, based on the average percentage of streamflow recharge contributed by these basins.

Precipitation recharge for 1931-98 is estimated using relations between precipitation and streamflow (or basin yield) for representative gaging stations. Basin yields are first normalized, relative to drainage area, by expressing in inches per unit of drainage area. Yields are further converted to yield efficiencies, by dividing by precipitation on contributing drainage areas. Relations between yield efficiency and precipitation are identified, which are developed for use in generically estimating annual yield for given areas, based on average yield efficiency and annual precipitation. The resulting annual yield is used as a surrogate for estimating annual recharge from infiltration of precipitation on outcrop areas of the Madison and Minnelusa aquifers. Annual yield (or recharge) efficiencies are estimated to

range from about 2 percent to in excess of 30 percent, with corresponding average annual recharge estimates ranging from 0.4 inch in the southern Black Hills to about 8.7 inches in the northwestern Black Hills.

Estimates of precipitation recharge for 1931-49 are used to estimate streamflow recharge for the same period, based on correlations between the two variables for 1989-98. Combined streamflow and precipitation recharge to both aquifers averaged about 344 ft^3/s for 1931-98. Streamflow recharge averaged about 93 ft^3/s, or 27 percent of combined recharge, and precipitation recharge averaged about 251 ft^3/s, or 73 percent of combined recharge. Combined recharge ranged from 62 ft^3/s in 1936 to 847 ft^3/s in 1995. The lowest recharge amounts generally occurred during the 1930's; however, a more prolonged period of low recharge occurred during 1947-61.

For 1931-98, average precipitation recharge to the Madison aquifer is about 3.6 inches, compared with 2.6 inches for the Minnelusa aquifer. However, recharge volumes to these aquifers are nearly identical because the outcrop area of the Minnelusa Formation is larger than the outcrop area of the Madison Limestone. Streamflow recharge to the Madison aquifer is presumed slightly larger than for the Minnelusa aquifer, primarily because of preferential recharge resulting from an upgradient location. Considering both precipitation and streamflow recharge, the Madison aquifer receives about 55 percent of combined recharge, relative to about 45 percent for the Minnelusa aquifer.

The western flank of the Black Hills is almost entirely dominated by precipitation recharge, because of the large outcrop areas of Madison Limestone and Minnelusa Formation and absence of perennial streams. Recharge along the southeastern flank of the Black Hills generally is dominated by streamflow recharge. The relative contribution from streamflow and precipitation recharge is highly variable along the northern and northeastern flanks of the Black Hills.

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 area 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 major emphasis of the Black Hills Hydrology Study. These aquifers are utilized for domestic, municipal, agricultural, and industrial uses. Recharge to these aquifers occurs primarily from infiltration of streamflow losses and infiltration of precipitation on outcrop areas. Long-term estimates of recharge to the Madison and Minnelusa aquifers are important for managing the water resources in the Black Hills area.

Purpose and Scope

The purpose of this report is to describe methods for quantifying recharge to the Madison and Minnelusa aquifers in the Black Hills area of South Dakota and Wyoming and to estimate combined recharge to these aquifers. Annual estimates for water years 1931-98 are presented for recharge from (1) infiltration of streamflow losses (streamflow recharge), and (2) infiltration of precipitation (precipitation recharge). Recharge estimates for the two aquifers are combined because streamflow recharge cannot be quantified separately for most streams. Individual estimates of precipitation recharge are provided because calculations can be based on individual outcrop areas. Recharge estimates are for "regional recharge," which consists of recharge to outcrops of the Madison Limestone and Minnelusa Formation that are connected to the regional flow system, as discussed in a subsequent section. This excludes recharge to outcrops that are isolated from the regional flow system (erosional remnants).

Based on water-level data for paired wells (Driscoll, Bradford, and Moran, 2000), there is the potential for leakage to the Madison aquifer from the underlying Deadwood aquifer in some areas and from the Madison aquifer to the Deadwood aquifer in other areas. There also is potential for upward leakage from the Madison and Minnelusa aquifers to overlying aquifers such as the Inyan Kara aquifer. No attempt is made to quantify leakage to or from the Madison and Minnelusa aquifers because of insufficient information; the scope of this report is limited to streamflow recharge and precipitation recharge.

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 for the Black Hills Hydrology Study includes most of the larger communities in western South Dakota and contains about one-third of the State's population.

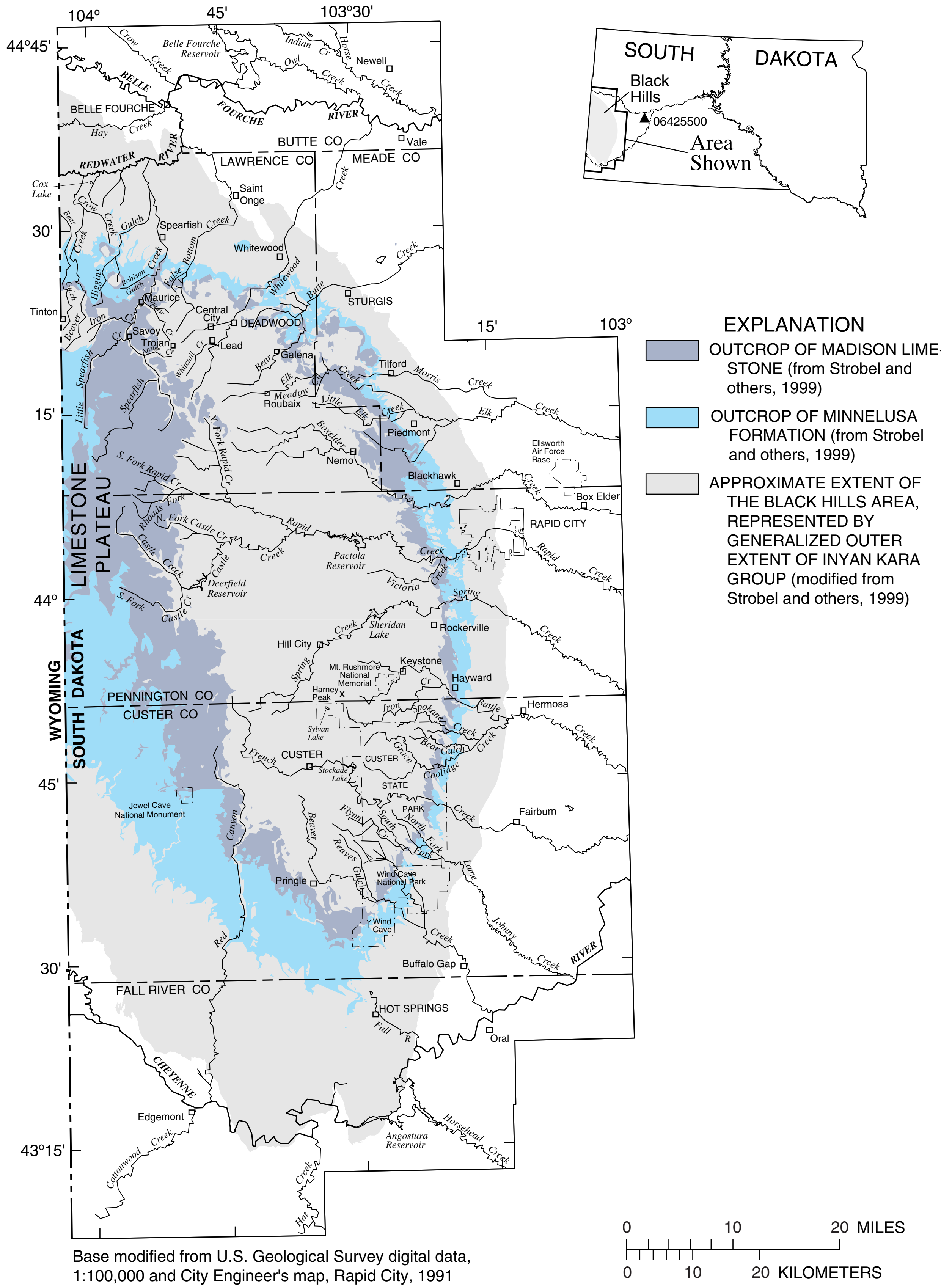
Physiography, Land Use, and Climate

The Black Hills uplift formed as an elongated dome about 60 to 65 million years ago during the Laramide orogeny (DeWitt and others, 1986). The dome trends north-northwest and is about 120 mi long and 60 mi wide. 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 elevations 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.

Beginning in the 1870's, the Black Hills have been explored and mined for many mineral resources including gold, silver, tin, tungsten, mica, feldspar, bentonite, beryl, lead, zinc, uranium, lithium, sand, gravel, and oil (U.S. Department of Interior, 1967). Mining methods have included placer mining, small surface pits, large open pits, and underground mines.

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

The average annual precipitation for the study area (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, Hamade, and Kenner, 2000). The largest precipitation amounts typically occur in the northern Black Hills near Lead, where average annual precipitation exceeds 29 inches. Annual averages (1931-98) for counties within the study area range from 16.35 inches for Fall River County to 23.11 inches for Lawrence County (Driscoll, Hamade, and Kenner, 2000). 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. Average annual evaporation generally exceeds average annual precipitation throughout the study area. Average pan evaporation for April through October is about 30 inches at Pactola Reservoir and about 50 inches at Oral.



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

Figure 1. Area of investigation for the Black Hills Hydrology Study. Streamflow-gaging station located outside of study area that was used in developing recharge estimates is shown on index map.

Geologic Setting

The oldest geologic units in the study area are the Precambrian crystalline (metamorphic and igneous) rocks (fig. 2), which form a basement under the Paleozoic, Mesozoic, and Cenozoic rocks and sediments. The Precambrian rocks range in age from 1.7 to about 2.5 billion years, and were eroded to a gentle undulating plain at the beginning of the Paleozoic era (Gries, 1996). The Precambrian rocks are highly variable, but are composed mostly of igneous rocks or metasedimentary rocks, such as schists and graywackes. The Paleozoic and Mesozoic rocks were deposited as nearly horizontal beds. Subsequent uplift during the Laramide orogeny and related erosion exposed the Precambrian rocks in the crystalline core of the Black Hills, with the Paleozoic and Mesozoic sedimentary rocks exposed in roughly concentric rings around the core. Deformation during the Laramide orogeny contributed to the numerous fractures, folds, and other 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 crystalline core is a layered series of sedimentary rocks (fig. 3) including outcrops of the Madison Limestone (also locally known as the Pahasapa Limestone) and the Minnelusa Formation. 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. 4). Following are descriptions for Paleozoic bedrock formations in the Black Hills, which includes the Madison Limestone, Minnelusa Formation, and stratigraphically adjacent units.

The oldest sedimentary formation 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 is a massive, gray to buff limestone that is locally dolomitic (Strobel and others, 1999). The Madison Limestone, which was deposited as a marine carbonate, was exposed above 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). The thickness of the Madison Limestone 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). Local variations in thickness are due largely to the karst topography that developed before the deposition of the overlying formations (DeWitt and others, 1986). 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. 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.

ERATHEM	SYSTEM	ABBREVIATION FOR STRATIGRAPHIC INTERVAL	GEOLOGIC UNIT	THICKNESS IN FEET	DESCRIPTION
CENOZOIC	QUATERNARY & TERTIARY (?)	QTu	UNDIFFERENTIATED SANDS AND GRAVELS	0-50	Sand, gravel, and boulders
		Tw	WHITE RIVER GROUP	0-300	Light colored clays with sandstone channel fillings and local limestone lenses.
	TERTIARY[1]	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	[2]80-300	Impure chalk and calcareous shale.
			CARLILE SHALE: Turner Sandy Member; Wall Creek Member	[2]350-750	Light-gray shale with numerous large concretions and sandy layers. Dark-gray shale
			GREENHORN FORMATION	(25-30) (200-350)	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	20-150	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	250-800	Red sandy shale, soft red sandstone and siltstone with gypsum and thin limestone layers. Gypsum locally near the base.
PALEOZOIC	PERMIAN	Pmk	MINNEKAHTA LIMESTONE	[2]25-65	Thin to medium-bedded fine-grained, purplish gray laminated limestone.
		Po	OPECHE SHALE	[2]25-150	Red shale and sandstone.
	PENNSYLVANIAN	PIPm	MINNELUSA FORMATION	[2]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	[2]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	[2]0-235	Buff dolomite and limestone.
			WINNIPEG FORMATION	[2]0-150	Green shale with siltstone.
	CAMBRIAN	OꞒd	DEADWOOD FORMATION	[2]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		pꞒu	UNDIFFERENTIATED METAMORPHIC AND IGNEOUS ROCKS		Schist, slate, quartzite, and arkosic grit. Intruded by diorite, metamorphosed to amphibolite, and by granite and pegmatite.

[1] Also may include intrusive igneous rocks
[2] Modified based on drill-hole data

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

Figure 2. Stratigraphic section for the Black Hills.

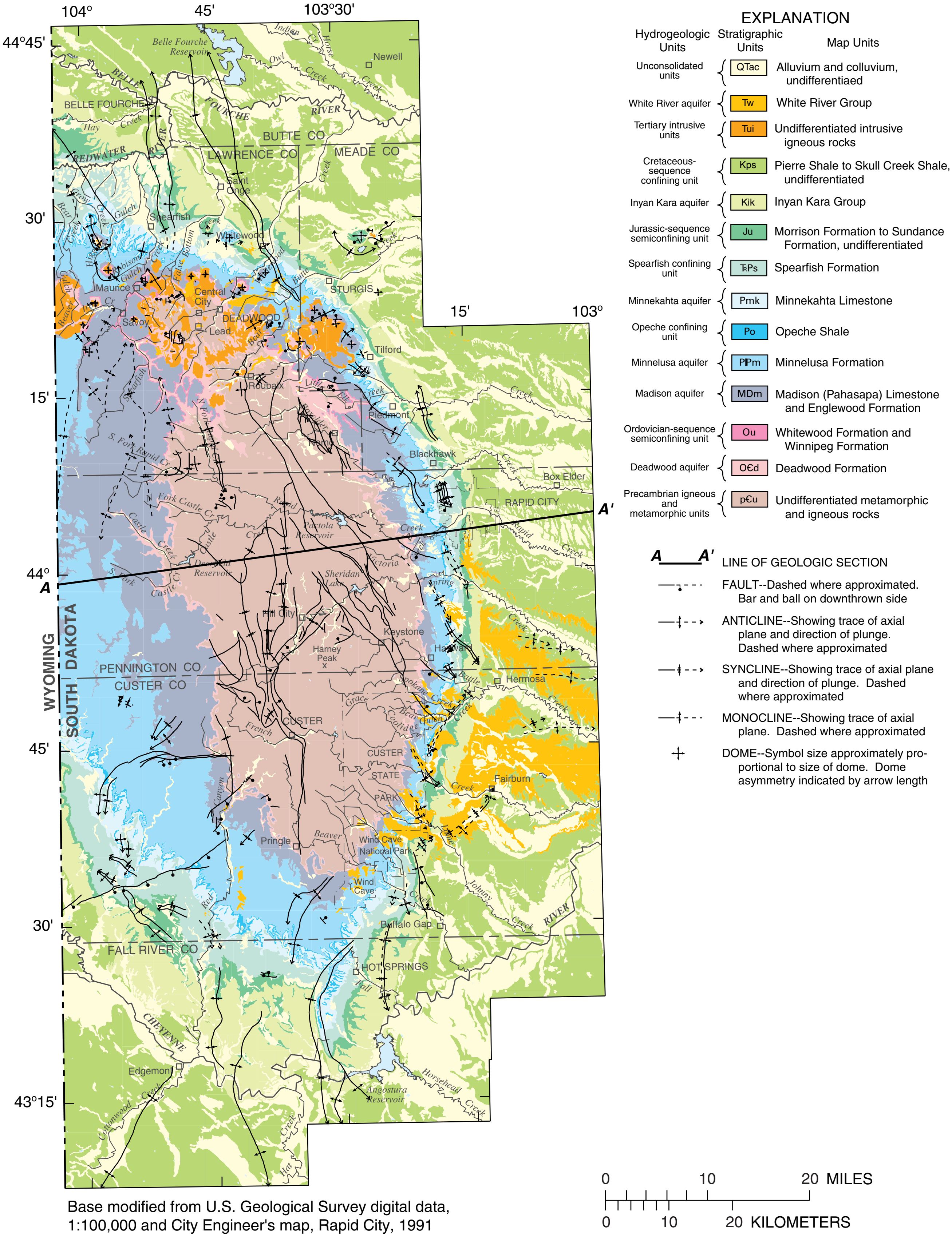


Figure 3. Distribution of hydrogeologic units in the Black Hills area (modified from Strobel and others, 1999).

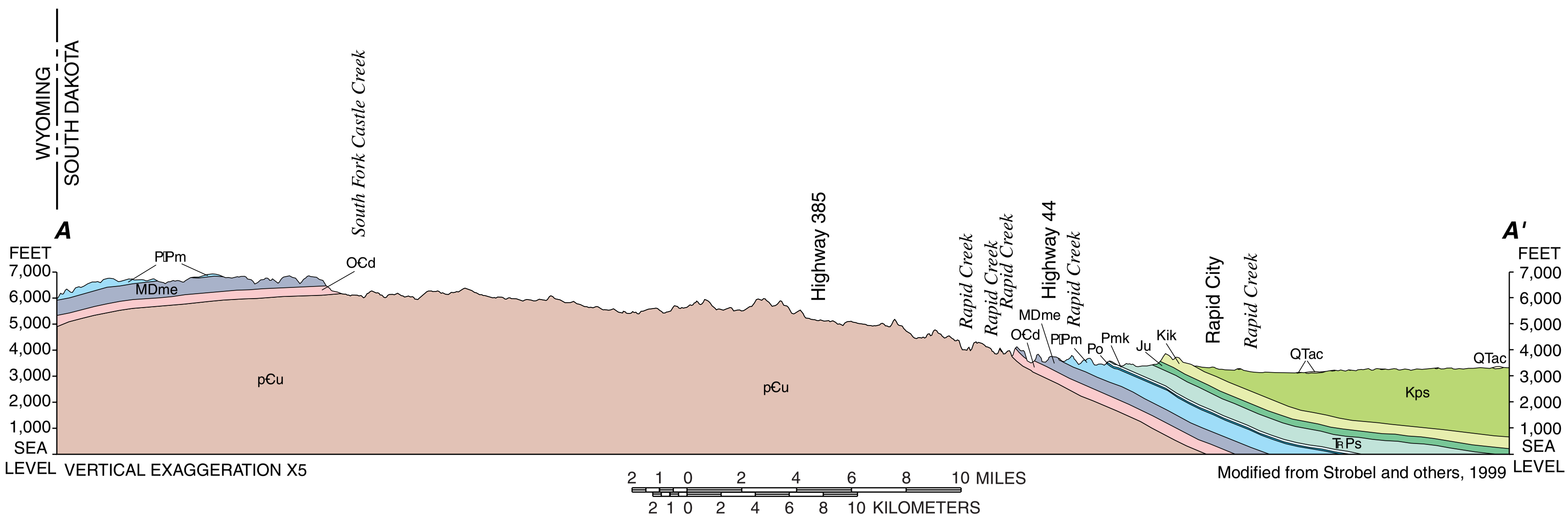


Figure 4. Geologic section A-A' (Location of section is shown in figure 3. Abbreviations for stratigraphic intervals are explained in figure 2.).

The Permian-age Minnekahta Limestone is a fine-grained, purple to gray laminated limestone, with thicknesses ranging 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.

Hydrologic Setting

The Precambrian basement rocks generally have low permeability and form the lower confining unit for the series of sedimentary aquifers in the Black Hills area. Localized aquifers occur in Precambrian rocks in many locations in the 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 wells completed in the Precambrian rocks are located along stream channels.

Many of the sedimentary formations contain aquifers, both within and beyond the study area. Within the Paleozoic rock interval, aquifers in the Deadwood Formation, Madison Limestone, Minnelusa Formation, and Minnekahta Limestone are used extensively. 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 formations. Extremely variable leakage 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 the 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 semi-confining 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 in the aquifer. The Madison aquifer receives significant recharge from streamflow losses and precipitation on the outcrop. The Madison aquifer is confined by low permeability layers in the overlying Minnelusa Formation.

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

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

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

Artesian (confined) conditions generally exist within the aforementioned aquifers, where an upper confining layer is present. Under artesian conditions, water in a well 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. The hydrogeologic setting of the Black Hills area is schematically illustrated in figure 5.

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

Most streams generally lose all or part of their flow as they cross the outcrop of the Madison Limestone (Rahn and Gries, 1973; Hortness and Driscoll, 1998). Karst features of the Madison Limestone, including sinkholes, collapse features, solution cavities, and caves, are responsible for the Madison aquifer's capacity to accept recharge from streamflow. Large streamflow losses also occur in many locations within the outcrop of the Minnelusa Formation, and limited losses probably also occur within the outcrop of the Minnekahta Limestone (Hortness and Driscoll, 1998). Large artesian springs occur in many locations downgradient from 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

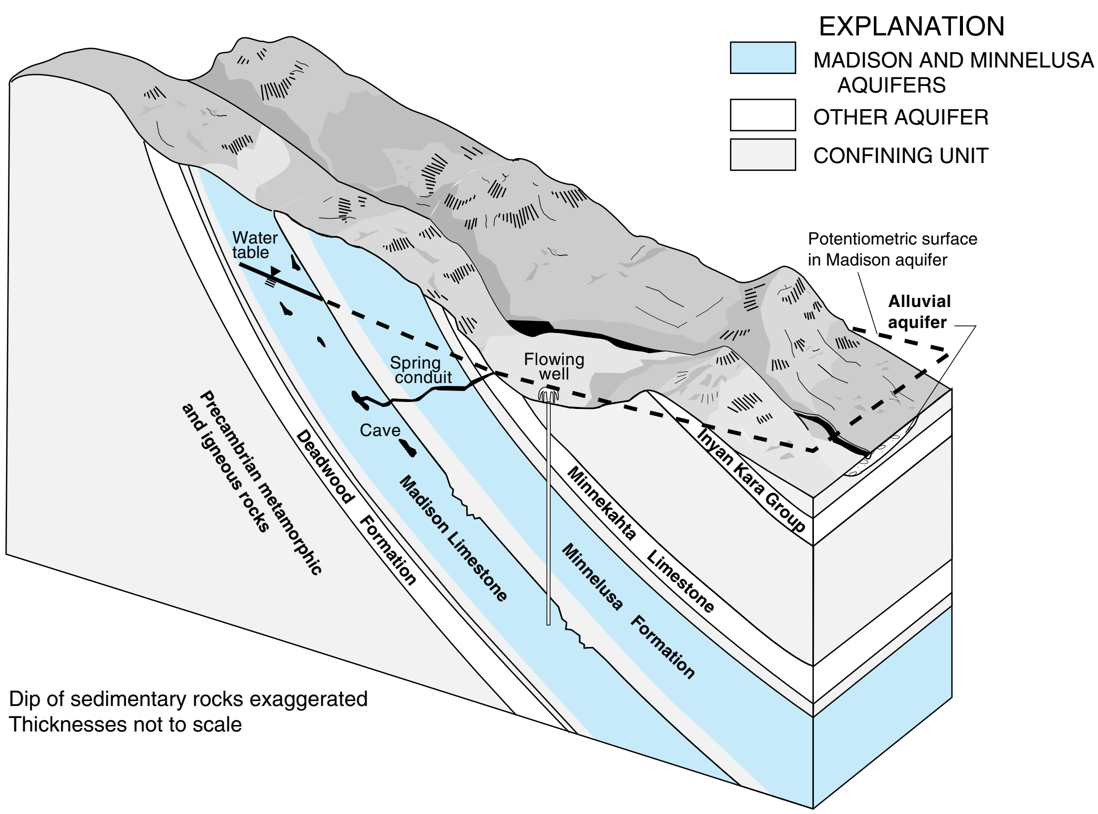


Figure 5. Schematic showing simplified hydrogeologic setting of the Black Hills area.

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.

RECHARGE PROCESSES AND GENERAL METHODS FOR QUANTIFYING RECHARGE

This section describes processes affecting recharge to the Madison and Minnelusa aquifers and provides an overview of the general methods used to quantify recharge. An overview of previous investigations regarding recharge to the Madison and Minnelusa aquifers also is provided.

Previous Investigations

Numerous previous investigators have studied recharge to the Madison and Minnelusa aquifers. Most of the previous investigations have focused on streamflow losses. Losses from local Black Hills streams to outcrops of various sedimentary formations were first noted by Dodge (1876), although it was then believed that most losses occurred to the Minnelusa Formation and overlying sandstone units (Newton and Jenney, 1880). Streamflow losses for various Black Hills streams were estimated by Brown (1944), Crooks (1968), Rahn and Gries (1973), Peter (1985), and Greene (1997). The most comprehensive study of streamflow losses in the Black Hills area was by Hortness and Driscoll (1998), who documented losses for 24 streams based on extensive measurements and analyses of streamflow records.

Cox (1962) estimated recharge for the Minnelusa aquifer in the northern Black Hills as 2 inches from infiltration of precipitation. Minimum precipitation recharge for the Madison and Minnelusa aquifers was estimated by Rahn and Gries (1973) to range from 0.6 in/yr in the southern Black Hills to 6.8 in/yr in the northern Black Hills. Peter (1985) estimated that between 1 and 2 inches of the annual precipitation becomes recharge to the Madison and Minnelusa aquifers in the Rapid City area. Annual recharge to the Madison aquifer on the western flanks of the Black Hills in the Limestone Plateau area was estimated to be 6.8 inches (Downey, 1986).

Recharge Processes

As discussed, many previous investigations have addressed quantification of streamflow loss rates. These investigations have provided various insights regarding the processes affecting recharge to the Madison and Minnelusa aquifers. One very important factor is the potential for extremely large secondary porosity within these aquifers, which is evidenced by the large infiltration rates that are associated with dramatic streamflow losses that can be as large as tens of cubic feet per second for some stream reaches (Hortness and Driscoll, 1998). Large secondary porosity and associated infiltration rates also are consistent with the physical nature of both formations, which commonly have fractures and solution features in outcrop sections. The Madison Limestone is especially prone to solution openings, as exemplified by large caves such as Wind Cave and Jewel Cave, which are two of the largest caves in the world.

The fact that both the Madison and Minnelusa aquifers have large secondary porosity in some locations does not necessarily imply that infiltration rates will be uniformly large in all outcrop sections. Both aquifers are prone to large heterogeneity, or variability in aquifer characteristics (Cox, 1962; Greene, 1993; Greene and Rahn, 1995), as evidenced by the extremely large range in well yields that can occur. This is visually apparent in many locations in caves within the Madison Limestone, where rates of cave drip can be very small in the ceilings of man-size passageways (Wiles, 1992).

Rates of recharge resulting from infiltration of precipitation on outcrops can be highly affected by conditions in the soil horizon. Much of the precipitation that occurs is eventually returned to the atmosphere though evaporation and transpiration (evapotranspiration). Recharge can occur only when water infiltrates to sufficient depth to escape the root zone. Thus, recharge rates can be affected by infiltration rates, along with thicknesses and associated storage capacities of overlying soils, which can be highly variable.

A perspective on the infiltration capacity of the Madison and Minnelusa aquifers on a watershed scale can be obtained by examination of streamflow information for selected gaging stations. Duration hydrographs are presented in figure 6 for four streamflow-gaging stations (graphs B through E) that are located in or near the Limestone Plateau area, which is dominated by large outcrop areas of the Madison Limestone and

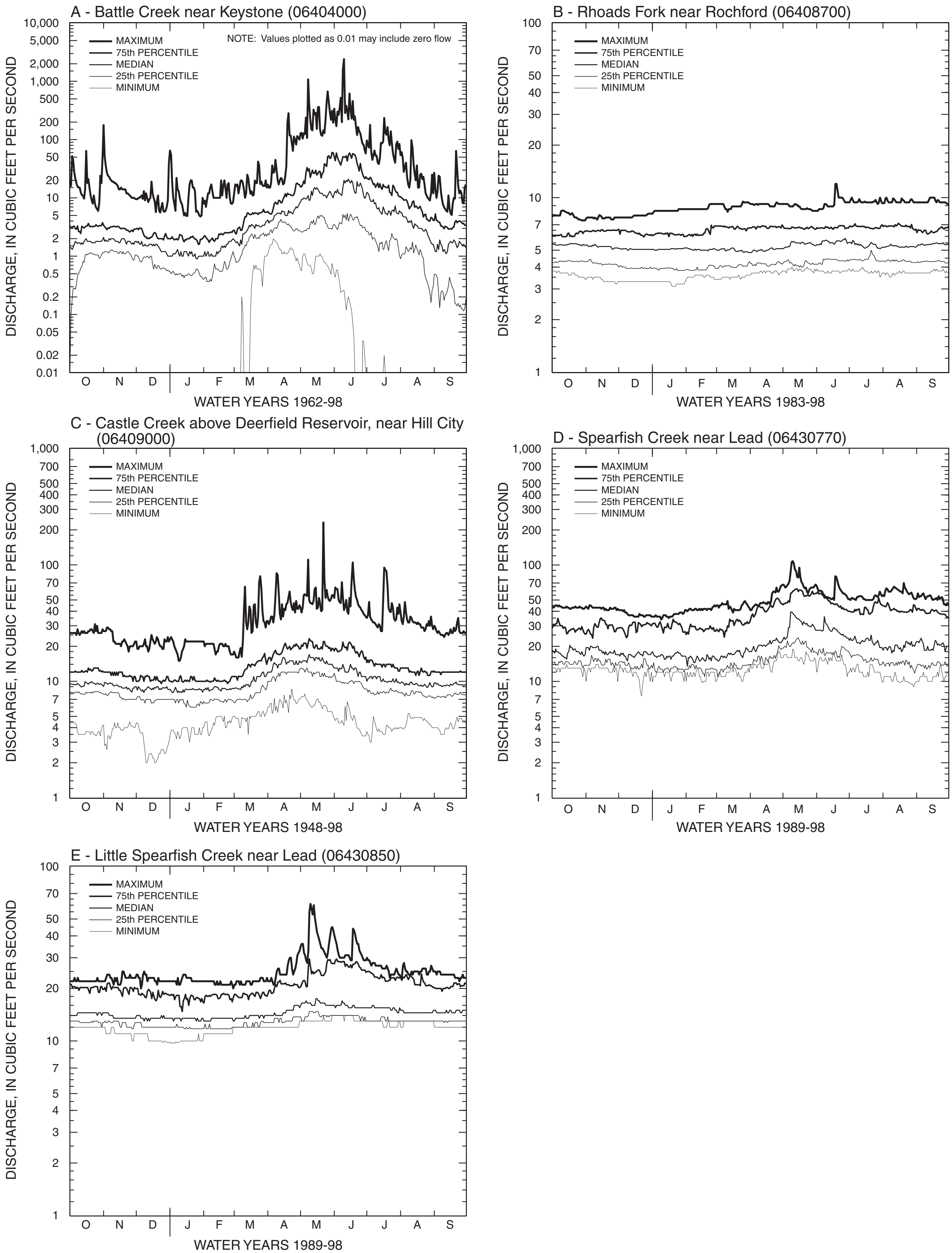


Figure 6. Daily-duration hydrographs for selected gaging stations.

Minnelusa Formation (fig. 1). Locations of gaging stations are shown in figure 7. Flow at these sites is dominated by base flow originating from ground-water discharge from the Madison and Minnelusa aquifers. For comparison, a duration hydrograph also is presented for a gaging station on Battle Creek (graph A in fig. 6), the drainage area of which is dominated by Precambrian igneous and metamorphic rocks. Flow in Battle Creek is highly variable and responsive to short-term climatic conditions, indicating dominance from surface-water flow components relative to ground-water flow components. Additional discussions of differences in flow characteristics for different hydrogeologic settings were presented by Miller and Driscoll (1998).

An important observation from examination of the duration hydrographs is that direct surface runoff from outcrops of the Madison Limestone and Minnelusa Formation is very unusual. Surface runoff is virtually nonexistent for Rhoads Fork (graph B), for which the surface drainage area is comprised almost entirely of Madison Limestone outcrops. The entire range in variability in daily flow for this site falls easily within one order of magnitude, compared with a range spanning in excess of five orders of magnitude for Battle Creek. Increasingly larger components of surface runoff are apparent for graphs E, D, and C, respectively, which can be attributed to increasingly larger percentages of outcrops other than the Madison Limestone and Minnelusa Formation within these drainage basins (figs. 3 and 7).

The preceding discussions are used as the basis of an assumption that direct surface runoff from the Madison Limestone and Minnelusa Formation is almost nonexistent and can be neglected for many purposes associated with calculation of recharge to these aquifers. This assumption is very important in developing methods for quantification of recharge from direct precipitation, as discussed in the following section.

General Methods for Quantifying Recharge

Quantifying recharge to the Madison and Minnelusa aquifers requires methods for quantification of both streamflow recharge and precipitation recharge, as discussed in this section. Various considerations regarding areas and uncertainties associated with recharge estimates also are discussed.

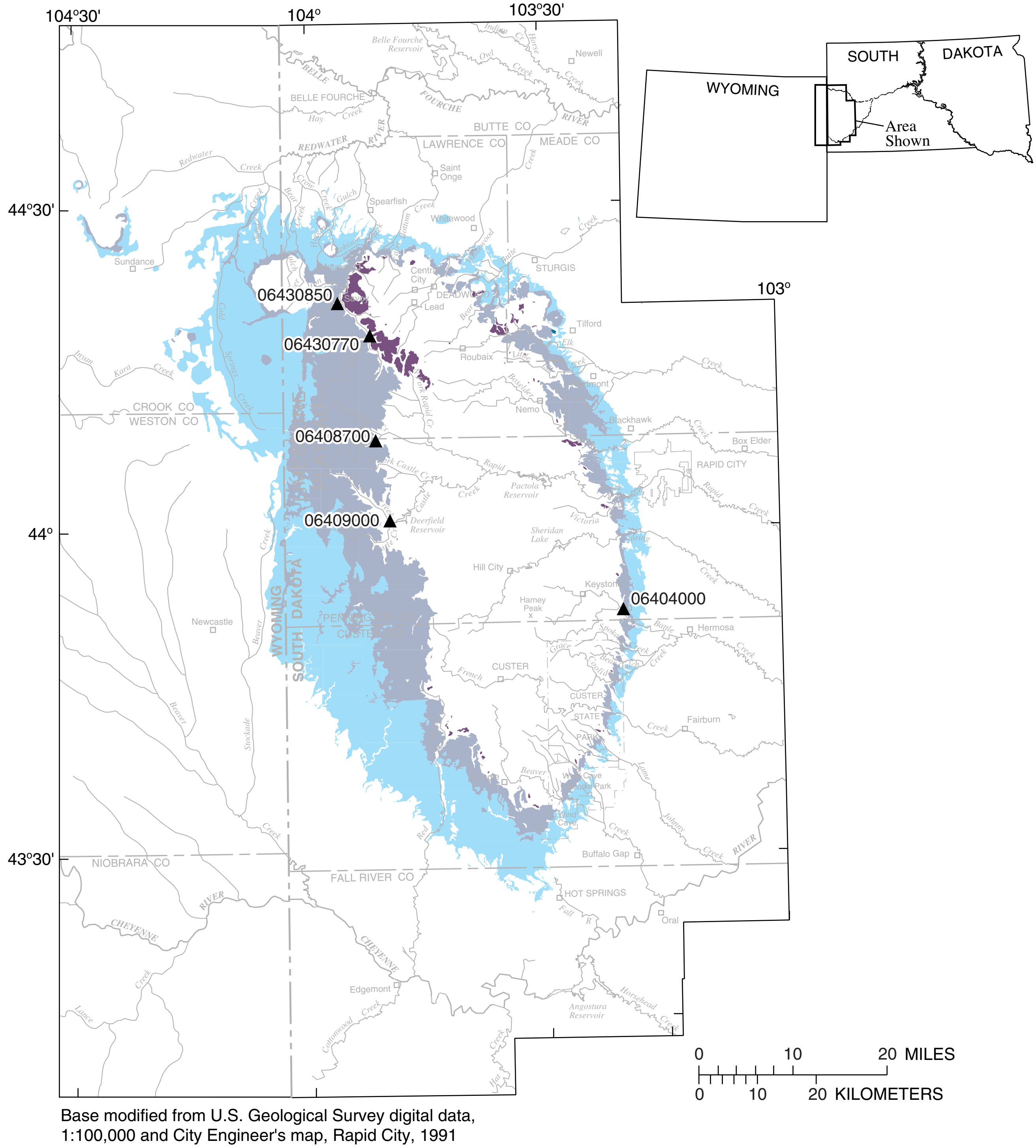
Annual recharge estimates are made for water years 1931-98, which corresponds with a period for which precipitation records have been compiled for the Black Hills area (Driscoll, Hamade, and Kenner, 2000). All recharge estimates provided in this report are by water year, which represents the period from October 1 through September 30, and all discussions of time-frames refer to water years, rather than calender years, unless noted otherwise.

Considerations Regarding Recharge Areas

Because outcrops of the Madison Limestone and Minnelusa Formation are not entirely continuous throughout the study area, quantifying precipitation recharge requires identification of outcrop areas where effective recharge occurs. Outcrops that are considered “isolated” from the regional ground-water flow system (erosional remnants) are identified in figure 7. Recharge that occurs in isolated outcrops does not directly join the regional ground-water flow system because these outcrops are not hydraulically connected to a regional aquifer. Thus, for subsequent calculations, precipitation recharge is prescribed only for the “connected” outcrops of the Madison Limestone and Minnelusa Formation.

Subsequent calculations of streamflow recharge require determination of drainage areas contributing to streamflow loss zones that occur within outcrop areas of the Madison Limestone and Minnelusa Formation. For these calculations, isolated outcrops of the Madison Limestone and Minnelusa Formation are included as drainage areas contributing to loss zones. Direct runoff from the isolated outcrops probably is uncommon; however, these areas generally contribute base flow to streams upstream from loss zones. Several small basins upstream from loss zones contain minor connected outcrops that are subtracted from the drainage areas contributing to streamflow loss zones.

Isolated outcrop areas were determined from hydrogeologic and structure-contour maps of the study area (DeWitt and others, 1989; Carter and Redden, 1999c, 1999d; Strobel and others, 1999) and are identified in figure 7. Outcrop areas generally are considered isolated where surrounded by outcrops of an older formation or by Tertiary intrusives because recharge would not be able to move laterally without eventually being discharged at the contact with the older formation or intrusive. An exception to this criterion is that outcrops of the Minnelusa Formation that are surrounded by outcrops of the Madison Limestone are considered connected, rather than isolated.



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--Area is considered in estimates of precipitation recharge

ISOLATED OUTCROP OF THE MADISON LIMESTONE--Area is considered in estimates of streamflow recharge

CONNECTED OUTCROP OF THE MINNELUSA FORMATION--Area is considered in estimates of precipitation recharge

ISOLATED OUTCROP OF THE MINNELUSA FORMATION--Area is considered in estimates of streamflow recharge

▲ STREAMFLOW-GAGING STATION--Number indicates station identification number

Figure 7. Connected and isolated outcrop areas of the Madison Limestone and Minnelusa Formation for recharge considerations (geology modified from Strobel and others, 1999; DeWitt and others, 1989). Location of streamflow-gaging stations for which duration hydrographs also are presented.

Recharge estimates presented in this report consists of "regional recharge," which refers to recharge to outcrops connected to the regional flow system. Precipitation recharge to isolated outcrops of the Madison Limestone and Minnelusa Formation is excluded because most of this recharge is ultimately discharged as base flow to streams, which may be subsequently recharged in loss zones located farther downstream. The term "regional recharge" is used primarily because of considerations regarding large headwater springs located mainly along Rapid Creek and Spearfish Creek and recharged in the Limestone Plateau area (fig. 1). Some of this water from headwater springs also contributes to subsequent streamflow recharge farther downstream; however, two important distinctions exist between infiltration of precipitation on the Limestone Plateau area and on isolated outcrops. First, the water in the Limestone Plateau area is part of the regional flow system recharged in the continuous part of the formation outcrops prior to discharge at headwater springs; hence the term regional recharge. Second, much of the discharge from the headwater springs in Rapid Creek and Spearfish Creek does not necessarily contribute to subsequent streamflow recharge. Streamflow losses in these streams are small, relative to the drainage areas, and streamflow generated from other areas generally is sufficient to satisfy the loss thresholds.

Methods for Quantifying Streamflow Recharge

The Madison and Minnelusa aquifers receive relatively consistent recharge from area streams, which generally lose flow crossing the formation outcrops. During periods of base flow, most streams generally lose their entire flow as they cross these outcrops (loss zones), up to "threshold" rates that are unique for each stream. Hortness and Driscoll (1998) concluded that loss thresholds for individual streams generally are relatively constant, without measurable effects from flow rate or duration of flow through loss zones. Minor variability in apparent loss rates was attributed to localized springflow within loss reaches.

Estimates of streamflow recharge are based, when possible, on loss thresholds that were determined by Hortness and Driscoll (1998) for 24 area streams. This constitutes the majority of drainage areas that provide streamflow recharge to the Madison and Minnelusa aquifers. Some of the loss thresholds determined by Hortness and Driscoll (1998) were based on measurement sites that do not include the entire drainage area above the outcrops. Therefore, some of the thresholds are adjusted to account for additional, unmeasured flow from the additional minor drainage areas. Estimates of streamflow recharge exclude alluvial ground-water flow upstream from loss zones because alluvial flow could not be determined.

Some of the stream reaches measured by Hortness and Driscoll (1998) included outcrops of the Deadwood Formation or Minnekahta Limestone, primarily because of access considerations. Thus, some of the calculated loss thresholds may apply to these outcrops. Examination of additional information led to a conclusion by Hortness and Driscoll (1998) that losses to the Deadwood Formation generally are minimal. Losses to the Minnekahta Limestone were difficult to isolate from potential losses to extensive alluvial deposits that commonly occur near outcrops of the Minnekahta Limestone. For this report, all streamflow losses are assumed to recharge the Madison and Minnelusa aquifers, except those specifically identified by Hortness and Driscoll (1998) for other aquifers.

Estimates of streamflow recharge are developed for three types of drainage basins: (1) those with continuous-record streamflow-gaging stations, (2) those with only miscellaneous-record measurement sites; and (3) those with no available measurements (ungaged). Loss thresholds have not been determined for the ungaged basins, but were available from Hortness and Driscoll (1998) for the other two types of basins.

For the basins with continuous-record gaging stations, daily mean flows are available, and loss threshold values can be used along with daily flow records to calculate recharge rates. The general method for calculating recharge rates follows: (1) if the daily mean flow measured at the gaging station was less than the loss threshold rate, daily recharge to the Madison and/or Minnelusa aquifers was equal to the measured flow; or (2) if the measured flow was greater than or equal to the loss threshold rate, daily recharge to the aquifers was equal to the threshold rate. Calculated daily losses were aggregated to provide estimates of annual recharge.

For some streams, Hortness and Driscoll (1998) were able to quantify individual loss thresholds to the Madison and Minnelusa aquifers; thus, individual and combined recharge to the aquifers can be determined. For stations for which individual loss thresholds had been determined, the loss threshold for the Madison aquifer is applied first to daily mean flows, and any flow greater than this threshold then is applied to the loss threshold for the Minnelusa aquifer. Combined recharge rates are equal to the sum of the individual recharge rates of the Madison and Minnelusa aquifers.

Flows from selected continuous-record gaging stations are used to estimate daily flows for streams with miscellaneous-record measurement sites. The daily flow estimates are based strictly on the ratio of the drainage area for each basin, relative to the drainage area for a representative continuous-record gage. Daily losses are calculated in the same fashion as those for the continuous-record gaging stations, and annual recharge again is computed by aggregating daily losses.

The ungaged basins generally consist of small drainage areas with undetermined loss thresholds that are situated between larger basins for which loss thresholds have been determined. Hortness and Driscoll (1998) did not attempt to quantify loss thresholds for these small basins; however, field observations indicated that flow seldom occurs below the loss zone. Therefore, a simplifying assumption that 90 percent of runoff generated within these basins becomes recharge to the Madison and Minnelusa aquifers is made for estimating recharge from ungaged streams. Annual flows for ungaged basins are estimated strictly from annual flows for representative continuous-record gages, again using drainage-area ratios. Because the ungaged basins contain outcrops of the Deadwood Formation, which would receive precipitation recharge to the Deadwood aquifer, streamflow recharge to the Madison and Minnelusa aquifers is overestimated slightly. However, this slight overestimation is assumed to be equal to the alluvial ground-water flow upstream from loss zones that could not be determined.

All of the continuous-record gages used for direct calculation of daily losses have daily records at least for water years 1992-98, with the oldest records dating to 1962. A variety of regression methods are used to estimate streamflow back to 1950 for calculation of streamflow recharge, which requires utilization of gages with longer records. Estimates of streamflow recharge are further extended to 1931 using correlations with estimates of precipitation recharge. Additional details are provided in subsequent sections. An evaluation of uncertainties associated with recharge estimates also is provided.

Methods for Quantifying Precipitation Recharge

Recharge resulting from infiltration of direct precipitation can be a very difficult variable to quantify. Pan evaporation, which can be measured directly, might be useful in computing precipitation recharge. However, evaporation data are sparse and evaporation rates are quite variable in the study area, primarily because of differences in energy input resulting from differences in elevation and aspect (Wrage, 1994). Furthermore, pan evaporation exceeds precipitation for most parts of the Black Hills during all but the wettest years. Thus, evapotranspiration generally is limited by precipitation amounts and availability of soil moisture. Measured evapotranspiration rates of the Black Hills pine forest do not exist, and estimation of evapotranspiration generally involves extensive modeling efforts that require input of hourly climatic data (Fluke, 1996).

Development of the assumption that surface runoff from outcrops of the Madison Limestone and Minnelusa Formation is negligible (as discussed in a previous section) provides a simplified approach to quantifying precipitation recharge. By neglecting surface runoff, it can be assumed that all precipitation on outcrops of the Madison Limestone and Minnelusa Formation that is not evapotranspired becomes recharge, as schematically illustrated in figure 8.

Streamflow in drainage basins within the crystalline core of the Black Hills area can be used as an indirect measure of evapotranspiration. This concept also is schematically illustrated in figure 8. A similar approach was used by Anderson (1980) in three watersheds in the Sturgis area. Recharge does occur to numerous localized aquifers in fractured crystalline rocks, especially where extensive weathering has occurred in outcrop areas. However, these aquifers are not regional, as indicated by the fact that wells constructed in Precambrian rocks in western South Dakota outside of the Black Hills have not encountered measurable amounts of ground water (Rahn, 1985). Therefore, regional ground-water flow in the crystalline rocks can reasonably be considered negligible.

Streamflow records are available for numerous drainage basins within the crystalline core area, which are appropriate for use in estimating basin yield. In the absence of a regional ground-water flow component, basin yield can be considered as the residual between precipitation and evapotranspiration, for periods sufficiently long to neglect change in storage. As discussed, localized aquifers are common in the fractured crystalline rocks, and streams draining these rocks generally

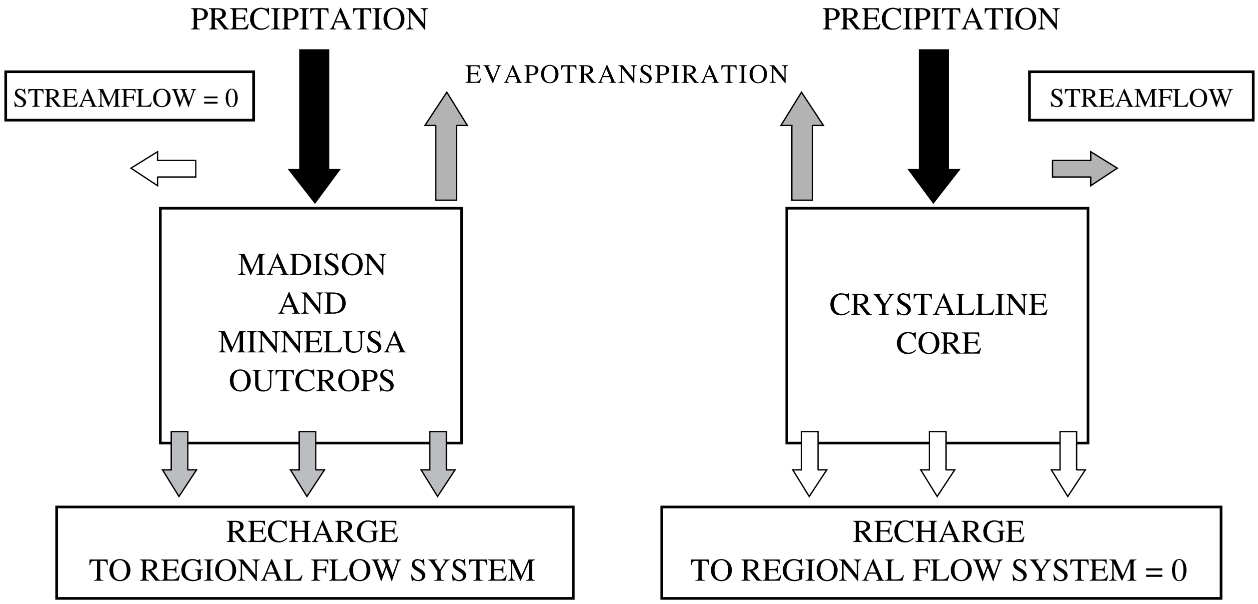


Figure 8. Schematic diagram illustrating recharge and streamflow characteristics for selected outcrop types.

have at least some component of base flow that can be attributed to ground-water discharge. However, the relatively minor ground-water components in these areas primarily reflect changes in storage in the crystalline rocks. Thus, streamflow (or basin yield) effectively represents the entire quantity of water not lost through evapotranspiration, which for the crystalline areas consists predominantly of runoff with a minor ground-water component.

In this report, basin yields are first normalized, relative to drainage area, by expressing in inches per unit of drainage area. Yields are further converted to yield efficiencies, by dividing by precipitation on contributing drainage areas. Relations between yield efficiency and precipitation are identified, which are developed for use in generically estimating annual yield for given areas, based on average yield efficiency and annual precipitation. The resulting annual yield is used as a surrogate for estimating annual recharge from infiltration of precipitation on outcrop areas of the Madison and Minnelusa aquifers. Additional details are provided in subsequent sections.

Uncertainties Associated with Recharge Estimates

There are a large number of uncertainties associated with the recharge estimates provided in this report. Most of the uncertainties cannot be accurately evaluated because of unknowns associated with the variables involved and the broad assumptions necessary in estimating recharge. It is possible, however, to provide a sense of the relative level of uncertainty associated with most of the methods used. Following are preliminary discussions of uncertainties associated with some of these methods. Additional discussions are provided in subsequent sections, where additional details regarding methods or results are available.

Uncertainties for estimates of streamflow recharge for the continuous-record gages probably are small, relative to other uncertainties, because uncertainties associated with measured flow records and the determination of loss thresholds are relatively small. Estimates of streamflow recharge for 1992-98 are better than estimates for earlier periods because more continuous-record gaging stations were in operation. Additional uncertainties are introduced when flow estimates are based on flow records for other gages, which is done for continuous-record gages outside of the period of record, miscellaneous-record measurement sites, and ungaged basins. Estimates for ungaged basins have additional uncertainty associated with the assumption that 90 percent of streamflow in these ungaged areas becomes recharge. This additional uncertainty is not particularly critical, however, because the ungaged basins constitute less than 10 percent of the drainage area contributing streamflow recharge to the Madison and Minnelusa aquifers, compared with about 80 percent for basins with continuous flow records. The largest uncertainties for streamflow recharge estimates are for 1931-50, when estimates are based on correlations with estimates of precipitation recharge.

Uncertainties associated with estimates of precipitation recharge result from: (1) the methods used and associated assumptions, which may be large and cannot be quantified (additional discussions of these uncertainties will be provided later in the report); and (2) measurement of precipitation. Uncertainties become progressively larger for earlier periods due to sparser precipitation data.

The methods that are used for estimating precipitation recharge provide a consistent, systematic approach that is based on precipitation measurements that have a relatively small level of uncertainty. Minor uncertainty is associated with the spatial distribution of measured precipitation; however, the method used (Driscoll, Hamade, and Kenner, 2000) is consistent and systematic, and probably introduces little bias. Thus, errors associated with the spatial distribution of precipitation probably are random and tend to cancel out over time.

Large uncertainties are associated with the approach that is used for generically estimating annual basin yield and yield efficiency, along with the assumption that yield efficiency is a reasonable surrogate for estimating recharge rates for the Madison and Minnelusa aquifers. There also is considerable potential for systematic bias associated with this assumption. A likely source of bias is that precipitation recharge to the Madison and Minnelusa aquifers may be consistently underestimated. An inherent assumption associated with the approach is that the amount of water escaping the root zone in the outcrops of the Madison Limestone and Minnelusa Formation is similar to that escaping the root zone in lower permeability settings such as the Precambrian rocks, where the ground-water component of streamflow is relatively small. Because of the large secondary porosities associated with outcrops of the Madison Limestone and Minnelusa Formation, it is likely that the amount of water escaping the root zone in these outcrops is larger than in other settings. Therefore, the recharge estimates presented in this report probably are conservative.

In general, the best recharge estimates are streamflow recharge values for 1992-98 that are calculated from measured loss thresholds and daily streamflow records for continuous-record gages. Estimates of streamflow recharge become progressively more uncertain for previous periods, as availability of streamflow records becomes sparser. The uncertainty associated with estimates of precipitation recharge generally is larger than for streamflow recharge. This does not necessarily imply that errors are large, but does recognize that potential for error is large. The uncertainty associated with estimates of precipitation recharge changes little over time and is influenced only by availability of precipitation measurement sites. Thus, uncertainties for combined recharge from streamflow and precipitation are subject to less change over time than estimates of streamflow recharge alone. Although recharge estimates are somewhat poorer for earlier periods, estimates for the 1930’s and 1950’s are especially important, because this is the driest period for which adequate precipitation data are available for hydrologic analysis.

As discussed, uncertainties associated with recharge estimates cannot be evaluated precisely at this time. Results of an initial water-budget analysis, which utilized the same general methods for estimation of recharge, were presented by Hamade (2000). These initial results indicate that recharge estimates are in a range that is compatible with other components of the water budget.

STREAMFLOW RECHARGE

Streamflow losses from area streams provide a consistent source of recharge to the Madison and Minnelusa aquifers. Streamflow records for 39 measurement sites (table 1 fig. 9) are considered in calculating streamflow recharge. One gage (06425500; site 22 in table 1) used in quantifying streamflow recharge is outside the study area and is shown in figure 1. Most of the gages are used for direct calculations of streamflow recharge. Several gages (sites 9, 15, 19, 22, 27, 28, 31, and 35) are used only in statistical correlations for extending streamflow records.

The streamflow measurement sites are used to delineate 13 drainage basins with continuous-record gages and 19 basins with miscellaneous measurement sites (fig. 10). In addition, 23 ungaged basins are delineated. Basins with continuous-record gages account for 78 percent of the study area, and basins with miscellaneous-record measurement sites account for 13 percent. The ungaged basins account for only 9 percent of the study area.

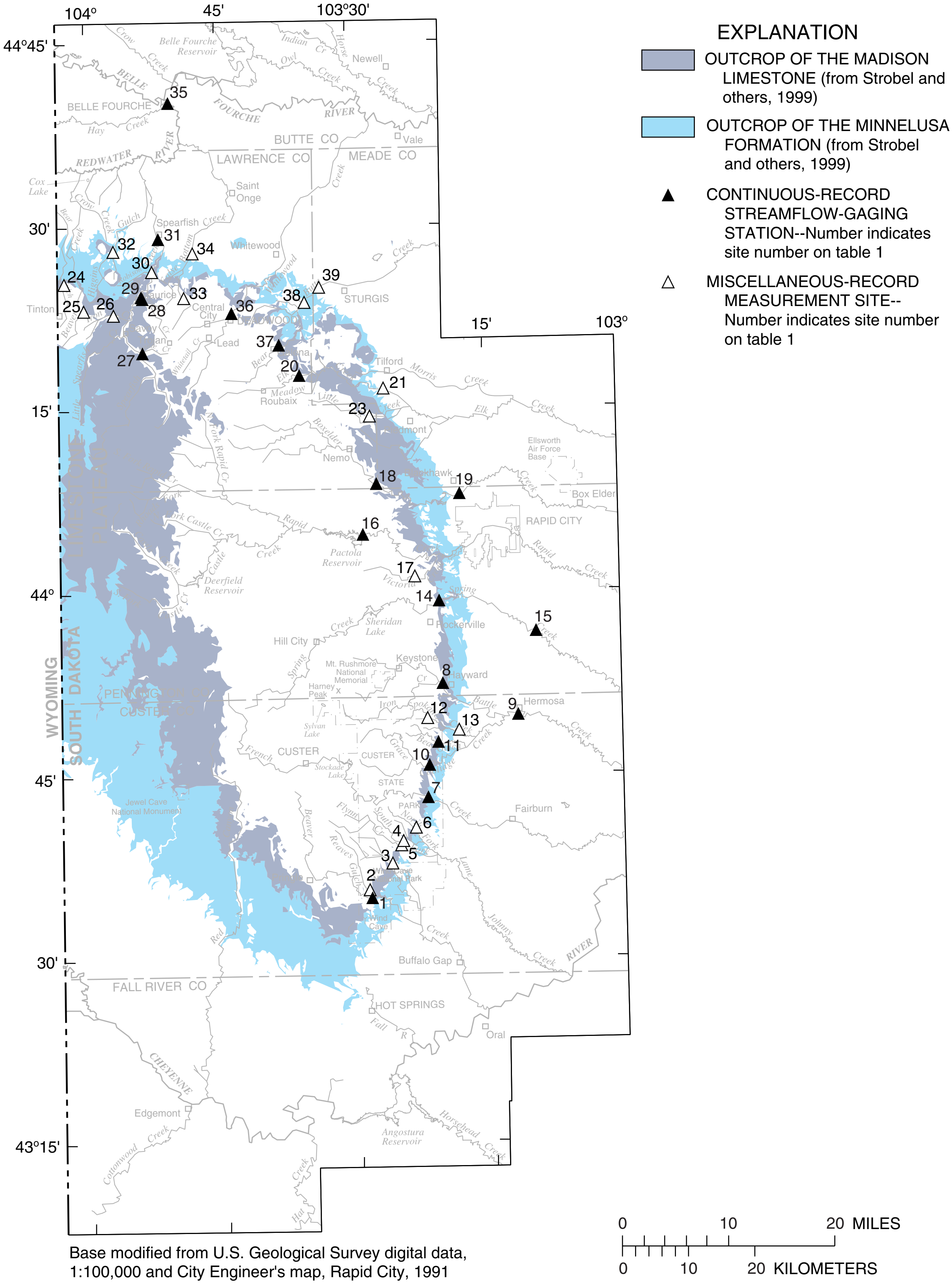


Figure 9. Location of gaging stations used to estimate streamflow recharge.

Table 1. Summary of selected site information for gaging stations used in determining streamflow recharge

[Type of station: C, continuous-record; M, miscellaneous-record. --, none used]

Site number	Station identification number	Station name	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Type of station	Drainage area (square miles)	Period of record used (water years)
1	06402430	Beaver Creek near Pringle	43 34 53	103 28 34	C	45.8	1991-98
2	433532103284800	Reaves Gulch above Madison outcrop, near Pringle	43 35 32	103 28 48	M	6.86	--
3	433745103261900	Highland Creek above Madison outcrop, near Pringle	43 37 45	103 26 19	M	8.69	--
4	433930103250000	South Fork Lame Johnny Creek above Madison outcrop, near Fairburn	43 39 30	103 25 00	M	4.34	--
5	433910103251000	Flynn Creek above Madison outcrop, near Fairburn	43 39 10	103 25 10	M	10.3	--
6	434105103240200	North Fork Lame Johnny Creek above Madison outcrop, near Fairburn	43 41 05	103 24 02	M	2.80	--
7	06403300	French Creek above Fairburn	43 43 02	103 22 03	C	105	1983-98
8	06404000	Battle Creek near Keystone	43 52 21	103 20 10	C	58.0	1962-98
9	06406000	Battle Creek at Hermosa	43 49 41	103 11 44	C[1]	178	1950-98
10	06404998	Grace Coolidge Creek near Game Lodge, near Custer	43 45 40	103 21 49	C	25.2	1977-98
11	06405800	Bear Gulch near Hayward	43 47 31	103 20 49	C	4.23	1990-98
12	434929103215700	Spokane Creek above Madison outcrop, near Hayward	43 49 29	103 21 57	M	4.92	--
13	434800103174400	Spokane Creek below Madison outcrop, near Hayward	43 48 00	103 17 44	M	3.76	--
14	06407500	Spring Creek near Keystone	43 58 45	103 20 25	C	163	1987-98
15	06408500	Spring Creek near Hermosa	43 56 31	103 09 32	C[1]	199	1950-98
16	06411500	Rapid Creek below Pactola Dam	44 04 36	103 28 54	C	320	1946-98
17	440105103230700	Victoria Creek below Victoria Dam, near Rapid City	44 01 05	103 23 07	M	6.82	--
18	06422500	Boxelder Creek near Nemo	44 08 38	103 27 16	C	96.0	1967-98
19	06423010	Boxelder Creek near Rapid City	44 07 54	103 17 54	C	128	1978-98
20	06424000	Elk Creek near Roubaix	44 17 41	103 35 47	C	21.5	1992-98
21	441614103253300	Elk Creek at Minnekahta outcrop, near Tilford	44 16 14	103 25 33	M	23.8	--
22	06425500	Elk Creek near Elm Springs	44 14 54	102 30 10	C[1]	540	1950-98
23	441412103275600	Little Elk Creek below Dalton Lake, near Piedmont	44 14 12	103 27 56	M	11.39	--

Table 1. Summary of selected site information for gaging stations used in determining streamflow recharge–Continued

[Type of station: C, continuous-record; M, miscellaneous-record. --, none used]

Site number	Station identification number	Station name	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Type of station	Drainage area (square miles)	Period of record used (water years)
24	06429920	Bear Gulch near Maurice	44 25 14	104 02 26	M	6.17	--
25	06430520	Beaver Creek near Maurice	44 22 57	104 00 13	M	6.86	--
26	442242103565400	Iron Creek below Sawmill Gulch, near Savoy	44 22 42	103 56 54	M	8.16	--
27	06430800	Annie Creek near Lead	44 19 37	103 53 38	C[1]	3.55	1989-98
28	06430898	Squaw Creek near Spearfish	44 24 04	103 53 35	C[1]	6.95	1989-98
29	06430900	Spearfish Creek above Spearfish	44 24 06	103 53 40	C	139	1989-97
30	06430950	Spearfish Creek below Robison Gulch, near Spearfish	44 26 14	103 52 32	M	8.44	--
31	06431500	Spearfish Creek at Spearfish	44 28 57	103 51 40	C	168	1947-98
32	442754103565000	Higgins Gulch below East Fork, near Spearfish	44 27 54	103 56 50	M	12.55	--
33	442405103485100	False Bottom Creek above Madison outcrop, near Central City	44 24 05	103 48 51	M	5.55	--
34	06432180	False Bottom Creek (below Minnelusa outcrop) near Spearfish	44 27 09	103 48 22	M	8.91	--
35	06433000	Redwater River above Belle Fourche	44 40 02	103 50 20	C[1]	920	1946-98
36	06436170	Whitewood Creek at Deadwood	44 22 48	103 43 25	C	40.6	1981-95
37	06437020	Bear Butte Creek near Deadwood	44 20 08	103 38 06	C	16.6	1989-98
38	442337103350600	Bear Butte Creek at Boulder Park, near Sturgis	44 23 37	103 35 06	M	32.23	--
39	442447103332800	Bear Butte Creek above Sturgis	44 24 47	103 33 28	M	5.59	--

[1]Continuous-record station used only for extension of streamflow records.

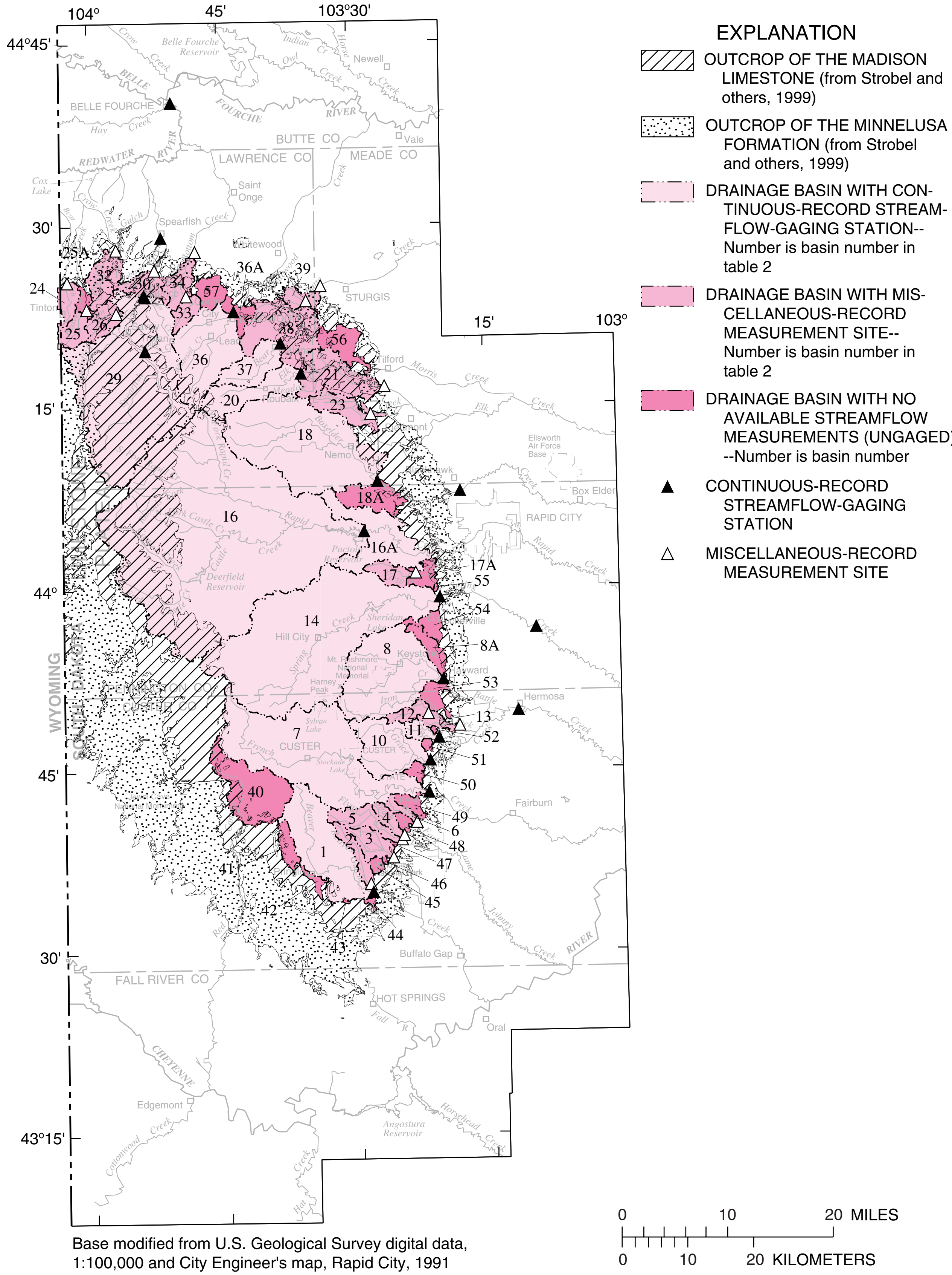


Figure 10. Drainage basins for which streamflow recharge was estimated.

Recharge from Gaged Streams

Gaged streams include basins with either continuous- or miscellaneous-record measurement sites. A summary of loss thresholds and drainage areas for gaged streams is provided in table 2. Loss threshold values for the gaged streams are from Hortness and Driscoll (1998), with the exception of six streams for which loss thresholds were adjusted (table 2), as previously described. Additional details regarding adjustment of loss thresholds are provided in subsequent discussions for individual streams. Loss threshold values denoted in table 2 with less than (<) or greater than (>) are not clearly defined, but are used in subsequent calculations without adjustment. Drainage areas are adjusted where applicable by subtracting any "connected" outcrop areas of the Madison Limestone and Minnelusa Formation, as previously described.

Continuous-Record Gaging Stations

Annual streamflow recharge is determined for 11 of the 13 basins with continuous streamflow records (fig. 10). Basins 16 and 16A are considered together for recharge calculations. Losses are not calculated for Whitewood Creek (basin 36) because the loss threshold is considered negligible (Hortness and Driscoll, 1998). Recharge calculations for five of the continuous-record basins (Battle, Boxelder, Elk, Spearfish, and Bear Butte Creeks) involve consideration of four miscellaneous-record basins (numbers 21, 30, 38, and 39) and two ungaged basins (numbers 8A and 18A). Thus, these six basins will not be included in subsequent sections addressing miscellaneous-record sites and ungaged streams.

Calculated Streamflow Recharge

Daily recharge to the Madison and Minnelusa aquifers is calculated using available records of daily flow for 11 continuous-record gages along with measured loss thresholds for these streams, using the general methods previously described. The daily recharge rates are aggregated to yield annual rates for each year of record. Details of recharge calculations follow, with results for all 11 streams summarized later in this section.

Beaver Creek (basin 1) and French Creek (basin 7) require no adjustments to drainage areas or loss thresholds (table 2). Individual losses to the Madison and Minnelusa are calculated for French Creek because individual loss thresholds have been determined. For Beaver Creek, an estimated average flow of 0.2 ft^3/s is used for the entire month of October 1992 because a complete record was not available.

The loss threshold for Battle Creek (basin 8) is adjusted (table 2) to include runoff generated in an ungaged tributary (basin 8A) using a drainage-area ratio of 1.1. This ratio is used to adjust measured flows reported by Hortness and Driscoll (1998) for site 8, which is used to adjust the loss threshold. The ratio also is used to generate a synthetic record of daily mean flows for site 8 that accounts for the increased drainage area.

No adjustments are needed for Grace Coolidge Creek (basin 10). Individual recharge rates are calculated for the Madison and Minnelusa aquifers for this basin.

The gaging station for Bear Gulch (basin 11) is located downstream of the loss zone and any flow measured at this gaging station must be flow that exceeded the loss threshold value of 0.4 ft^3/s. For days of zero flow, it is not known how much flow, if any, is recharge to the Madison aquifer. Thus, for calculation purposes, recharge is assumed equal to one-half the loss threshold, or 0.2 ft^3/s. For days with measured flow (greater than 0), the calculated recharge to the Madison aquifer is 0.4 ft^3/s.

Hortness and Driscoll (1998) concluded that sealing efforts along Spring Creek (basin 14) probably succeeded in reducing losses, based on reports by Powell (1940). Information regarding possible changes in loss rates is extremely sparse; thus, individual loss rates reported by Hortness and Driscoll (1998) for the Madison and Minnelusa aquifers are used for all calculations. This may result in overestimation of actual recharge for some years.

The Rapid Creek drainage is divided into two basins (fig. 10). Basin 16A is located downstream from site 16 (fig. 9), which measures releases from Pactola Dam. Releases generally are larger than the loss threshold of 10 ft^3/s; therefore, tributary inflows generally are inconsequential. From 1947 through 1998, the flow below Pactola Dam was less than the loss threshold only about 7 percent of the time (1,278 days out of 18,993 days). During periods of low flow, minimal tributary inflows would be expected; thus, inflows from basin 16A are neglected in calculating recharge from Rapid Creek.

Table 2. Summary of loss thresholds and associated drainage areas of selected streams

[Associated station type: C, continuous-record; M, miscellaneous-record; UG, ungaged. ft^3/s, cubic feet per second; mi^2, square miles; >, greater than; <, less than; e, estimated; --, none used; ND, not determined; NA, not applicable]

Basin number	Stream name	Associated station type	Drainage area (mi^2)	Adjusted drainage area[1] (mi^2)	Loss threshold[2] (ft^3/s)	Adjusted loss threshold (ft^3/s)	Aquifers potentially receiving recharge
1	Beaver Creek	C	45.8	--	5	--	Madison, Minnelusa, Minnekahta
2	Reaves Gulch	M	6.86	--	>0.2	--	Madison
3	Highland Creek	M	8.69	--	e10	--	Madison, Minnelusa, Minnekahta
4	South Fork Lame Johnny Creek	M	4.34	--	1.4	--	Madison, Minnelusa
5	Flynn Creek	M	10.3	--	([3])		
6	North Fork Lame Johnny Creek	M	2.80	--	2.3	--	Deadwood, Madison
7	French Creek	C	105	--	11 4	--	Madison Minnelusa
8	Battle Creek	C	58	--	12	14	Madison
8A	Battle Creek tributary	UG	6.59	5.33	([3])		
10	Grace Coolidge Creek	C	25.2	--	18 3	--	Madison Minnelusa
11	Bear Gulch	C	4.23	--	.4	--	Deadwood, Madison, White River Group
12	Spokane Creek	M	4.92	--	2.2	3.7	Deadwood, Madison, Minnelusa, Minnekahta
13	Spokane Creek	M	3.76	2.52	([3])		
14	Spring Creek	C	163	--	21 3.5	--	Madison Minnelusa
16	Rapid Creek	C	320	--	10	--	Deadwood, Madison, Minnelusa
16A	Rapid Creek	C	33.33	--	([3])		
17	Victoria Creek	M	6.82	--	1	2.1	Deadwood, Madison
17A	Victoria Creek	UG	5.33	4.27	([3])		
18	Boxelder Creek	C	96	90	>25 <20	--	Madison Minnelusa
18A	Boxelder Creek tributary	UG	13.3	--	([3])		
20	Elk Creek	C	21.5	--	11 8	--	Madison Minnelusa
21	Elk Creek	M	23.8	12.1	([3])		
23	Little Elk Creek	M	12.56	--	0.7 2.6	--	Madison Minnelusa
24	Bear Gulch	M	6.17	--	4	--	Deadwood, Madison, Minnelusa
25	Beaver Creek	M	6.86	--	9	13	Deadwood, Madison, Minnelusa, Minnekahta
25A	Beaver Creek	UG	2.90	2.15	ND		
26	Iron Creek	M	8.16	--	0	--	NA

Table 2. Summary of loss thresholds and associated drainage areas of selected streams–Continued

[Associated station type: C, continuous-record; M, miscellaneous-record; UG, ungaged. ft^3/s, cubic feet per second; mi^2, square miles; >, greater than; <, less than; e, estimated; --, none used; ND, not determined; NA, not applicable]

Basin number	Stream name	Associated station type	Drainage area (mi^2)	Adjusted drainage area[1] (mi^2)	Loss threshold[2] (ft^3/s)	Adjusted loss threshold (ft^3/s)	Aquifers potentially receiving recharge
29	Spearfish Creek	C	139	--	[4]2	--	Madison, Minnelusa
30	Spearfish Creek	M	8.44	--	[5]21	--	Madison, Minnelusa
32	Higgins Gulch	M	12.55	--	0	--	NA
33	False Bottom Creek	M	5.55	--	1.4 7.3	2.9 15.1	Madison Minnelusa
34	False Bottom Creek	M	8.91	4.92	ND		
36	Whitewood Creek	C	40.6	--	0	--	NA
36A	Whitewood Creek	UG	5.15	--			
37	Bear Butte Creek	C	16.6	--	3.8 4.1	--	Madison Minnelusa
38	Bear Butte Creek	M	32.23	19.2			
39	Bear Butte Creek	M	5.59	3.33	4.2		Minnelusa

[1]Outcrop areas of the Madison Limestone and Minnelusa Formation that are considered to contribute to the regional basin were subtracted.
[2]From Hortness and Driscoll, 1998.
[3]Basin has common loss zone with preceding basin; same loss thresholds and aquifers apply.
[4]Loss within diversion aqueduct.
[5]Threshold loss when flow in Spearfish Creek exceeds the estimated capacity of the diversion aqueduct (115 to 135 ft^3/s).

Recharge calculations from Boxelder Creek (basin 18) are complicated by tributary inflows from basin 18A, springflow that occurs within the loss zone, and an isolated outcrop of the Madison Limestone that occurs within the reach largely underlain by the Minnelusa Formation. Hortness and Driscoll (1998) estimated the loss threshold to be greater than 25 ft^3/s for the Madison aquifer and probably less than 20 ft^3/s for the Minnelusa aquifer because recharge that may occur to the isolated outcrop of the Madison Limestone cannot be quantified. Calculations of the combined recharge to the Madison and Minnelusa aquifers probably are more accurate than the individual recharge estimates.

Daily mean flows for site 18 (Boxelder Creek near Nemo) are used to generate a synthetic record of daily mean flows that accounts for runoff generated in the ungaged area that is tributary to Boxelder Creek (basin 18A), using a drainage-area ratio of 1.1. This synthetic record is used to estimate individual and combined recharge to the Madison and Minnelusa aquifers.

Inflows to Elk Creek from tributaries in basin 21, which are located downstream from site 20, are not included in the measured flow at site 20; however, these tributaries were considered by Hortness and Driscoll (1998) in determining the loss threshold. The contribution of the tributaries is estimated using a drainage-area ratio of 1.56, which is the sum of the adjusted drainage areas for sites 20 and 21, divided by the drainage area for site 20. Individual losses to the Madison and Minnelusa aquifers are calculated.

Calculation of recharge from Spearfish Creek is complicated by a hydroelectric diversion installed by Homestake Mining Company in 1910 (Blackstone, 1914). An aqueduct diverts flow from a diversion dam located just downstream from site 29 (fig. 9). Flow is returned to Spearfish Creek at a hydroelectric plant located just upstream from site 31. The aqueduct bypasses the loss zone along Spearfish Creek, which is located between sites 30 and 31. The maximum capacity of the aqueduct diversion was estimated by Hortness and Driscoll (1998) to be between 115 to 135 ft^3/s. Above this threshold, excess flows are carried to the loss zone along the natural channel of Spearfish Creek, which has a loss threshold of 21 ft^3/s (table 2). A transmission loss of approximately 2 ft^3/s, which is assumed to recharge the Madison and Minnelusa aquifers, occurs in the aqueduct (Hortness and Driscoll, 1998).

In calculating recharge from Spearfish Creek, a constant transmission loss of 2 ft^3/s in the aqueduct is assumed. Routine losses also occur in the natural channel from tributary inflows and springflow in the reach between sites 29 and 30 (basin 30). Numerous miscellaneous flow measurements are available for site 30, which are used to develop a synthetic daily record, based on correlations with daily flow records for site 29. A linear regression analysis using measured values for site 30 for 1988-97 yielded a poor R^2 (coefficient of determination) value (R^2=0.35), but performed well for predicting low to moderate flows. A second regression was performed using only the period 1988-93, which was dominated by low to moderate flows. The second regression equation was similar to the first, but the resulting R^2 value was much higher (R^2=0.84). Because the flows at site 30 only are important during low to moderate flows, the second equation [Flow (site 30) = 0.0916*Flow(site 29) - 0.79] is used to generate a synthetic record from 1950-98 using daily mean flows at site 29.

Additional recharge occurs in the natural channel when the flow of Spearfish Creek exceeds the estimated maximum diversion of 115 to 135 ft^3/s. Daily flow values for site 31 are adjusted for the transmission loss (2 ft^3/s) and natural-channel loss (21 ft^3/s), as necessary, for computing daily losses. When the flow at site 31 is less than 113 ft^3/s, it is assumed that the flow upstream of the aqueduct diversion is less than 115 ft^3/s, with no flow bypassing the diversion. When flow exceeds 133 ft^3/s, it is assumed that flow upstream of the aqueduct diversion is greater than 156 ft^3/s and has exceeded the capacity of the aqueduct and the loss threshold of the natural channel; thus, calculated recharge is 21 ft^3/s in the natural channel. When the flow is between 113 and 133 ft^3/s, it is assumed that the flow upstream has exceeded the capacity of the aqueduct but has not exceeded the loss threshold. For these cases, it is estimated that one-half the loss threshold, or 10.5 ft^3/s, is recharged in the natural channel.

Inflows to Bear Butte Creek from major tributaries in basins 38 and 39, which are located downstream from site 37, are not included in the measured flow at site 37. Tributaries were considered, however, by Hortness and Driscoll (1998) in determining loss thresholds to the Madison and Minnelusa aquifers. Thus, no adjustments are made to the loss thresholds (table 2); however, contributions of tributaries within basins 38 and 39 are accounted for in estimating streamflow recharge within the Bear Butte Creek Basin. Basin 38 consists of outcrops of the Madison Limestone and Minnelusa Formation, intermixed with various other outcrops. Thus, it is assumed that 90 percent of flow generated within this basin would be streamflow recharge, which is assumed to be equally divided between the Madison and Minnelusa aquifers. The contribution for basin 39 is attributed entirely to the Minnelusa aquifer. The contributions of the tributaries within basins 38 and 39 are estimated using drainage-area ratios. Adjusted drainage areas for both basins are divided by the drainage area of basin 37, which yields 1.16 for basin 38 and 0.20 for basin 39. These values then are multiplied by the daily mean flow for site 37 to generate a synthetic record of daily mean flows for the entire period of record for both basin 38 and basin 39.

Annual recharge rates for the 11 streams with continuous-record gaging stations are summarized in table 3, which is ordered by length of available streamflow record for subsequent analyses. The shaded cells in table 3 indicate years for which recharge can be calculated directly from daily flow records, which includes at least 1992-98 for all 11 streams. Estimates for periods without daily records also are presented in table 3 (unshaded cells); methods used for deriving the estimates are described in a subsequent section (Extrapolation of Streamflow Recharge Estimates). Table 3 also provides a subtotal of annual recharge from 9 of the streams that have minimal effects from regulation, along with the total for all 11 streams.

Annual recharge for the streams with continuous-record gaging stations is highly variable. For example, calculated recharge in 1997 is over three times greater than in 1992 (table 3). The proportions of annual streamflow recharge contributed by each of the nine individual streams with minimal regulation, relative to the subtotal for these nine streams, is fairly uniform, however, as shown in table 4. Rapid Creek and Spearfish Creek, which are subject to substantial regulation, are excluded from that analysis. Annual recharge rates for Rapid Creek and Spearfish Creek are quite consistent relative to other basins (table 3), which would indicate large variability in percentage contribution for these two streams.

Table 3. Annual recharge for basins with continuous-record stations, water years 1950-98

[Shaded cells show calculated values for period of daily flow record. Unshaded cells show values derived from extrapolation of streamflow recharge estimates. --, not determined]

Water year	Annual recharge (cubic feet per second)												
	Rapid Creek (basins 16 and 16A)	Spearfish Creek (basins 29 and 30)	Battle Creek (basins 8 and 8A)	Boxelder Creek (basins 18 and 18A)	Grace Coolidge Creek (basin 10)	French Creek (basin 7)	Spring Creek (basin 14)	Bear Butte Creek (basins 37, 38, 39)	Bear Gulch (basin 11)	Beaver Creek (basin 1)	Elk Creek (basins 20 and 21)	Subtotal[1]	Total[2]
1950	10.00	5.14	3.50	9.89	2.22	4.22	6.33	8.62	0.36	1.74	7.62	44.50	59.64
1951	9.96	4.65	3.36	8.14	2.34	3.87	5.91	7.72	.35	1.22	7.06	39.96	54.57
1952	9.98	5.58	5.01	12.70	3.97	5.05	18.95	9.61	.33	.81	7.26	63.67	79.23
1953	10.00	5.83	3.84	11.46	2.27	4.33	11.93	8.79	.36	1.81	7.72	52.51	68.34
1954	10.00	4.84	3.01	7.19	1.80	3.31	2.22	7.47	.35	1.17	6.79	33.32	48.16
1955	10.00	5.48	2.87	7.28	1.71	3.53	0.00	7.80	.36	1.51	7.15	32.21	47.69
1956	9.97	4.71	3.06	6.60	1.98	3.21	3.74	7.00	.34	.86	6.51	33.29	47.97
1957	9.02	4.95	5.50	12.90	4.98	5.64	19.99	10.15	.31	.39	7.19	67.05	81.02
1958	8.65	4.81	3.44	7.60	2.48	3.63	6.41	7.48	.33	.81	6.65	38.83	52.29
1959	9.45	4.38	3.01	5.39	1.93	2.64	4.74	6.21	.32	.29	5.82	30.35	44.18
1960	8.71	4.08	2.97	5.55	1.82	2.63	4.58	6.25	.33	.40	5.90	30.41	43.20
1961	9.67	3.70	2.87	4.39	1.72	2.14	4.70	5.56	.31	.00	5.34	27.04	40.41
1962	7.82	4.78	4.43	16.39	4.54	6.36	16.78	12.49	.35	1.64	8.47	71.45	84.05
1963	7.78	6.45	6.61	13.56	4.10	6.07	4.94	12.21	.35	1.80	8.47	58.12	72.35
1964	10.00	6.64	5.61	11.78	2.59	5.17	4.68	10.11	.38	2.39	8.53	51.24	67.88
1965	10.00	8.19	5.79	21.06	5.53	8.58	7.59	17.16	.38	3.07	10.53	79.70	97.89
1966	10.00	6.56	3.94	12.22	2.31	4.85	9.11	9.59	.38	2.34	8.35	53.08	69.64
1967	10.00	6.44	5.18	18.13	4.33	7.05	11.54	11.91	.35	1.72	7.75	67.97	84.41
1968	10.00	5.84	3.84	9.57	2.97	4.22	7.28	9.04	.32	.27	6.05	43.57	59.41
1969	9.99	6.15	3.11	9.18	2.33	3.81	6.21	7.47	.32	.20	5.12	37.76	53.90
1970	10.00	8.26	3.89	16.76	3.18	6.14	9.45	9.14	.35	1.49	6.11	56.50	74.76
1971	10.00	8.02	5.01	19.21	4.21	7.27	11.64	11.55	.35	1.90	7.54	68.68	86.70
1972	9.86	8.01	5.59	18.18	4.68	7.24	12.08	12.78	.35	1.73	8.26	70.89	88.76
1973	10.00	8.72	5.56	16.79	4.63	6.86	11.64	12.73	.35	1.49	8.23	68.29	87.01
1974	10.00	6.63	1.81	6.58	1.15	2.57	3.76	4.69	.31	.00	3.48	24.35	40.98

Table 3. Annual recharge for basins with continuous-record stations, water years 1950-98–Continued

[Shaded cells show calculated values for period of daily flow record. Unshaded cells show values derived from extrapolation of streamflow recharge estimates. --, not determined]

Water year	Annual recharge (cubic feet per second)												
	Rapid Creek (basins 16 and 16A)	Spearfish Creek (basins 29 and 30)	Battle Creek (basins 8 and 8A)	Boxelder Creek (basins 18 and 18A)	Grace Coolidge Creek (basin 10)	French Creek (basin 7)	Spring Creek (basin 14)	Bear Butte Creek (basins 37, 38, 39)	Bear Gulch (basin 11)	Beaver Creek (basin 1)	Elk Creek (basins 20 and 21)	Subtotal[1]	Total[2]
1975	9.99	6.55	3.67	14.89	2.95	5.55	8.62	8.67	0.34	1.17	5.83	51.69	68.23
1976	10.00	6.59	5.16	15.18	4.25	6.27	10.65	11.87	.34	1.22	7.73	62.67	79.26
1977	10.00	6.72	2.93	14.73	1.27	5.20	7.60	7.08	.34	1.14	4.89	45.18	61.90
1978	9.99	7.67	4.46	15.84	3.90	6.14	9.93	10.37	.34	1.33	6.83	59.14	76.80
1979	10.00	6.28	4.13	8.79	3.66	4.14	7.42	9.65	.32	.13	6.41	44.64	60.92
1980	10.00	5.59	2.72	5.94	1.17	2.79	4.76	6.65	.31	.00	4.63	28.98	44.57
1981	10.00	5.03	3.01	4.55	2.45	2.54	4.71	7.25	.31	.00	4.99	29.80	44.83
1982	9.90	6.30	4.14	10.14	3.89	4.50	7.84	9.69	.32	.36	6.43	47.32	63.52
1983	10.00	7.82	3.81	21.64	2.48	7.05	10.78	8.97	.36	2.31	6.01	63.42	81.24
1984	10.00	8.03	4.89	19.63	3.97	6.86	11.60	11.28	.36	1.97	7.37	67.92	85.95
1985	10.00	5.48	1.22	7.17	.82	3.53	3.16	3.42	.31	.00	2.73	22.36	37.84
1986	10.00	5.65	4.32	13.10	2.03	3.63	8.94	10.07	.33	.87	6.66	49.97	65.62
1987	10.00	4.83	6.22	10.92	3.49	5.50	10.64	14.15	.33	.50	9.07	60.82	75.65
1988	10.00	4.92	.76	5.07	.61	2.11	1.80	2.44	.31	.00	2.15	15.25	30.17
1989	10.00	5.03	.89	4.19	1.20	1.02	.98	5.56	.30	.00	2.31	16.46	31.49
1990	10.00	5.04	5.09	6.18	3.40	3.65	6.76	6.76	.33	.00	7.63	39.80	54.84
1991	9.99	4.94	5.15	11.21	4.92	5.63	10.92	11.25	.29	.23	7.71	57.32	72.25
1992	10.00	4.78	3.72	7.57	2.98	4.48	7.46	5.03	.32	.33	4.67	36.55	51.33
1993	10.00	5.26	6.66	18.05	7.12	7.26	13.35	12.76	.34	.76	8.36	74.66	89.92
1994	10.00	6.78	5.21	17.53	3.27	6.02	11.63	14.24	.35	1.35	9.15	68.75	85.53
1995	10.00	8.56	6.17	21.09	7.20	8.91	13.64	21.52	.36	2.77	10.04	91.70	110.26
1996	10.00	9.20	8.10	25.55	6.45	10.92	18.02	18.12	.39	3.98	11.52	103.07	122.27
1997	10.00	10.92	10.50	34.08	9.31	13.07	22.15	25.60	.39	3.89	13.91	132.89	153.81
1998	10.00	9.59	8.26	28.30	7.57	12.12	18.89	15.27	.39	3.56	12.25	106.61	126.20

[1]Subtotal for nine basins with minimal regulation (excludes Rapid and Spearfish Creeks). Individual values may not sum to subtotal due to independent rounding.
[2]Total for all basins. Individual values may not sum to total due to independent rounding.

Table 4. Calculated percentages of annual streamflow recharge for nine streams with minimal regulation, water years 1992-98

[ft^3/s, cubic feet per second; --, not determined]

Water year	Percent of subtotal of annual recharge[1]									Subtotal of annual recharge[2] (ft^3/s)
	Battle Creek (basins 8 and 8A)	Boxelder Creek (basins 18 and 18A)	Grace Coolidge Creek (basin 10)	French Creek (basin 7)	Spring Creek (basin 14)	Bear Butte Creek (basins 37, 38, 39)	Bear Gulch (basin 11)	Beaver Creek (basin 1)	Elk Creek (basins 20 and 21)	
1992	10.17	20.71	8.15	12.27	20.40	13.77	0.88	0.89	12.77	36.55
1993	8.92	24.17	9.54	9.73	17.87	17.10	.46	1.02	11.19	74.66
1994	7.58	25.51	4.75	8.75	16.92	20.72	.51	1.96	13.31	68.75
1995	6.73	23.00	7.86	9.72	14.88	23.47	.39	3.02	10.94	91.70
1996	7.86	24.79	6.26	10.60	17.49	17.58	.38	3.86	11.18	103.07
1997	7.90	25.64	7.01	9.83	16.66	19.26	.29	2.93	10.47	132.89
1998	7.75	26.54	7.10	11.37	17.72	14.32	.37	3.34	11.49	106.61
Average	8.13	24.34	7.24	10.32	17.42	18.03	0.47	2.43	11.62	--

[1]Individual values may not sum to 100 percent because of independent rounding.
[2]Subtotals taken from table 3.

Individual threshold values available for the Madison and Minnelusa aquifers were available for six streams (French, Grace Coolidge, Spring, Boxelder, Elk, and Bear Butte Creeks). Annual recharge rates, by aquifer, are summarized for these streams in table 5.

Extrapolation of Streamflow Recharge Estimates

Calculated streamflow recharge for 1992-98 is not representative of the long-term average because of above-average precipitation during this period (Driscoll, Hamade, and Kenner, 2000). To determine an unbiased average, estimates of recharge over an extended period that includes both above- and below-average precipitation conditions are needed. A record extending back to the 1950's would include these conditions. However, only the records from Rapid Creek and Spearfish Creek extend back to 1950, and the majority of the records do not extend prior to the late 1980's (table 1). This section describes methods used to extrapolate recharge estimates back to 1950 for streams with continuous-record gaging stations.

Of the unregulated streams with continuous-record gages (excluding Rapid Creek and Spearfish Creek), Battle Creek and Boxelder Creek have the longest periods of record. Single and multiple linear regression analyses were performed, using annual recharge from Battle Creek and Boxelder Creek as possible explanatory variables for annual recharge from the other seven streams (data presented in table 3). The best regression equation with either one or both explanatory variables was selected based on the R^2 values and statistical significance of the explanatory variables. Results of the multiple/single regression analyses are summarized in table 6, with resulting R^2 values ranging from 0.69 to 0.99. The equations determined by the multiple/single regression (table 6) were used to extrapolate recharge for the streams with continuous-record gages for years without streamflow records for 1967-91.

The preceding regressions provided satisfactory estimates for missing values during 1967-91. Another method was needed, however, to estimate recharge for 1950-66. Several gaging stations in the Black Hills area that are located downstream of loss zones have continuous records of flow dating back to at least 1950 (Miller and Driscoll, 1998). Four gaging stations (table 1) were selected as possible representative indicators of flow for the nine gages with no records for 1950-67. Locations of Battle Creek at Hermosa (site 9), Spring Creek near Hermosa (site 15), and Redwater River above Belle Fourche (site 35) are shown in figure 9. The location of Elk Creek near Elm Springs (site 22; 06425500) is shown in figure 1.

Table 5. Annual recharge, by aquifer, for streams with continuous-record stations, water years 1967-98

[--, not determined]

Water year	Annual recharge[1] (cubic feet per second)											
	French Creek (basin 7)		Grace Coolidge Creek (basin 10)		Spring Creek (basin 14)		Boxelder Creek[2] (basins 18 and 18A)		Elk Creek (basins 20 and 21)		Bear Butte Creek (basins 37, 38, and 39)	
	Madison	Minnelusa	Madison	Minnelusa	Madison	Minnelusa	Madison	Minnelusa	Madison	Minnelusa	Madison	Minnelusa
1967	--	--	--	--	--	--	13.96	4.17	--	--	--	--
1968	--	--	--	--	--	--	9.50	.07	--	--	--	--
1969	--	--	--	--	--	--	8.60	.59	--	--	--	--
1970	--	--	--	--	--	--	12.40	4.36	--	--	--	--
1971	--	--	--	--	--	--	14.21	4.99	--	--	--	--
1972	--	--	--	--	--	--	14.48	3.70	--	--	--	--
1973	--	--	--	--	--	--	13.82	2.97	--	--	--	--
1974	--	--	--	--	--	--	6.58	.00	--	--	--	--
1975	--	--	--	--	--	--	11.05	3.84	--	--	--	--
1976	--	--	--	--	--	--	12.95	2.23	--	--	--	--
1977	--	--	1.27	0.00	--	--	12.09	2.65	--	--	--	--
1978	--	--	3.66	.24	--	--	12.89	2.95	--	--	--	--
1979	--	--	3.52	.14	--	--	8.74	.05	--	--	--	--
1980	--	--	1.17	.00	--	--	5.93	.01	--	--	--	--
1981	--	--	2.36	.08	--	--	4.55	.00	--	--	--	--
1982	--	--	3.76	.13	--	--	8.66	1.48	--	--	--	--
1983	6.47	0.59	2.49	.00	--	--	17.18	4.45	--	--	--	--
1984	5.82	1.05	3.85	.11	--	--	14.94	4.69	--	--	--	--
1985	3.50	.03	.82	.00	--	--	6.97	.20	--	--	--	--
1986	3.44	.19	2.03	.00	--	--	11.38	1.72	--	--	--	--
1987	5.01	.50	3.49	.00	9.94	0.71	10.10	.82	--	--	--	--
1988	1.95	.16	.60	.01	1.80	.00	5.05	.02	--	--	--	--
1989	1.02	.00	1.18	.02	.98	.01	4.18	.00	--	--	3.19	2.37
1990	3.21	.44	3.31	.09	6.28	.48	6.18	.00	--	--	3.64	3.12
1991	4.85	.79	4.60	.32	9.97	.96	9.05	2.17	--	--	5.65	5.60
1992	4.34	.14	2.98	.00	7.45	.01	7.57	.00	4.61	.06	3.07	1.96
1993	6.02	1.24	6.82	.30	11.99	1.36	13.41	4.64	5.97	2.38	6.22	6.54
1994	5.36	.65	3.27	.00	11.07	.56	13.75	3.78	6.95	2.20	7.23	7.01
1995	7.28	1.63	6.76	.44	12.56	1.08	15.72	5.37	7.91	2.13	10.87	10.65
1996	9.25	1.67	6.27	.19	16.72	1.31	19.00	6.55	8.87	2.65	9.09	9.03
1997	10.39	2.68	8.99	.32	19.72	2.43	22.60	11.48	9.96	3.95	12.60	13.01
1998	9.98	2.14	7.42	.15	16.67	2.22	21.07	7.23	8.97	3.28	7.66	7.61

[1]Individual recharge estimates may not sum exactly to combined estimates in table 3 due to independent rounding.

[2]Individual recharge estimates probably are not as accurate as combined recharge estimates.

Table 6. Regression equations used to estimate average annual streamflow recharge for nine streams with continuous-record stations

[--, not used; all regressions performed using units of cubic feet per second]

Stream	Recharge regression[1] (1967-91)				Streamflow regression[2] (1950-66)					
	Intercept	Battle Creek coefficient	Boxelder Creek coefficient	R^2 for equation	Intercept	Battle Creek at Hermosa coefficient	Spring Creek near Hermosa coefficient	Elk Creek near Elm Springs coefficient	Redwater River above Belle Fourche coefficient	R^2 for equation
Battle Creek	--	--	--	--	2.4377	0.1027	--	0.0149	--	0.6376
Boxelder Creek	--	--	--	--	.6269	.1744	--	.0661	0.0629	.7812
Grace Coolidge Creek	-0.5681	0.8617	0.0239	0.8600	1.5650	.1498	--	--	--	.8300
French Creek	.0618	.4255	.2640	.9504	.2904	.0952	--	--	.0307	.8050
Spring Creek	-.5360	1.3025	.2938	.9859	9.8398	1.2121	-1.2064	.2807	-.1120	.8931
Bear Butte Creek	.8113	2.1422	--	.6932	3.4155	--	.2080	--	.0487	.9121
Bear Gulch	.2911	--	.0033	.7581	.2635	-.0020	--	--	.0009	.8484
Beaver Creek	-1.3553	--	.1696	.8457	-1.9310	-.0531	--	--	.0341	.9053
Elk Creek	1.1810	1.2676	--	.8768	2.4484	--	--	--	.0396	.7175

[1]Regression performed using calculated annual recharge for selected streams (dependent variable) with average annual recharge for Battle Creek and/or Boxelder Creek (explanatory variable).
[2]Stepwise regression performed using calculated annual recharge for selected streams (dependent variable) with annual flow at selected streams (explanatory variable).

A stepwise regression analysis was performed using the average annual mean flow of these four representative streams as possible explanatory variables for annual streamflow recharge for selected streams. The explanatory variables were considered significant only if the p-values (attained level of significance) were less than 0.15. Results of stepwise regression analyses are provided in table 6. The best regression for some of the streams included only one of the four representative gaging stations, whereas the best regression for Spring Creek included all four representative gaging stations. The results of the stepwise regression generally were good with R^2 values ranging from 0.64 to 0.91. The equations determined by the stepwise regression (table 6) were used to estimate recharge for selected streams beginning with 1950.

The recharge estimates based on both the recharge regressions (1967-91) and the stepwise regressions (1950-98) are presented in table 17 in the Supplemental Information section. The calculated recharge rates also are included in table 17 for comparison purposes, along with a summary of mean values for calculated values and estimates for the periods 1950-98, 1967-98, and 1992-98. Comparisons of calculated values and means to estimated values and means for 1992-98 are particularly informative. Differences between calculated and estimated values generally are small and exhibit no apparent bias (consistently lower or higher). It is recognized that large uncertainties exist for estimates for any site for any year. However, these favorable comparisons provide confidence that the methods used provide credible, unbiased estimates. The recharge estimates used in the final streamflow recharge total are presented in table 3.

Miscellaneous-Record Measurement Sites

This section presents estimates of streamflow recharge for 11 basins with miscellaneous-record measurement sites. Daily flow records are not available for these basins; however, loss thresholds (table 2) were determined by Hortness and Driscoll (1998). Four basins with miscellaneous-record measurement sites (basins 21, 30, 38, and 39) were considered earlier with continuous-record gaging stations. Hortness and Driscoll (1998) determined that Iron Creek (basin 26) and Higgins Gulch (basin 32) are gaining streams across the outcrops of the Madison Limestone and Minnelusa Formation; therefore, no recharge is calculated for these two sites.

Loss thresholds are adjusted for Spokane Creek, Victoria Creek, Beaver Creek, and False Bottom Creek (table 2) using the methods previously described. The loss thresholds for Victoria Creek and Beaver Creek include losses from ungaged areas (basins 17A and 25A). Therefore, these ungaged areas are included with the following analyses and will not be included in a subsequent section addressing ungaged streams.

Annual recharge was calculated by applying previously determined loss thresholds against synthetic records of daily flow. A representative continuous-record gaging station was selected for each miscellaneous-record basin based on proximity, streamflow characteristics, and elevation. Daily flow records were synthesized by applying drainage-area ratios to daily flows for the representative continuous-record gages. Representative gaging stations and drainage-area ratios, which are based on adjusted drainage areas, are listed in table 7. In several cases, two basins associated with the same stream are combined for calculation of recharge. Individual recharge to the Madison and Minnelusa aquifers is determined for two basins.

Annual recharge from the miscellaneous-record basins is summarized in table 8 for 1992-98. The miscellaneous-record basins in the northern Black Hills (Little Elk, Bear Gulch, Beaver, and False Bottom) generally provide more recharge than those in the central or southern Black Hills. Estimates of recharge from these basins for 1950-91 are presented in a subsequent section (Summary of Streamflow Recharge, 1950-98).

Table 7. Summary of selected information used to estimate recharge from streams with miscellaneous-record measurement sites

Stream name and basin number	Representative continuous-record gaging station	Drainage-area ratio
Reaves Gulch (2)	French Creek (site 7)	0.065
Highland Creek (3)	French Creek (site 7)	.083
South Fork Lame Johnny Creek and Flynn Creek (4 and 5)	French Creek (site 7)	.139
North Fork Lame Johnny Creek (6)	French Creek (site 7)	.027
Spokane Creek (12 and 13)	Battle Creek (site 8)	.128
Victoria Creek (17 and 17A)	Battle Creek (site 8)	.191
Little Elk Creek (23)	Boxelder Creek (site 18)	.131
Bear Gulch (24)	Annie Creek (site 27)	1.74
Beaver Creek (25 and 25A)	Squaw Creek (site 28)	1.30
False Bottom Creek (33 and 34)	Squaw Creek (site 28)	1.50

Table 8. Annual recharge for streams with miscellaneous-record measurement sites, water years 1992-98

Water year	Annual recharge (cubic feet per second)										
	Reaves Gulch (basin 2)	Highland Creek (basin 3)	South Fork Lame Johnny Creek and Flynn Creek (basins 4 and 5)	North Fork Lame Johnny Creek (basin 6)	Spokane Creek (basins 12 and 13)	Victoria Creek (basins 17 and 17A)	Little Elk Creek (basin 23)	Bear Gulch (basin 24)	Beaver Creek (basins 25 and 25A)	False Bottom Creek (basins 33 and 34)	Total[1]
1992	0.17	0.37	0.60	0.12	0.45	0.64	0.90	0.56	1.23	1.46	6.50
1993	.15	.96	.79	.30	1.14	1.06	1.69	1.36	3.16	3.88	14.49
1994	.17	.59	.72	.19	.65	.88	1.72	1.50	2.97	3.66	13.05
1995	.19	2.27	.95	.63	1.24	1.13	1.96	2.27	5.07	6.27	21.98
1996	.20	1.45	1.22	.46	1.17	1.33	2.39	1.79	5.08	6.36	21.45
1997	.20	2.01	1.34	.64	1.79	1.67	2.89	2.13	4.75	5.92	23.36
1998	.20	1.59	1.30	.51	1.25	1.33	2.67	2.25	3.33	4.01	18.45

[1]Individual estimates may not sum to total due to independent rounding.

Annual recharge rates, by aquifer, are presented in table 9 for the two miscellaneous-record measurement sites for which individual loss thresholds had been determined by Hortness and Driscoll (1998). For both Little Elk Creek and False Bottom Creek, annual recharge estimates for the Madison aquifer were relatively consistent for 1992-98; whereas, recharge for the Minnelusa aquifer in 1992 was much smaller than in the other years. This is because most of the flow in 1992 was lost to the Madison aquifer before reaching the outcrop of the Minnelusa Formation.

Recharge from Ungaged Streams

Ungaged basins generally consist of small drainage areas with undetermined loss thresholds that are situated between larger basins for which loss thresholds have been determined (fig. 10). Recharge for five ungaged basins were considered earlier with either continuous-record gaging stations (basins 8A, 18A, and 36A) or miscellaneous-record measurement sites (basins 17A and 25A). Flow seldom occurs downstream from the loss zones in these small basins; thus, a simplifying assumption is made that 90 percent of streamflow generated within these basins becomes recharge to the Madison and Minnelusa aquifers. Annual streamflow for selected representative continuous-record gages is used to estimate annual streamflow in the ungaged streams based on the ratio of drainage areas.

Table 9. Annual recharge, by aquifer, for streams with miscellaneous-record measurement sites, water years 1992-98

Water year	Annual recharge[1] (cubic feet per second)			
	Little Elk Creek (basin 23)		False Bottom Creek (basins 33 and 34)	
	Madison	Minnelusa	Madison	Minnelusa
1992	0.66	0.24	1.17	0.29
1993	.59	1.11	1.63	2.25
1994	.70	1.03	1.69	1.98
1995	.70	1.27	2.43	3.84
1996	.70	1.70	2.49	3.87
1997	.70	2.19	2.59	3.33
1998	.70	1.99	1.97	2.04

[1]Individual recharge estimates may not sum exactly to combined estimates in table 8 due to independent rounding.

Four continuous-record gages were selected to represent streamflow in 18 ungaged basins (fig. 11), with each ungaged basin assigned to one of the representative gages. The drainage areas for all ungaged basins associated with each gage were summed, and common drainage-area ratios were computed. Annual streamflow for 1992-98 for each of the representative gages was then multiplied by the applicable ratio to yield annual streamflow for each group of ungaged basins. Annual recharge for the ungaged basins (computed as 90 percent of streamflow) is summarized by group in table 10. Estimates of recharge from ungaged basins for 1950-91 are addressed in the following section.

Table 10. Annual streamflow recharge from ungaged basins, water years 1992-98

[--, not determined]

Water year	Annual recharge (cubic feet per second)					
	Ungaged basins and representative continuous-record stations					Total[1]
	Basins 40-50 (French Creek)	Basins 51-55 (Battle Creek)	Basin 56 (Bear Butte Creek)	Basin 57 (Squaw Creek)	Wyoming basins	
1992	2.02	0.67	1.31	0.89	3.58	8.47
1993	5.29	2.91	4.36	2.83	9.04	24.42
1994	3.11	.97	5.03	3.52	8.94	21.58
1995	15.30	5.33	8.41	7.60	14.68	51.33
1996	7.76	2.77	6.53	4.96	13.74	35.76
1997	10.89	4.56	9.79	5.38	13.76	44.38
1998	8.60	2.48	4.86	3.02	11.16	30.12
Combined area (square miles)	51.47	12.41	10.55	6.96	--	--

[1]Individual recharge estimates may not sum to total due to independent rounding.

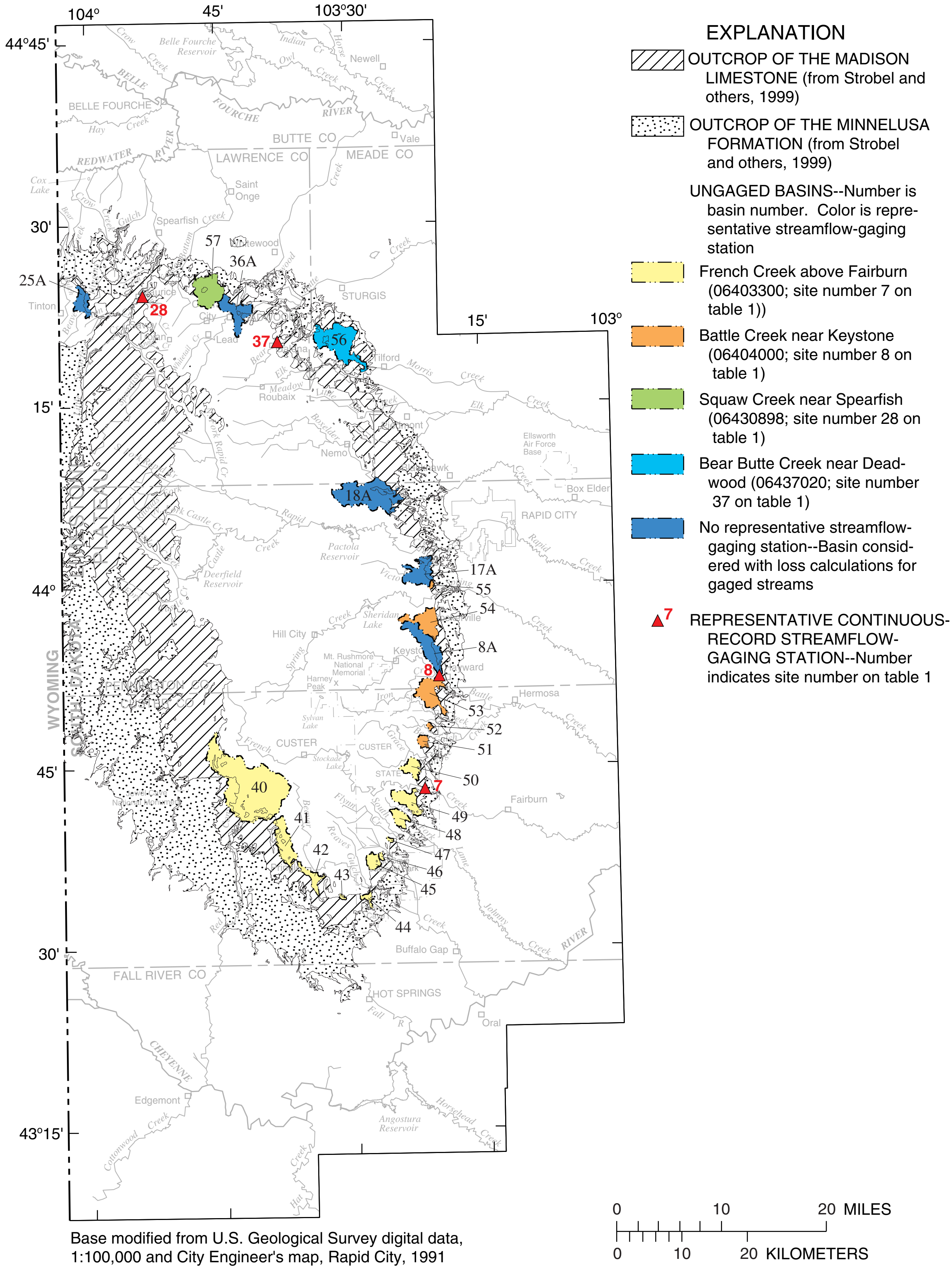


Figure 11. Assignment of representative streamflow-gaging stations for ungaged streams.

In addition to the 18 ungaged basins in South Dakota, there are several small areas in Wyoming where the Madison and Minnelusa aquifers probably receive recharge from streams originating on outcrops of Tertiary intrusives. No information regarding the streamflow characteristics, loss thresholds, or basin delineation for recharge purposes is available regarding these areas. The small outcrop areas are approximately twice as large as combined drainage areas for the miscellaneous-record measurement sites of Bear Gulch (basin 24) and Beaver Creek (basins 25 and 25A), with similar elevations. Thus, it is assumed that streamflow recharge in Wyoming is equal to twice the sum of estimated recharge in Bear Gulch and Beaver Creek (table 8) basins. The recharge estimated for the Wyoming basins also is presented in table 10.

Summary of Streamflow Recharge, 1950-98

Estimates of annual streamflow recharge from streams with continuous-record gaging stations are complete from 1950-98. Estimates for basins with miscellaneous-record measurement sites and ungaged streams are complete only for 1992-98; thus, recharge estimates need to be extrapolated to calculate combined streamflow recharge from all sources for 1950-98.

Combined streamflow recharge for all sources (excluding Rapid and Spearfish Creeks) for 1992-98 is provided in table 11, along with the annual percentages of combined recharge for each of the three types of basins. The annual percentages for each basin type are relatively uniform in comparison to combined recharge, which varies considerably. Streams with continuous-record gages (excluding Rapid and Spearfish Creeks) account for about 65 percent of combined recharge, the miscellaneous-record streams account for about 13 percent, and ungaged streams account for about 22 percent (table 11). These average percentages are used in estimating recharge for the period 1950-91 for the miscellaneous-record and ungaged streams. First, the subtotal of annual recharge for the nine continuous-record streams with minimal regulation (table 3) was divided by 0.65 (representing 65 percent) to estimate combined streamflow recharge from all sources (excluding Rapid and Spearfish Creeks). This figure was multiplied by 13 percent to estimate annual recharge for the miscellaneous-record streams, and by 22 percent for the ungaged streams to complete estimates for 1950-91.

Estimates of total streamflow recharge for 1950-98, including recharge attributed to Rapid Creek and Spearfish Creek, are presented in table 12. Streamflow recharge for 1950-98 averages about 98 ft^3/s and

Table 11. Estimated streamflow recharge for selected continuous-record, miscellaneous-record, and ungaged basins, water years 1992-98

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

Water year	Continuous record[1]		Miscellaneous record		Ungaged		Combined recharge (ft^3/s)
	Annual recharge (ft^3/s)	Percent of combined recharge[2]	Annual recharge (ft^3/s)	Percent of combined recharge[2]	Annual recharge (ft^3/s)	Percent of combined recharge[2]	
1992	36.55	70.95	6.50	12.62	8.47	16.44	51.52
1993	74.66	65.74	14.49	12.76	24.42	21.50	113.57
1994	68.75	66.50	13.05	12.62	21.58	20.88	103.38
1995	91.70	55.57	21.98	13.32	51.33	31.11	165.01
1996	103.07	64.31	21.45	13.38	35.76	22.31	160.28
1997	132.89	66.24	23.36	11.64	44.38	22.12	200.63
1998	106.61	68.70	18.45	11.89	30.12	19.41	155.18
Average	87.75	65.43	17.04	12.60	30.87	21.97	135.66

[1]Excluding recharge from Rapid Creek and Spearfish Creek.
[2]Individual values may not sum to 100 percent due to independent rounding.

has ranged from about 38 ft^3/s in 1988 to about 222 ft^3/s in 1997. Of these amounts, the combined contributions from Rapid and Spearfish Creeks average about 16 percent and have ranged from 9 to 39 percent. The highest annual recharge rates generally occurred during the late 1990's; thus, the earlier presumption (based on above-average precipitation) that using recharge estimates for 1992-98 would overestimate long-term streamflow recharge is substantiated.

Moving averages for 3-, 5-, and 10-year periods also are shown in table 12. These moving averages are useful for identifying multi-year trends in streamflow recharge. Some of the lowest recharge rates occurred during the early 1960's, early 1980's, and late 1980's based on the 3-year averages (table 12).

PRECIPITATION RECHARGE

Infiltration of precipitation on outcrops of the Madison Limestone and Minnelusa Formation provides recharge to the Madison and Minnelusa aquifers. Precipitation in the study area increases from south to north and with increasing elevation as shown in the isohyetal map for water years 1950-98 (fig. 12). This map was derived from 1,000-by-1,000-meter grids based on precipitation data presented by Driscoll, Hamade, and Kenner (2000), who used a geographic information system (GIS) to generate spatial precipitation distributions from point precipitation data for 94 gages in the Black Hills area.

An overview of processes involved and assumptions made in estimating precipitation recharge was presented in a previous section discussing methods for quantifying precipitation recharge. In general, yield efficiencies (the ratio of basin yield to precipitation) are computed for selected drainage basins and are used to generate a map of generalized average yield efficiency for the Black Hills area. A simplifying assumption is made that yield efficiency is a reasonable surrogate for the efficiency of precipitation recharge to the Madison and Minnelusa aquifers. Relations between annual yield efficiency and annual precipitation are used to develop an algorithm for computing annual yield, as a surrogate for recharge, based on annual precipitation for 1,000-by-1,000-meter grids. The method is used to estimate annual precipitation recharge for 1931-98.

Yield Efficiency

Annual yields, which are calculated by dividing annual streamflow by drainage area and converting to inches, have been determined for 20 selected gaging stations (fig. 13) for the periods of record shown in table 13. Effects from various forms of regulation such as withdrawals or diversions generally are relatively minor for these stations; thus, streamflow records are reasonably representative of basin yield. Annual yields generally increase from south to north, with the largest yields occurring in streams draining the higher elevations of the northern Black Hills. These variations in annual yield are consistent with climatic patterns for the Black Hills area, including: (1) increasing precipitation from south to north; (2) increasing precipitation with increasing elevation; and (3) decreasing evapotranspiration rates with increasing elevation (Miller and Driscoll, 1998).

The annual yields listed in table 13 and shown in figure 13 cannot be directly compared because of large differences in periods of record. Measured yields for many of the stations with short periods of record are representative of extremely wet climatic conditions that have prevailed since about 1990. In addition, basin yields are calculated from surface drainage areas, which are not necessarily congruent with contributing ground-water areas. Drainage basins where streamflow is known to be dominated by ground-water discharge (fig. 6) include Rhoads Fork, Castle Creek, Spearfish Creek, and Little Spearfish Creek (sites 9, 10, 13, and 15 in table 13). Jarrell (2000) documented incongruences in contributing surface- and ground-water areas for these basins based on structure contours of the top of the Deadwood Formation. The most notable differences in annual yield (fig. 13) are for Rhoads Fork and Castle Creek, which are located in close proximity (fig. 13) and have similar precipitation patterns (fig. 12).

Yields in the Spearfish Creek basins generally resemble yields of other nearby basins. The yield of Annie Creek (site 14) is somewhat lower than adjacent basins, which could result from extensive mining activities within the basin, which utilize substantial quantities of water through evaporation for heap-leach processes.

Table 12. Estimated total streamflow recharge, in cubic feet per second, from all sources, water years 1950-98

[--, not computed]

Water year	Annual recharge						Moving averages for total streamflow recharge		
	Continuous-record streams			Miscel-laneous-record streams	Ungaged streams	Total[2]	3-year average	5-year average	10-year average
	Rapid Creek	Spearfish Creek	Others[1]						
1950	10.00	5.14	44.50	9.59	10.27	79.50	--	--	--
1951	9.96	4.65	39.96	7.99	13.53	76.09	--	--	--
1952	9.98	5.58	63.67	12.73	21.55	113.52	89.70	--	--
1953	10.00	5.83	52.51	10.50	17.77	96.62	95.41	--	--
1954	10.00	4.84	33.32	6.66	11.28	66.10	92.08	86.37	--
1955	10.00	5.48	32.21	6.44	10.90	65.04	75.92	83.47	--
1956	9.97	4.71	33.29	6.66	11.27	65.90	65.68	81.43	--
1957	9.02	4.95	67.05	13.41	22.69	117.12	82.68	82.15	--
1958	8.65	4.81	38.83	7.77	13.14	73.20	85.41	77.47	--
1959	9.45	4.38	30.35	6.07	10.27	60.53	83.61	76.36	81.36
1960	8.71	4.08	30.41	6.08	10.29	59.57	64.43	75.26	79.37
1961	9.67	3.70	27.04	5.41	9.15	54.97	58.36	73.08	77.26
1962	7.82	4.78	71.45	14.29	24.18	122.52	79.02	74.16	78.16
1963	7.78	6.45	58.12	11.62	19.67	103.64	93.71	80.25	78.86
1964	10.00	6.64	51.24	10.25	17.34	95.48	107.21	87.24	81.80
1965	10.00	8.19	79.70	15.94	26.97	140.80	113.31	103.48	89.37
1966	10.00	6.56	53.08	10.62	17.97	98.23	111.50	112.13	92.61
1967	10.00	6.44	67.97	13.59	23.00	121.00	120.01	111.83	92.99
1968	10.00	5.84	43.57	8.71	14.75	82.87	100.70	107.68	93.96
1969	9.99	6.15	37.76	7.55	12.78	74.24	92.70	103.43	95.33
1970	10.00	8.26	56.50	11.30	19.12	105.19	87.43	96.31	99.89
1971	10.00	8.02	68.68	13.74	23.24	123.68	101.03	101.40	106.76
1972	9.86	8.01	70.89	14.18	23.99	126.93	118.60	102.58	107.20
1973	10.00	8.72	68.29	13.66	23.11	123.78	124.79	110.76	109.22
1974	10.00	6.63	24.35	4.87	8.24	54.09	101.60	106.73	105.08
1975	9.99	6.55	51.69	10.34	17.50	96.06	91.31	104.91	100.61
1976	10.00	6.59	62.67	12.53	21.21	113.01	87.72	102.77	102.08
1977	10.00	6.72	45.18	9.04	15.29	86.23	98.43	94.63	98.61
1978	9.99	7.67	59.14	11.83	20.02	108.65	102.63	91.61	101.19

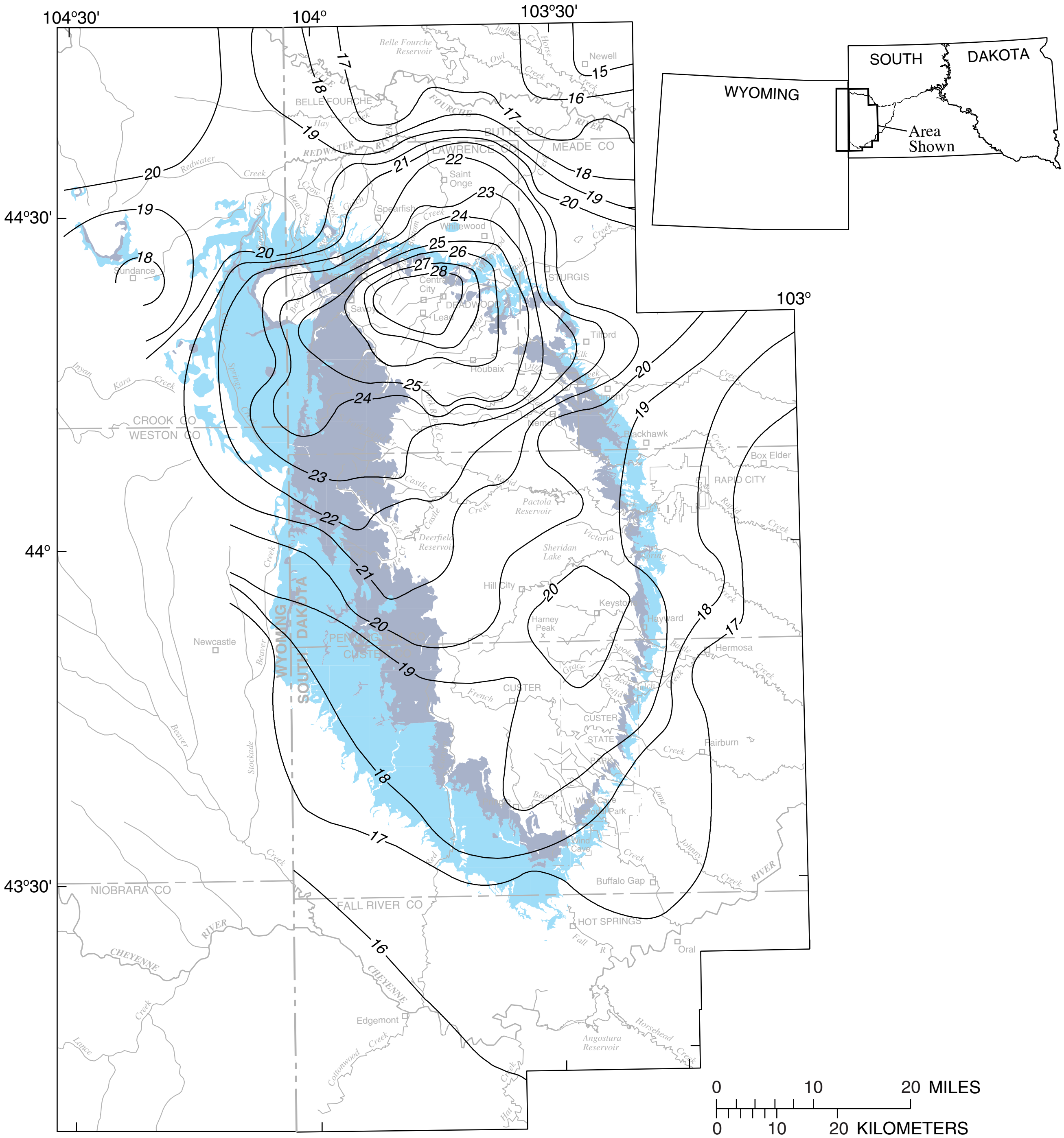
Table 12. Estimated total streamflow recharge, in cubic feet per second, from all sources, water years 1950-98–Continued

[--, not computed]

Water year	Annual recharge						Moving averages for total streamflow recharge		
	Continuous-record streams			Miscel-laneous-record streams	Ungaged streams	Total[2]	3-year average	5-year average	10-year average
	Rapid Creek	Spearfish Creek	Others[1]						
1979	10.00	6.28	44.64	8.93	15.11	84.96	93.28	97.78	102.26
1980	10.00	5.59	28.98	5.80	9.81	60.17	84.59	90.60	97.76
1981	10.00	5.03	29.80	5.96	10.09	60.88	68.67	80.18	91.48
1982	9.90	6.30	47.32	9.46	16.02	89.00	70.02	80.73	87.68
1983	10.00	7.82	63.42	12.68	21.46	115.39	88.42	82.08	86.84
1984	10.00	8.03	67.92	13.58	22.99	122.53	108.97	89.59	93.69
1985	10.00	5.48	22.36	4.47	7.57	49.88	95.93	87.54	89.07
1986	10.00	5.65	49.97	9.99	16.91	92.52	88.31	93.86	87.02
1987	10.00	4.83	60.82	12.16	20.59	108.41	83.60	97.74	89.24
1988	10.00	4.92	15.25	3.05	5.16	38.38	79.77	82.34	82.21
1989	10.00	5.03	16.46	3.29	5.57	40.36	62.38	65.91	77.75
1990	10.00	5.04	39.80	7.96	13.47	76.27	51.67	71.19	79.36
1991	9.99	4.94	57.32	11.46	19.40	103.11	73.25	73.30	83.58
1992	10.00	4.78	36.55	6.50	8.47	66.30	81.89	64.88	81.31
1993	10.00	5.26	74.66	14.49	24.42	128.83	99.42	82.97	82.66
1994	10.00	6.78	68.75	13.05	21.58	120.16	105.10	98.93	82.42
1995	10.00	8.56	91.70	21.98	51.33	183.57	144.18	120.39	95.79
1996	10.00	9.20	103.07	21.45	35.76	179.48	161.07	135.67	104.49
1997	10.00	10.92	132.89	23.36	44.38	221.55	194.87	166.72	115.80
1998	10.00	9.59	106.61	18.45	30.12	174.77	191.93	175.90	129.44
Average	9.81	6.25	53.50	10.64	18.18	98.39	--	--	--

[1]Other streams with minimal regulation, including Battle Creek, Boxelder Creek, Grace Coolidge Creek, French Creek, Spring Creek, Bear Butte Creek, Bear Gulch, Beaver Creek, and Elk Creek.

[2]Values may not exactly sum to total due to independent rounding.



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 1 inch

Figure 12. Isohyetal map showing distribution of average annual precipitation for Black Hills area, water years 1950-98.

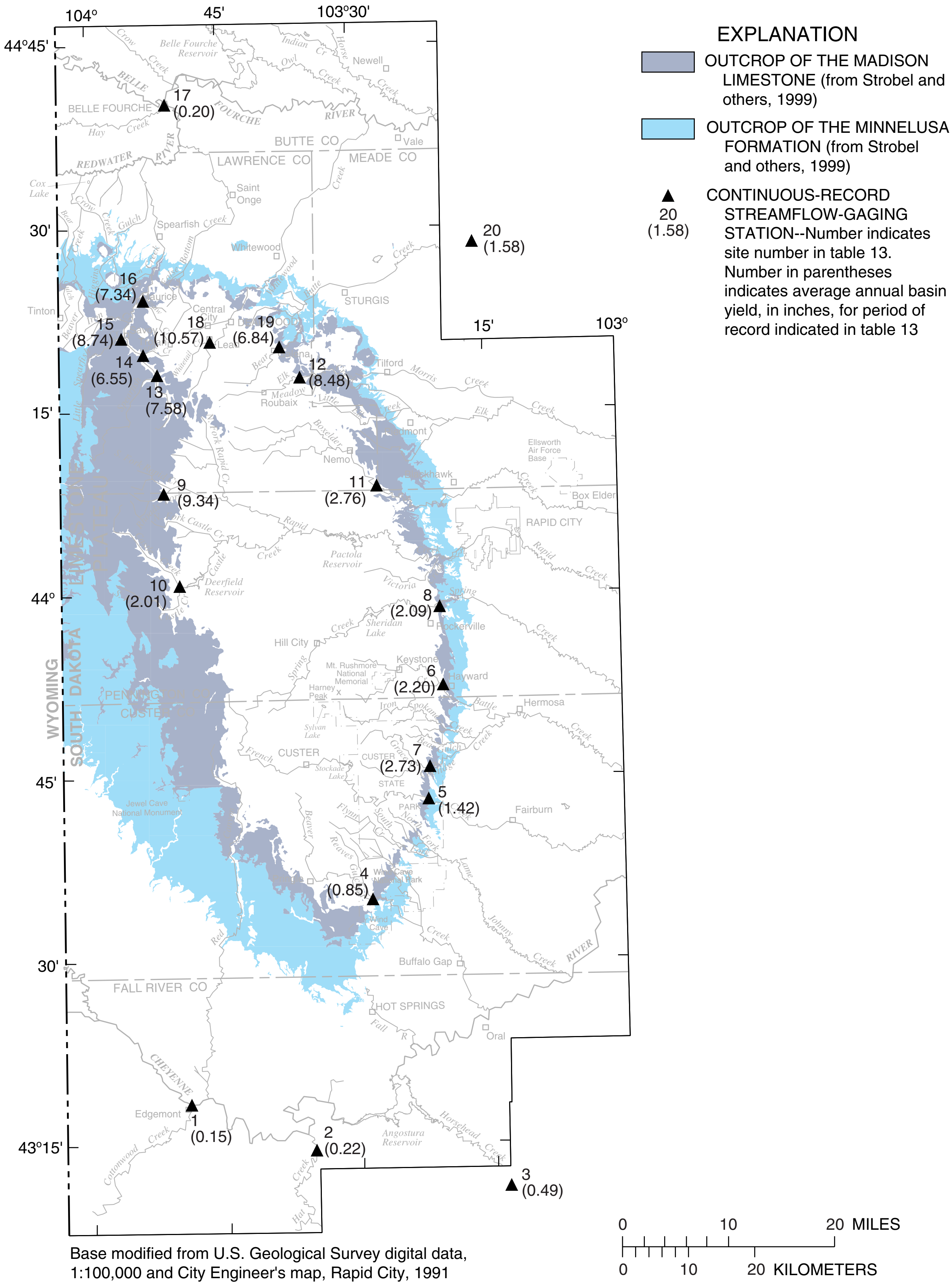


Figure 13. Measured average annual basin yields, based on surface drainage areas, for selected streamflow-gaging stations (periods of record for measured yield are not consistent).

Table 13. Summary of selected site information for streamflow-gaging stations used in determining annual yield

Site number	Station number	Station name	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Elevation of gage	Drainage area (square miles)	Period of record used (water years)	Measured annual yield for period of record (inches)	Used in determining best-fit runoff efficiency
1	06395000	Cheyenne River at Edgemont	43 18 20	103 49 14	3,415	7,143	1947-98	0.15	No
2	06400000	Hat Creek near Edgemont	43 14 24	103 35 16	3,296	1,044	1951-98	.22	No
3	06400875	Horsehead Creek at Oelrichs	43 11 17	103 13 34	3,320	187	1984-98	.49	No
4	06402430	Beaver Creek near Pringle	43 34 53	103 28 34	4,180	45.8	1991-98	.85	Yes
5	06403300	French Creek above Fairburn	43 43 02	103 22 03	3,850	105	1983-98	1.42	Yes
6	06404000	Battle Creek near Keystone	43 52 21	103 20 10	3,800	58.0	1962-98	2.20	Yes
7	06404998	Grace Coolidge Creek near Game Lodge, near Custer	43 45 40	103 21 49	4,100	25.2	1977-98	2.73	Yes
8	06407500	Spring Creek near Keystone	43 58 45	103 20 25	3,885	163	1987-98	2.09	Yes
9	06408700	Rhoads Fork near Rochford	44 08 12	103 51 29	5,965	[1]7.95	1983-98	9.34	No
10	06409000	Castle Creek above Deerfield Reservoir, near Hill City	44 00 49	103 49 48	5,920	[1]79.2	1948-98	2.01	No
11	06422500	Boxelder Creek near Nemo	44 08 38	103 27 16	4,320	96.0	1967-98	2.76	Yes
12	06424000	Elk Creek near Roubaix	44 17 41	103 35 47	4,881	21.5	1992-98	8.48	Yes
13	06430770	Spearfish Creek near Lead	44 17 56	103 52 02	5,310	[1]63.5	1989-98	[2]7.58	No
14	06430800	Annie Creek near Lead	44 19 37	103 53 38	5,125	3.55	1989-98	6.55	Yes
15	06430850	Little Spearfish Creek near Lead	44 20 58	103 56 08	5,020	[1]25.8	1989-98	8.74	No
16	06430898	Squaw Creek near Spearfish	44 24 04	103 53 35	4,480	6.95	1989-98	7.34	Yes
17	06433500	Hay Creek at Belle Fourche	44 40 01	103 50 46	3,005	121	1954-96	.20	No
18	06436156	Whitetail Creek at Lead	44 20 36	103 45 57	5,080	6.15	1989-98	10.57	Yes
19	06437020	Bear Butte Creek near Deadwood	44 20 08	103 38 06	4,750	16.6	1989-98	6.84	Yes
20	06437500	Bear Butte Creek near Sturgis	44 28 35	103 15 50	2,780	[3]120	1946-72	1.58	No

[1]Contributing areas for surface water and ground water are not necessarily congruent.
[2]A flow of 10 cubic feet per second was added to the measured streamflow to account for diverted flow.
[3]Approximate drainage area below loss zone. Actual drainage area is 192 square miles.

Because of differences in apparent yield characteristics resulting from various factors, a method was developed to estimate long-term basin yield in relation to annual precipitation. A digital grid (with cell sizes of 1,000-by-1,000 meters) showing average annual precipitation distribution for 1950-98 ($P_{average}$ grid), which corresponds with figure 12, was generated using data from Driscoll, Hamade, and Kenner (2000). Similar grids of annual precipitation for each year during 1931-98 also were generated to extend recharge estimates back as far as possible. Annual and average precipitation were determined for 1950-98 for drainage areas for stations listed in table 13, using the digital precipitation grids. The average precipitation for the period of record and for 1950-98 for each station are presented in table 14.

Although precipitation records are available for 1950-98, few streamflow records available are for that entire period. The majority of the gaging stations have streamflow records that begin in the late 1980’s to early 1990’s. Thus, a method was developed for estimating long-term annual yields for the gaging stations with incomplete record, based on precipitation. The first step was to examine relations between precipitation and yield efficiency, which is computed as:

$$YE_{annual} = \frac{Q_{annual}}{P_{annual}} \times 100 \qquad (1)$$

where

YE_{annual} = annual yield efficiency, in percent;
Q_{annual} = annual yield, in inches; and
P_{annual} = annual precipitation, in inches.

Regression analyses of yield efficiency as a function of annual precipitation were performed for all gaging stations, with resulting equations and R^2 values shown in table 14. The equations were then used with annual precipitation data to predict average yield efficiency for 1950-98. Equations for three gages are not realistic and are not included in table 14 (Rhoads Fork, Castle Creek, and Little Spearfish Creek). For these gages, average yield efficiencies for the available period of record are used to represent efficiencies for 1950-98. The linear relations between yield efficiency and precipitation for 15 of the gages with the best relations (R^2 values) are shown in figure 14, along with exponential curves for selected gages that are described in subsequent discussions.

Average yield efficiency values for 1950-98 (from table 14), which are based on surface areas, are shown in figure 15. A map of generalized average annual yield efficiency (the percentage of precipitation that is available either for runoff or recharge) for the study area is presented in figure 16. Contouring was done to reflect conditions upstream from representative gages, including influences of contributing ground-water areas in the Limestone Plateau area (Jarrell, 2000). Additional yield efficiency values estimated for gages located outside the study area (including Wyoming) also were used. Topography and precipitation also were considered when contouring in areas with sparse yield efficiency data. A digital grid (1,000-by-1,000 meters) of the yield efficiency distribution shown in figure 16 was generated for subsequent analyses.

A systematic approach was developed for predicting annual yield efficiency, by adjusting average efficiency on the basis of relations between annual and average precipitation. The following exponential equation provided good results:

$$YE_{annual} = \left[\frac{P_{annual}}{P_{average}}\right]^n \times YE_{average} \qquad (2)$$

where

YE_{annual} = annual yield efficiency, in percent;
P_{annual} = annual precipitation, in inches;
$P_{average}$ = average precipitation for 1950-98, in inches;
$YE_{average}$ = average yield efficiency for 1950-98, in percent; and
n = exponent.

Best-fit exponential curves and curves for an exponent of 1.6 (ultimately selected for the systematic approach) are shown in figure 14. Gages dominated by ground-water discharge (sites 9, 10, 13, 15) and those not located on or near the Precambrian core (sites 1, 2, 3, and 17) were not used for curve fitting. In addition, site 20 was not used because of its non-recent period of record. The best-fit exponents range from 1.1 to 2.5 (table 14), and R^2 values generally are similar or better than for the linear regression equations. For most gages, both of the exponential curves closely resemble results from the linear regressions through most of the range of measured precipitation.

Table 14. Summary of selected precipitation information, equations, and runoff estimates for streamflow-gaging stations used in estimating precipitation recharge

[--, not computed]

Site number	Station name	Average precipitation over drainage basin (inches): Period of record (streamflow)	Average precipitation over drainage basin (inches): 1950-98	Yield efficiency, Linear regression equation: Intercept	Yield efficiency, Linear regression equation: Precipitation coefficient	Yield efficiency, Linear regression equation: R^2	Yield efficiency, Linear regression equation: Average yield efficiency[1] 1950-98 (percent)	Yield efficiency, Exponential regression equation: Best-fit exponent	Yield efficiency, Exponential regression equation: R^2	Annual yield, Period of record: Measured (inches)	Annual yield, Period of record: Computer algorithm[1] (inches)	Annual yield, Linear regression equation: Intercept	Annual yield, Linear regression equation: Precipitation coefficient	Annual yield, Linear regression equation: R^2	Annual yield, Linear regression equation: Estimated average annual yield 1950-98 (inches)	Annual yield: Computer algorithm[2] annual yield 1950-98 (inches)
1	Cheyenne River	17.21	17.22	-0.0019	0.0006	0.0941	[3]0.9	--	--	0.15	--	--	--	--	--	--
2	Hat Creek	16.00	15.95	-.0076	.0013	.1049	1.3	--	--	.22	--	--	--	--	--	--
3	Horsehead Creek	17.31	16.59	-.0604	.0049	.4220	2.1	--	--	.49	--	--	--	--	--	--
4	Beaver Creek	24.16	18.88	-.0310	.0026	.3208	1.8	2.2	0.3813	.85	1.34	-1.6328	0.1027	0.5223	0.36	0.74
5	French Creek	20.95	19.45	-.0476	.0052	.4902	5.4	1.9	.5654	1.42	1.67	-2.4960	.1867	.6480	1.15	1.36
6	Battle Creek	21.56	20.27	-.0628	.0072	.6067	8.3	1.6	.5920	2.20	2.32	-3.3050	.2552	.7636	1.89	2.01
7	Grace Coolidge Creek	21.37	19.95	-.1087	.0104	.6433	9.9	1.9	.6809	2.73	1.94	-5.2603	.3740	.7344	2.29	1.62
8	Spring Creek	21.77	19.90	-.1222	.0095	.6967	6.7	2.5	.7463	2.09	2.15	-4.4738	.3013	.8045	1.58	1.69
9	Rhoads Fork	22.63	23.23	--	--	--	[4]41.8	--	--	9.34	5.87	7.2214	.0772	.0399	9.01	5.72
10	Castle Creek	21.65	21.76	--	--	--	[3]9.3	--	--	2.01	3.58	0.0985	-.0002	.3146	2.02	3.63
11	Boxelder Creek	22.98	22.79	-.0995	.0091	.4463	10.8	2.1	.5210	2.76	2.77	-5.0893	.3417	.5981	2.71	2.68
12	Elk Creek	31.06	26.05	-.0352	.0096	.3424	21.5	1.1	.3421	8.48	9.36	-8.7673	.5552	.7026	5.70	6.08
13	Spearfish Creek	27.63	24.67	.1009	.0061	.2975	25.1	--	--	[5]7.58	10.49	-4.8582	.4501	.7192	6.24	7.86
14	Annie Creek	29.46	26.57	-.2342	.0150	.6753	16.4	2.1	.6858	6.55	9.85	-13.8630	.6929	.8187	4.66	7.61
15	Little Spearfish Creek	27.44	25.26	--	--	--	[4]31.8	--	--	8.74	9.95	-.4435	.3346	.5229	8.01	7.97
16	Squaw Creek	29.02	26.89	-.0751	.0108	.5195	21.5	1.3	.5224	7.34	7.30	-10.0420	.5990	.7963	6.07	5.81
17	Hay Creek	18.28	18.16	-.0137	.0013	.4052	1.0	--	--	.20	--	--	--	--	--	--
18	Whitetail Creek	31.19	28.08	-.1464	.0149	.6216	27.2	1.4	.5968	10.57	10.59	-14.421	.8013	.8152	8.10	8.13
19	Bear Butte Creek (Deadwood)	29.62	26.86	-.0975	.0106	.5032	18.7	1.4	.4860	6.84	8.02	-9.5062	.5519	.7850	5.34	6.25
20	Bear Butte Creek (Sturgis)	23.68	23.85	-.1144	.0075	.5614	6.0	--	--	1.58	--	--	--	--	--	--

[1]Unless noted otherwise, estimated using regression equation for runoff efficiency versus precipitation.
[2]Estimated using exponent of 1.6.
[3]Period of record sufficient for computation of yield efficiency.
[4]Estimated using average runoff efficiency for the available period of record.
[5]A flow of 10 cubic feet per second was added to the measured streamflow to account for diverted flow.

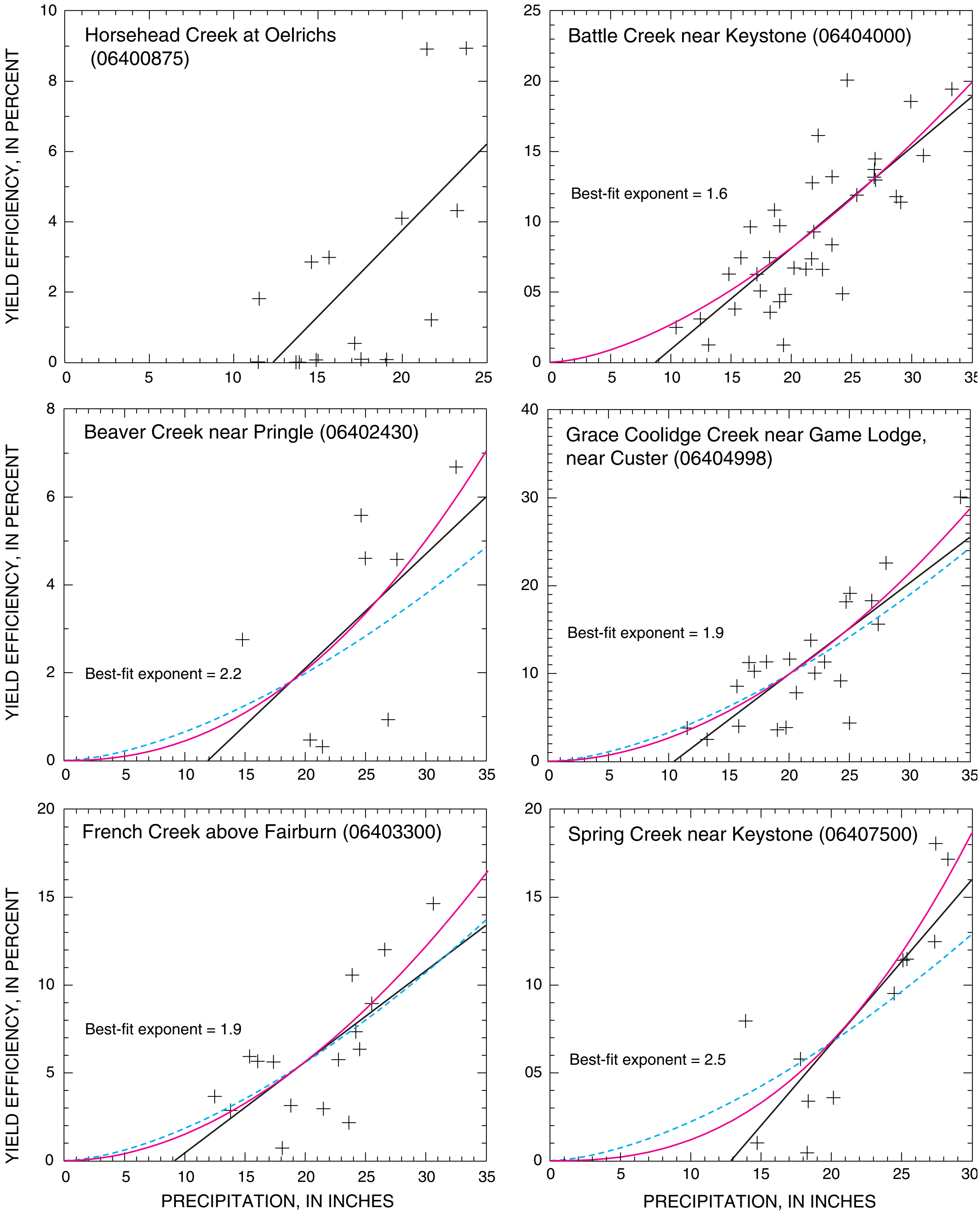


Figure 14. Regression plots of yield efficiency with precipitation for selected streamflow-gaging stations.

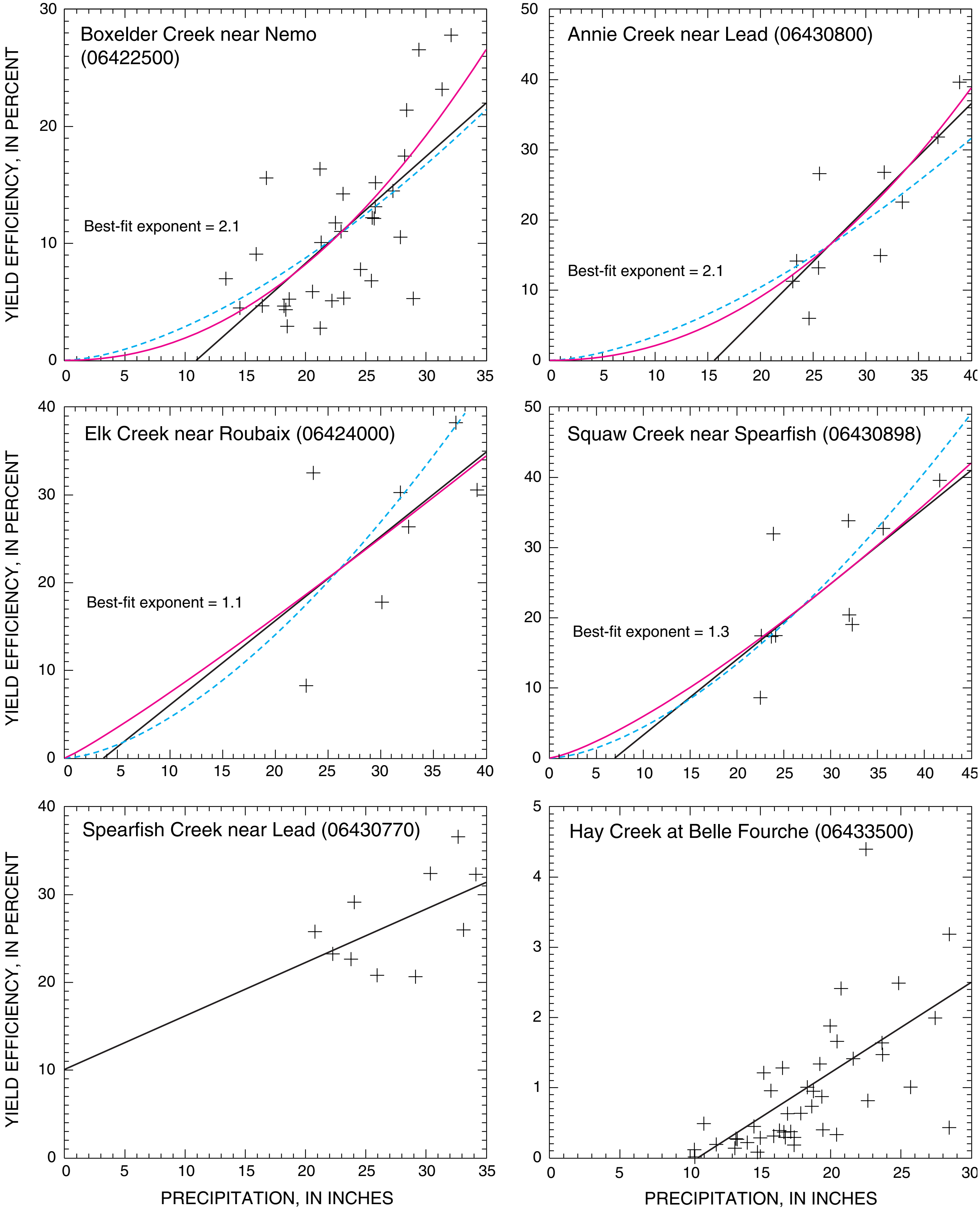


Figure 14. Regression plots of yield efficiency with precipitation for selected streamflow-gaging stations.--Continued

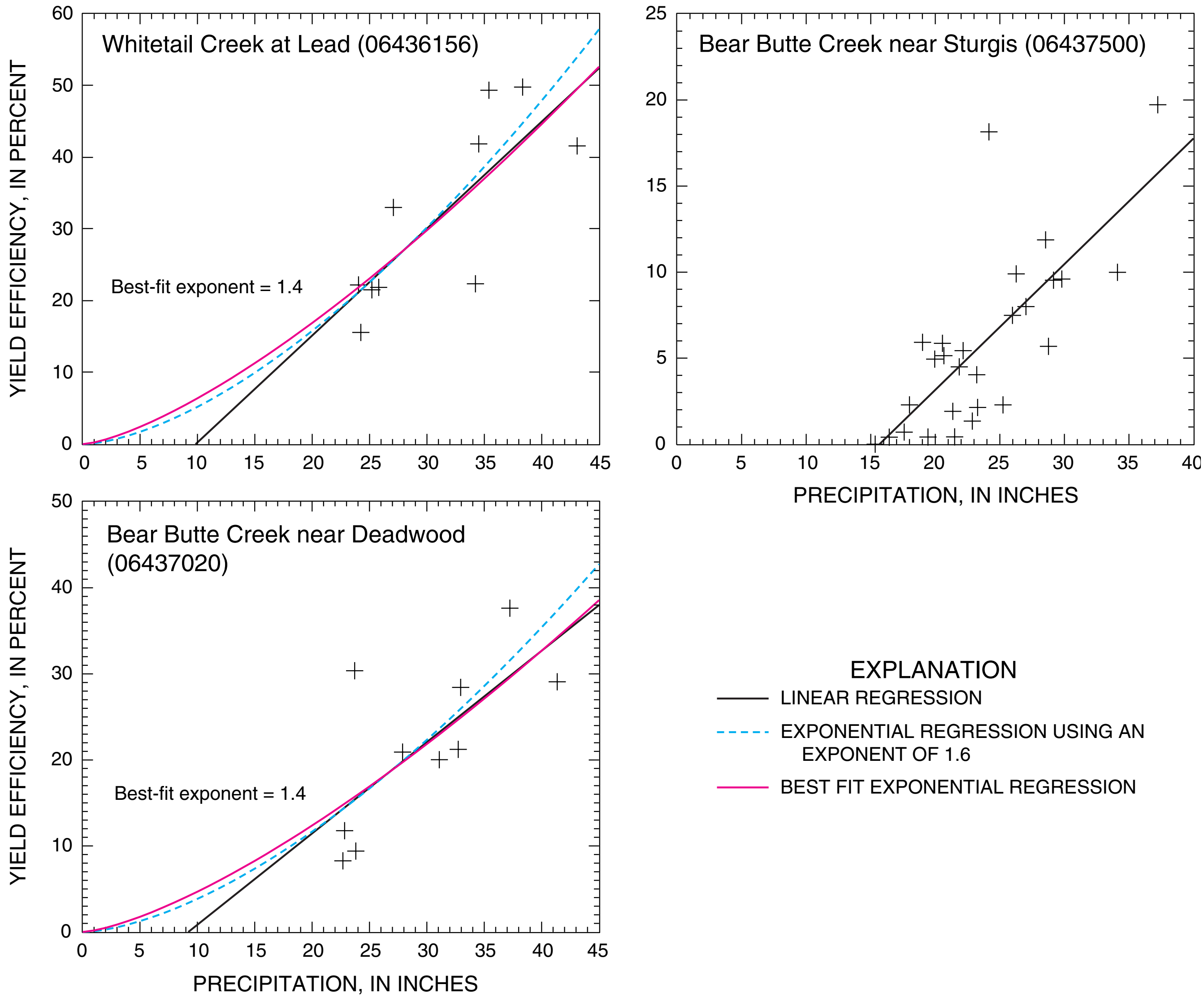


Figure 14. Regression plots of yield efficiency with precipitation for selected streamflow-gaging stations.--Continued

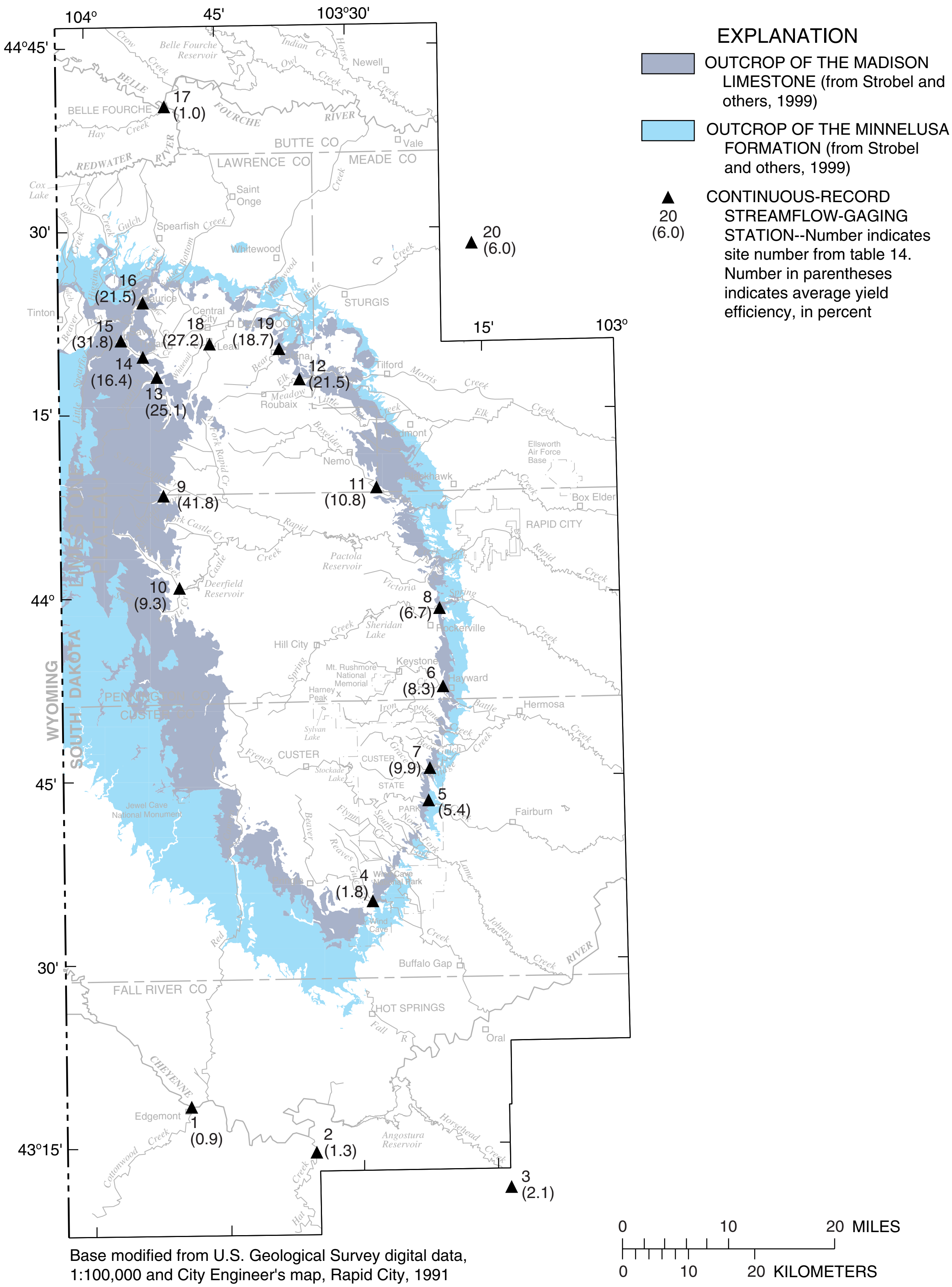
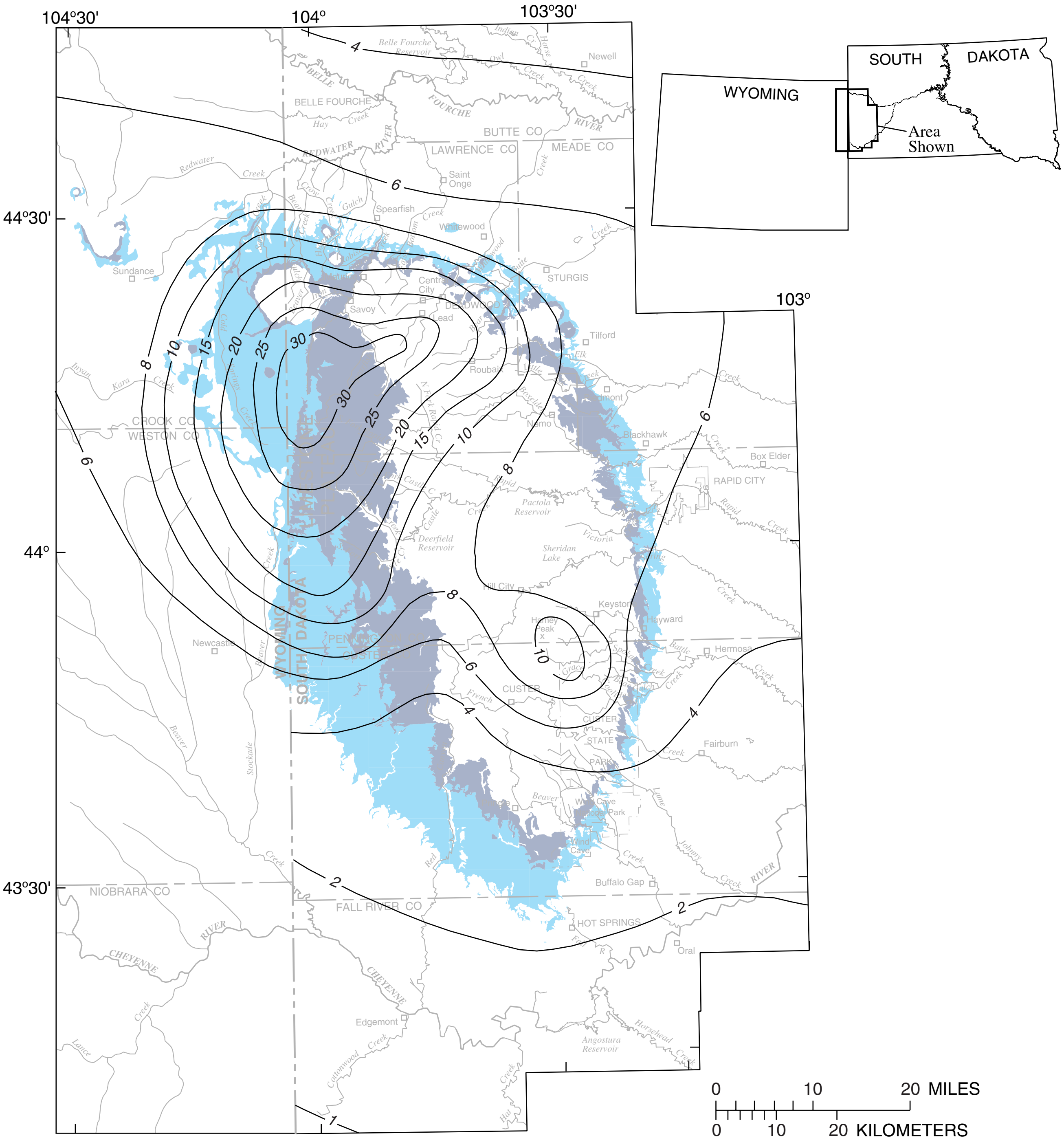


Figure 15. Estimated yield efficiencies for water years 1950-98, based on surface drainage areas, for selected gaging stations.



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 FOR WHICH PRECIPITATION RECHARGE IS PRESCRIBED (from Strobel and others, 1999; DeWitt and others, 1989)

CONNECTED OUTCROP OF THE MINNELUSA FORMATION FOR WHICH PRECIPITATION RECHARGE IS PRESCRIBED (from Strobel and others, 1999; DeWitt and others, 1989)

—15— LINE OF EQUAL AVERAGE ANNUAL YIELD EFFICIENCY-- Interval 1, 2, or 5 percent

Figure 16. Generalized average annual yield efficiency (in percent of annual precipitation), water years 1950-98.

Annual yield for a given year can be calculated using a selected value for n, by rearranging equation 1 to solve for Q_{annual} and by substituting equation 2 in place of YE_{annual} to produce the following equation:

$$Q_{annual} = \left[\frac{P_{annual}}{P_{average}}\right]^n \times \frac{YE_{average}}{100} \times P_{annual} \quad (3)$$

A computer algorithm, which utilizes the set of three digital grids ($P_{average}$, P_{annual}, and $YE_{average}$) with equation 3, was developed to generate digital grids of annual yield (Q_{annual}) for each year during 1950-98 using exponents of 1.4, 1.6, and 2.0. A value of 1.6 was selected and is used for calculation of precipitation recharge based on comparisons for selected gaging stations between measured annual yield and the computer algorithm annual yield (results using an exponent of 1.6 are presented in table 14).

Because the period of record is relatively short for many of the gaging stations, a method for comparing long-term annual yields to the computer algorithm was desired. For this, linear regression analyses were performed between annual yield and precipitation for the selected gaging stations for the period of record, with resulting equations (table 14) used to estimate the average annual yields for 1950-98 for each of the 15 gaging stations located on or near the Precambrian core. Estimates also were generated using the computer algorithm (table 14), which generally compare quite favorably with the regression estimates, with no apparent tendency of consistent overestimation or underestimation. An exception is Annie Creek, for which annual yields are notably lower than in adjacent basins (fig. 13). Estimates derived using the computer algorithm for Rhoads Fork and Castle Creek also are notably different than the regression estimates, but probably are much more representative of groundwater recharge that occurs within the surface drainage areas for these basins.

Recharge Estimates

As previously stated, the major assumptions in determining recharge to the Madison and Minnelusa aquifers from precipitation are that (1) all precipitation on outcrops of the Madison Limestone and Minnelusa Formation that is not evapotranspirated becomes recharge, and (2) yield efficiency is a reasonable surrogate for the efficiency of precipitation recharge. Therefore, *recharge* is assumed equal to *annual yield*. The computer algorithm using equation 3 was used to estimate annual recharge from infiltration of precipitation on outcrops of the Madison Limestone and Minnelusa Formation (table 15). A digital grid for the distribution of annual yield over the study area was generated for each year during 1931-98. Annual yield was then applied to the outcrop areas, from which annual recharge volumes were computed. Estimates of annual recharge, in inches, were obtained by dividing by the connected outcrop areas (fig. 7) of the Madison Limestone and Minnelusa Formation, which are about 301,160 acres and 427,160 acres, respectively.

The long-term (1931-98) average for precipitation recharge to both the Madison and Minnelusa aquifers is about 182,000 acre-ft per year, or an average of about 251 ft^3/s (table 15). The average for 1950-98 is about 10 percent higher, because the dry conditions of the 1930's are excluded. The minimum recharge rate (about 31 ft^3/s) occurred in 1936. This extreme value is important because it provides an indication of just how low the recharge rate could be during a severe drought. Also, the 10-year average for 1931-40 (about 130 ft^3/s) is much smaller than all other 10-year averages. The maximum 3-year average of about 577 ft^3/s for 1995-97 includes the annual maximum of about 664 ft^3/s for 1995.

The average (1931-98) recharge depth to the Madison aquifer (3.59 inches) is about 1 inch larger than for the Minnelusa aquifer because of the orographic effects. Average recharge volumes are nearly identical, however, because the outcrop area for the Minnelusa Formation is almost 50 percent larger than for the Madison Limestone. For 1950-98, precipitation recharge averages about 135 ft^3/s to each aquifer, compared with combined streamflow recharge of about 98 ft^3/s for both aquifers (table 12). Although streamflow recharge is presumed larger for the Madison aquifer, substantial streamflow recharge to the Minnelusa aquifer is apparent for many streams (tables 5 and 9). If the Madison aquifer is assumed to receive either 65 or 75 percent of combined streamflow recharge to both aquifers, the resulting proportion of total recharge (about 370 ft^3/s) is about 54 or 57 percent, respectively. Considering the margin of error associated with recharge estimates, it reasonably can be concluded that on average, the Madison aquifer receives about 55 percent of total recharge to both aquifers, relative to about 45 percent for the Minnelusa aquifer.

Table 15. Estimated precipitation recharge, water years 1931-98

[--, not applicable]

Water year	Average annual recharge								Moving averages for total precipitation recharge (cubic feet per second)		
	Madison aquifer			Minnelusa aquifer			Total[1]				
	Acre-feet	Inches	Cubic feet per second	Acre-feet	Inches	Cubic feet per second	Acre-feet	Cubic feet per second	3-year average	5-year average	10-year average
1931	18,893	0.75	26.03	22,689	0.64	31.34	41,582	57.37	--	--	--
1932	104,910	4.18	144.51	108,389	3.04	149.31	213,299	293.82	--	--	--
1933	93,592	3.73	128.92	96,909	2.72	133.86	190,501	262.78	204.66	--	--
1934	19,633	.78	27.05	20,020	.56	27.65	396,53	54.70	203.77	--	--
1935	49,792	1.98	68.59	49,917	1.40	68.95	99,710	137.54	151.67	161.24	--
1936	10,330	.41	14.23	12,235	.34	16.85	22,565	31.08	74.44	155.98	--
1937	36,772	1.47	50.65	42,780	1.20	59.09	79,552	109.75	92.79	119.17	--
1938	43,661	1.74	60.14	47,180	1.33	65.17	90,841	125.31	88.71	91.68	--
1939	45,769	1.82	63.05	46,685	1.31	64.49	92,455	127.53	120.86	106.24	--
1940	31,424	1.25	43.29	38,398	1.08	52.89	69,822	96.18	116.34	97.97	129.61
1941	123,352	4.92	169.92	141,690	3.98	195.71	265,041	365.63	196.45	164.88	160.43
1942	90,236	3.60	124.30	105,367	2.96	145.54	195,603	269.84	243.88	196.90	158.03
1943	73,755	2.94	101.60	70,489	1.98	97.36	144,244	198.96	278.14	211.63	151.65
1944	57,153	2.28	78.73	66,466	1.87	91.56	123,620	170.29	213.03	220.18	163.21
1945	126,361	5.03	174.06	131,968	3.71	182.28	258,329	356.35	241.87	272.21	185.09
1946	201,948	8.05	278.18	213,204	5.99	294.49	415,152	572.68	366.44	313.62	239.25
1947	83,367	3.32	114.84	85,390	2.40	117.95	168,757	232.79	387.27	306.21	251.56
1948	73,557	2.93	101.32	69,360	1.95	95.54	142,917	196.87	334.11	305.79	258.71
1949	42,660	1.70	58.76	44,713	1.26	61.76	87,373	120.53	183.39	295.84	258.01
1950	65,960	2.63	90.86	63,715	1.79	88.01	129,675	178.87	165.42	260.35	266.28
1951	54,942	2.19	75.68	61,586	1.73	85.07	116,528	160.75	153.38	177.96	245.79
1952	68,076	2.71	93.77	62,618	1.76	86.26	130,694	180.03	173.22	167.41	236.81
1953	69,612	2.77	95.89	64,021	1.80	88.43	133,632	184.32	175.03	164.90	235.35
1954	35,972	1.43	49.55	33,344	.94	46.06	69,315	95.61	153.32	159.92	227.88
1955	98,14	3.93	135.84	95,720	2.69	132.22	194,334	268.06	182.66	177.75	219.05
1956	48,578	1.94	66.92	48,743	1.37	67.14	97,320	134.06	165.91	172.42	175.19
1957	101,919	4.06	140.39	99,660	2.80	137.66	201,579	278.05	226.72	192.02	179.71
1958	67,458	2.69	92.92	66,854	1.88	92.34	134,313	185.27	199.13	192.21	178.55
1959	53,660	2.14	73.92	48,106	1.35	66.45	101,765	140.36	201.23	201.16	180.54
1960	45,077	1.80	62.09	40,288	1.13	55.50	85,365	117.59	147.74	171.07	174.41
1961	25,240	1.01	34.77	24,697	.69	34.11	49,937	68.88	108.95	158.03	165.22
1962	181,288	7.22	249.73	190,767	5.36	263.50	372,055	513.23	233.23	205.07	198.54
1963	160,252	6.39	220.75	148,987	4.19	205.79	309,239	426.54	336.22	253.32	222.76
1964	177,805	7.08	244.93	165,465	4.65	227.93	343,269	472.86	470.87	319.82	260.49
1965	189,703	7.56	261.32	191,479	5.38	264.49	381,182	525.80	475.07	401.46	286.26
1966	47,142	1.88	64.94	51,523	1.45	71.17	98,665	136.11	378.25	414.91	286.47
1967	112,610	4.49	155.12	118,968	3.34	164.33	231,578	319.45	327.12	376.15	290.61

Table 15. Estimated precipitation recharge, water years 1931-98–Continued

[--, not applicable]

Water year	Average annual recharge								Moving averages for total precipitation recharge (cubic feet per second)		
	Madison aquifer			Minnelusa aquifer			Total[1]				
	Acre-feet	Inches	Cubic feet per second	Acre-feet	Inches	Cubic feet per second	Acre-feet	Cubic feet per second	3-year average	5-year average	10-year average
1968	89,044	3.55	122.66	90,202	2.53	124.25	179,247	246.91	234.16	340.23	296.77
1969	81,287	3.24	111.97	75,237	2.11	103.92	156,524	215.90	260.75	288.83	304.33
1970	103,859	4.14	143.07	108,969	3.06	150.52	212,828	293.58	252.13	242.39	321.93
1971	131,686	5.25	181.40	133,218	3.74	184.01	264,904	365.41	291.63	288.25	351.58
1972	144,955	5.78	199.68	158,830	4.46	218.79	303,785	418.46	359.15	308.05	342.10
1973	101,269	4.04	139.50	104,185	2.93	143.91	205,454	283.41	355.76	315.35	327.79
1974	45,817	1.83	63.11	46,849	1.32	64.71	92,666	127.82	276.57	297.74	293.29
1975	64,831	2.58	89.30	64,523	1.81	89.12	129,353	178.43	196.55	274.71	258.55
1976	129,177	5.15	177.94	136,841	3.84	188.50	266,018	366.44	224.23	274.91	281.58
1977	101,136	4.03	139.32	94,250	2.65	130.19	195,386	269.50	271.46	245.12	276.59
1978	120,579	4.80	166.10	121,332	3.41	167.59	241,910	333.69	323.21	255.18	285.26
1979	87,646	3.49	120.73	81,463	2.29	112.52	169,110	233.26	278.82	276.26	287.00
1980	41,282	1.64	56.87	40,068	1.13	55.19	81,350	112.06	226.34	262.99	268.85
1981	60,203	2.40	82.93	63,398	1.78	87.57	123,601	170.50	171.94	223.80	249.36
1982	185,043	7.37	254.90	187,727	5.27	259.30	372,770	514.20	265.59	272.74	258.93
1983	62,625	2.50	86.27	58,874	1.65	81.32	121,498	167.59	284.10	239.52	247.35
1984	90,023	3.59	124.01	100,315	2.82	138.18	190,338	262.19	314.66	245.31	260.79
1985	25,120	1.00	34.60	24,839	.70	34.31	49,959	68.91	166.23	236.68	249.83
1986	117,823	4.69	162.30	140,696	3.95	194.34	258,519	356.64	229.25	273.91	248.85
1987	41,588	1.66	57.29	49,982	1.40	69.04	91,570	126.33	183.96	196.33	234.54
1988	35,186	1.40	48.47	39,128	1.10	53.90	74,314	102.37	195.11	183.29	211.40
1989	51,750	2.06	71.29	54,566	1.53	75.37	106,316	146.66	125.12	160.18	202.74
1990	66,118	2.63	91.08	72,304	2.03	99.87	138,422	190.95	146.66	184.59	210.63
1991	106,135	4.23	146.20	116,167	3.26	160.46	222,302	306.66	214.76	174.59	224.25
1992	73,065	2.91	100.65	71,624	2.01	98.66	144,689	199.31	232.31	189.19	192.76
1993	153,727	6.13	211.76	168,387	4.73	232.59	322,114	444.35	316.77	257.59	220.44
1994	71,800	2.86	98.90	75,722	2.13	104.59	147,522	203.50	282.39	268.95	214.57
1995	225,419	8.98	310.52	255,774	7.19	353.30	481,193	663.81	437.22	363.53	274.06
1996	185,600	7.40	255.66	193,579	5.44	266.66	379,179	522.32	463.21	406.66	290.62
1997	216,306	8.62	297.96	179,447	5.04	247.87	395,753	545.83	577.32	475.96	332.58
1998	178,568	7.12	245.98	153,771	4.32	212.40	332,339	458.38	508.84	478.77	368.18
Average 1950-98	97,808	3.90	134.73	98,751	2.77	136.31	196,559	271.04	--	--	--
Average 1931-98	89,996	3.59	123.97	91,951	2.58	126.93	181,947	250.90	--	--	--

[1]Individual recharge estimates may not sum to total due to independent rounding.

To illustrate recharge patterns throughout the study area, annual digital grids were averaged over 49 years to yield a distribution of average annual recharge for 1950-98 (fig. 17). The average annual recharge from precipitation ranges from 0.4 inch in the southern Black Hills to 8.7 inches in the northwestern Black Hills. This corresponds with average yield efficiencies in the outcrop areas that range from just over 2 percent in the south to almost 35 percent in the north (fig. 16) and annual precipitation ranging from about 17 to 26 inches (fig. 12).

COMBINED RECHARGE, 1931-98

Annual streamflow recharge (table 12) and precipitation recharge (table 15) were summed (table 16) to yield total combined recharge rates to the Madison and Minnelusa aquifers. Table 16 includes estimates of streamflow recharge for 1931-49 that were not included in table 12. Methods for deriving these estimates are described in the following discussion. Because precipitation recharge was very low during the 1930's, it was important to have estimates of combined recharge for this period. However, for all recharge estimates presented in this report, the earlier estimates have larger uncertainties due to sparser data.

Various regression methods were examined for estimating streamflow recharge for the period 1931-49, based on precipitation recharge rates and precipitation over the study area. The best regression (R^2= 0.8119) was based on recharge for the period 1989 through 1998, which is a period with abundant streamflow records and a wide range of recharge rates. This regression yielded the following equation to estimate streamflow recharge based on precipitation recharge: Streamflow Recharge = (0.294 x Precipitation Recharge) + 21.319.

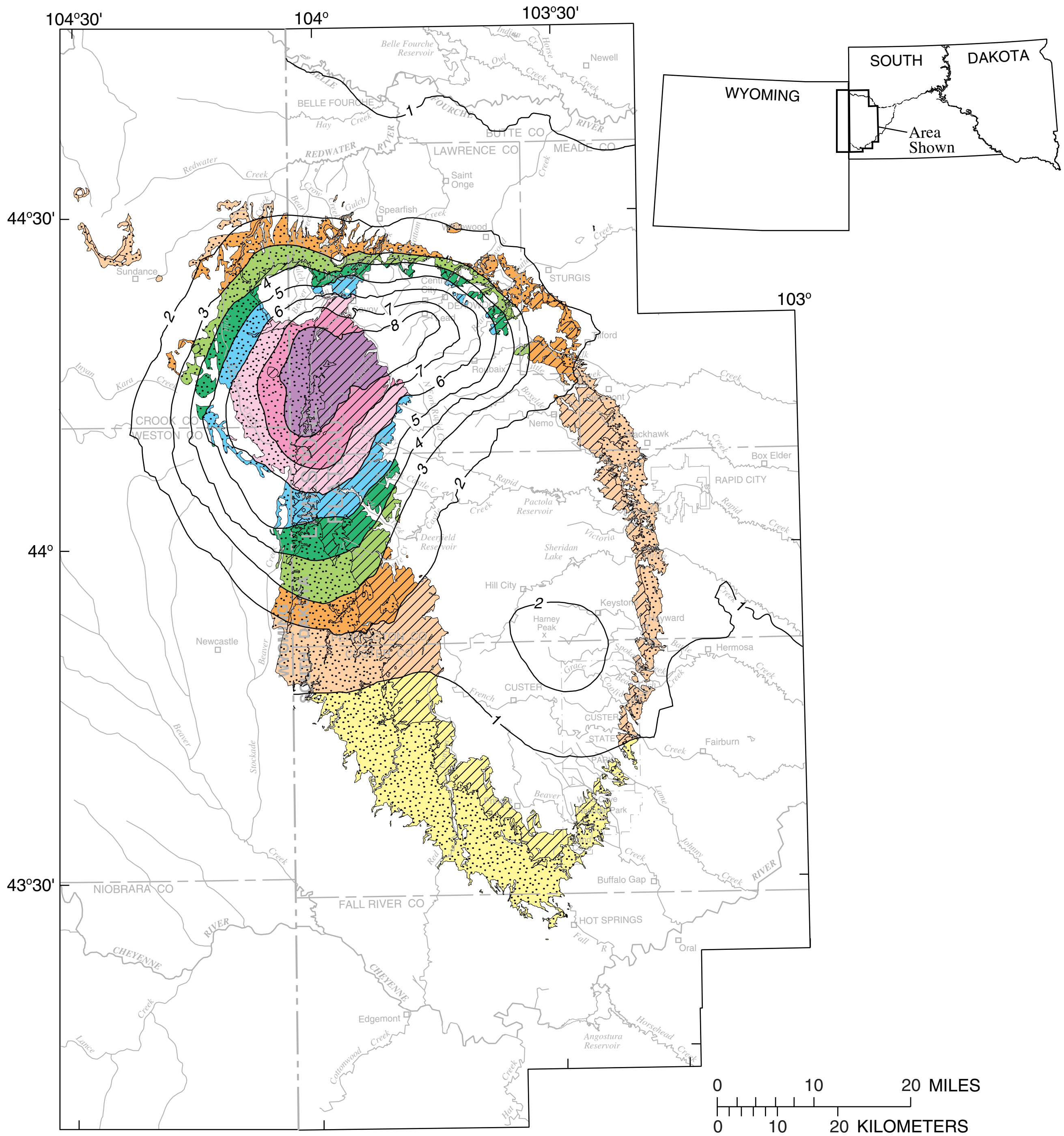
Annual ranks for streamflow recharge, precipitation recharge, and combined recharge are provided in table 16. Of recent years, the driest year for combined recharge is 1985, with a rank of 65. In comparison, 3 years during the 1930's (1931, 1934, and 1936) are much drier, with combined recharge rates that are considerably smaller. The 10-year moving average for 1931-40 is much smaller than any of the subsequent 10-year averages. This period also includes many minimal values for the 3- and 5-year averages, which again are much smaller than subsequent averages. This clearly illustrates the importance of estimating streamflow recharge for 1931-49.

Ranks for the different recharge categories generally are quite similar (table 16); however, because combined recharge generally is dominated by precipitation recharge, these categories have the most similarity. Trends in streamflow recharge occasionally lag precipitation recharge because of effects of antecedent conditions. A good example is 1997, which is the maximum year for streamflow recharge (table 16).

Combined streamflow and precipitation recharge averaged about 344 ft^3/s for 1931-98 and ranged from about 62 ft^3/s in 1936 to about 847 ft^3/s in 1995 (table 16). Streamflow recharge averaged about 93 ft^3/s, or 27 percent of combined recharge, and precipitation recharge averaged about 251 ft^3/s, or 73 percent of combined recharge.

Plots of annual streamflow recharge, precipitation recharge, and combined recharge are provided in figure 18. It is apparent that combined recharge for the period 1962-98 is much larger than for 1931-61, which was identified by Driscoll, Hamade, and Kenner (2000) as a period of generally deficit precipitation departures, relative to the 1931-98 average. Combined recharge during 1962-98 exceeds the 1931-98 average for 21 of 37 years; however, the 1931-98 average is exceeded for only 7 of 31 years during 1931-61 (table 16). The most prolonged low-recharge period is 1947-61, with only one year above average for combined recharge; however, recharge amounts generally were lower during the 1930's. The 1990's are distinct as the period of highest recharge.

The relative proportion of recharge contributed by streamflow losses and infiltration of precipitation is highly variable (fig. 18). The minimum value for combined recharge (about 62 ft^3/s for 1936) consists of 49.5 and 50.5 percent, respectively, from streamflow and precipitation recharge (table 16). This compares with 21.7 and 78.3 percent, respectively, for the maximum recharge value of about 847 ft^3/s in 1995. Thus, it is apparent that the relative proportion contributed by streamflow recharge increases as combined recharge decreases.



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

EXPLANATION

OUTCROP OF THE MADISON LIMESTONE FOR WHICH PRECIPITATION RECHARGE IS PRESCRIBED

OUTCROP OF THE MINNELUSA FORMATION FOR WHICH PRECIPITATION RECHARGE IS PRESCRIBED

— 2 — LINE OF EQUAL YIELD POTENTIAL--Number indicates average annual yield potential. Interval 1 inch

AVERAGE ANNUAL RECHARGE, IN INCHES

- Less than 1
- Between 1 and 2
- Between 2 and 3
- Between 3 and 4
- Between 4 and 5
- Between 5 and 6
- Between 6 and 7
- Between 7 and 8
- Between 8 and 9

Figure 17. Estimated annual yield potential and average annual recharge from precipitation on outcrops of the Madison Limestone and Minnelusa Formation, water years 1950-98.

Table 16. Summary of streamflow, precipitation, and combined recharge, water years 1931-98

[--, not applicable]

Water year	Streamflow recharge		Precipitation recharge		Combined recharge			Moving averages for combined recharge (cubic feet per second)		
	Total (cubic feet per second)	Rank	Total (cubic feet per second)	Rank	Total (acre-feet)	Total[1] (cubic feet per second)	Rank	3-year average	5-year average	10-year average
1931	38.17	66	57.37	66	69,161	95.53	66	--	--	--
1932	107.61	23	293.82	21	291,426	401.44	22	--	--	--
1933	98.50	28	262.78	28	261,555	361.28	27	286.08	--	--
1934	37.38	67	54.70	67	66,663	92.08	67	284.93	--	--
1935	61.71	51	137.54	50	144,250	199.25	52	217.54	229.92	--
1936	30.45	68	31.08	68	44,668	61.53	68	117.62	223.12	--
1937	53.55	61	109.75	60	118,224	163.30	60	141.36	175.49	--
1938	58.12	57	125.31	56	132,804	183.44	55	136.09	139.92	--
1939	58.78	56	127.53	54	134,882	186.31	54	177.68	158.77	--
1940	49.57	63	96.18	62	105,807	145.75	62	171.83	148.07	188.99
1941	128.70	8	365.63	14	357,886	494.34	13	275.47	234.63	228.87
1942	100.57	27	269.84	25	268,165	370.41	26	336.83	276.05	225.77
1943	79.75	39	198.96	36	201,784	278.72	38	381.16	295.11	217.51
1944	71.33	46	170.29	45	175,404	241.62	45	296.92	306.17	232.47
1945	125.98	10	356.35	17	349,191	482.33	15	334.22	373.48	260.78
1946	189.51	2	572.68	2	551,800	762.19	3	495.38	427.05	330.84
1947	89.69	34	232.79	32	233,458	322.47	32	522.33	417.47	346.76
1948	79.14	41	196.87	37	200,370	276.01	39	453.56	416.92	356.02
1949	56.72	58	120.53	57	128,316	177.24	57	258.57	404.05	355.11
1950	79.50	40	178.87	42	187,044	258.36	44	237.20	359.25	366.37
1951	76.09	43	160.75	47	171,464	236.84	46	224.15	254.18	340.62
1952	113.52	19	180.03	41	213,103	293.55	34	262.92	248.40	332.93
1953	96.62	30	184.32	40	203,391	280.94	37	270.44	249.39	333.16
1954	66.10	48	95.61	63	117,073	161.71	61	245.40	246.28	325.16
1955	65.04	50	268.06	27	241,146	333.09	29	258.58	261.23	310.24
1956	65.90	49	134.06	52	145,161	199.96	51	231.59	253.85	254.02
1957	117.12	17	278.05	24	286,090	395.17	24	309.41	274.17	261.29
1958	73.20	45	185.27	39	187,124	258.47	43	284.53	269.68	259.53
1959	60.53	53	140.36	49	145,438	200.89	50	284.84	277.52	261.90
1960	59.57	55	117.59	58	128,609	177.16	58	212.17	246.33	253.78
1961	54.97	59	68.88	65	89,663	123.85	64	167.30	231.11	242.48
1962	122.52	14	513.23	7	460,262	635.75	6	312.25	279.22	276.70
1963	103.64	25	426.54	11	383,833	530.18	12	429.93	333.57	301.62
1964	95.48	32	472.86	8	412,579	568.33	10	578.09	407.05	342.29
1965	140.80	6	525.80	4	482,596	666.60	5	588.37	504.94	375.64
1966	98.23	29	136.11	51	169,647	234.33	48	489.75	527.04	379.07
1967	121.00	15	319.45	19	318,871	440.45	19	447.13	487.98	383.60

Table 16. Summary of streamflow, precipitation, and combined recharge, water years 1931-98–Continued

[--, not applicable]

Water year	Streamflow recharge		Precipitation recharge		Combined recharge			Moving averages for combined recharge (cubic feet per second)		
	Total (cubic feet per second)	Rank	Total (cubic feet per second)	Rank	Total (acre-feet)	Total[1] (cubic feet per second)	Rank	3-year average	5-year average	10-year average
1968	82.87	38	246.91	30	239,404	329.78	30	334.85	447.90	390.73
1969	74.24	44	215.90	33	210,052	290.14	35	353.46	392.26	399.66
1970	105.19	24	293.58	22	288,696	398.77	23	339.56	338.69	421.82
1971	123.68	12	365.41	15	354,085	489.09	14	392.67	389.65	458.34
1972	126.93	9	418.46	12	395,933	545.40	11	477.75	410.64	449.31
1973	123.78	11	283.41	23	294,785	407.18	21	480.56	426.12	437.01
1974	54.09	60	127.82	53	131,704	181.92	56	378.17	404.47	398.37
1975	96.06	31	178.43	43	198,722	274.49	40	287.86	379.62	359.16
1976	113.01	20	366.44	13	348,057	479.45	16	311.95	377.69	383.67
1977	86.23	36	269.50	26	257,537	355.73	28	369.89	339.75	375.20
1978	108.65	21	333.69	18	320,240	442.34	18	425.84	346.79	386.45
1979	84.96	37	233.26	31	230,381	318.22	33	372.10	374.05	389.26
1980	60.17	54	112.06	59	125,030	172.23	59	310.93	353.59	366.61
1981	60.88	52	170.50	44	167,511	231.38	49	240.61	303.98	340.83
1982	89.00	35	514.20	6	436,697	603.20	8	335.60	353.47	346.61
1983	115.39	18	167.59	46	204,861	282.97	36	372.52	321.60	334.19
1984	122.53	13	262.19	29	279,288	384.72	25	423.63	334.90	354.47
1985	49.88	62	68.91	64	86,000	118.79	65	262.16	324.21	338.90
1986	92.52	33	356.64	16	325,184	449.17	17	317.56	367.77	335.88
1987	108.41	22	126.33	55	169,937	234.73	47	267.56	294.08	323.78
1988	38.38	65	102.37	61	102,170	140.74	63	274.88	265.63	293.62
1989	40.36	64	146.66	48	135,389	187.01	53	187.49	226.09	280.49
1990	76.27	42	190.95	38	193,458	267.22	41	198.32	255.77	289.99
1991	103.11	26	306.66	20	296,660	409.77	20	288.00	247.89	307.83
1992	66.30	47	199.31	35	192,820	265.61	42	314.20	254.07	274.07
1993	128.83	7	444.35	10	414,963	573.18	9	416.19	340.56	303.09
1994	120.16	16	203.50	34	234,312	323.65	31	387.48	367.89	296.99
1995	183.57	3	663.81	1	613,475	847.38	1	581.40	483.92	369.85
1996	179.48	4	522.32	5	509,472	701.80	4	624.28	542.32	395.11
1997	221.55	1	545.83	3	555,558	767.38	2	772.19	642.68	448.37
1998	174.77	5	458.38	9	458,380	633.15	7	700.78	654.67	497.62
Number		68		68			68			
Minimum	30.45		31.08		44,668	61.53		--	--	--
Maximum	221.55		663.81		613,475	847.38		--	--	--
Average	93.18		250.90		249,260	344.08		--	--	--

[1]Individual recharge estimates may not sum to total due to independent rounding.

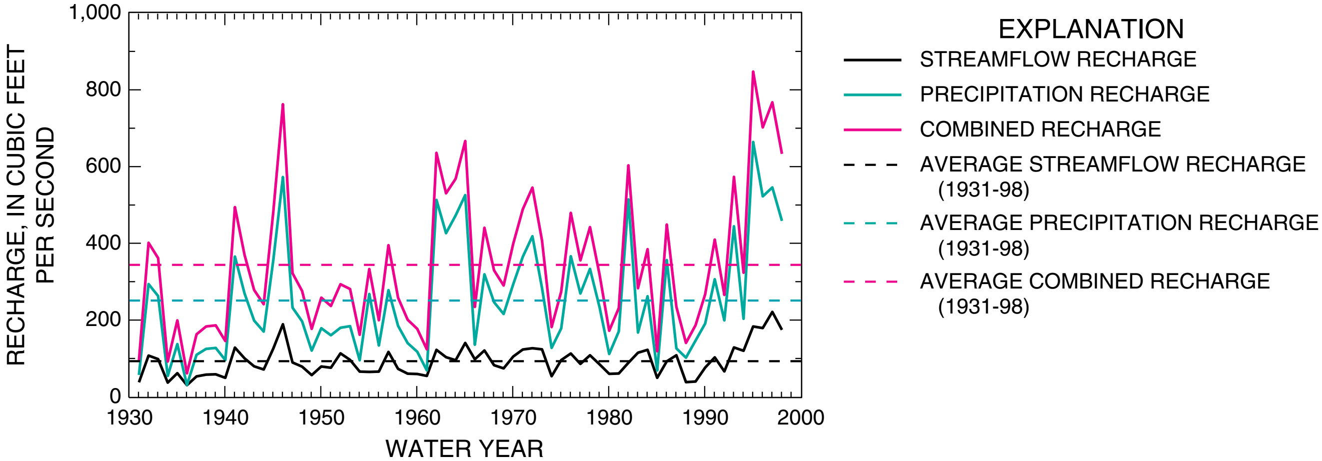


Figure 18. Average annual streamflow, precipitation, and combined recharge.

Recharge along the southeastern flank of the Black Hills probably is dominated by streamflow recharge. Distinctions between streamflow and precipitation recharge have not been computed for specific areas; however, the southeastern flank has small outcrops of Madison Limestone and Minnelusa Formation located in an area with minimal yield efficiency (fig. 16). A number of relatively large streams from Rapid Creek south to Beaver Creek provide a relatively consistent source of streamflow recharge. The western flank of the Black Hills is almost entirely dominated by precipitation recharge because of the large outcrop areas of Madison Limestone and Minnelusa Formation and absence of perennial streams that provide recharge.

The relative contribution from streamflow and precipitation recharge is highly variable along the northern and northeastern flanks of the Black Hills. Yield efficiencies generally are higher than along the southeastern flank; however, the width of outcrops varies considerably. Furthermore, many of the contributing areas for streamflow are small, relative to outcrop areas. In addition, streamflow recharge for Spearfish and Whitewood Creeks has been limited by anthropogenic effects.

Additional insights regarding the relative uncertainties of recharge estimates also are available from examination of table 16. It can be concluded that uncertainties regarding estimates of streamflow recharge for miscellaneous-record and ungaged basins are relatively small compared to overall uncertainty. These areas contribute only about 29 percent of average streamflow recharge (table 12), which constitutes only about 26 percent of total combined recharge (table 16). Thus, these areas generally contribute less than 10 percent of overall recharge. It is further apparent that the largest uncertainty regarding estimated recharge is associated with precipitation recharge, which dominates combined recharge for average conditions. Although the possibility of bias exists for estimates of precipitation recharge, the method used provides a consistent, systematic approach that could be adjusted in various ways, if a consistent bias is later identified and quantified. Results of initial water-budget analyses by Hamade (2000) showed no indication of large biases in estimates of precipitation recharge.

Minimum and maximum average annual precipitation amounts for the Black Hills area between 1931 and 1998 were estimated by Driscoll, Hamade, and Kenner (2000) as 10.22 inches for 1936 and 27.39 inches for 1995. These also are the years for which minimum and maximum recharge are estimated (table 16). Although the absolute level of accuracy for recharge estimates is unknown, there is confidence that on a relative scale the estimates presented herein are consistently realistic.

SUMMARY

The Madison and Minnelusa aquifers are two of the most important aquifers in the Black Hills area. Long-term estimates of recharge to the Madison and Minnelusa aquifers are important for managing the water resources in the Black Hills area of South Dakota and Wyoming. Recharge occurs primarily from streamflow losses and infiltration of precipitation on outcrop areas. Annual recharge from these combined sources is estimated for water years 1931-98. All estimates are for recharge that contributes to regional ground-water flow patterns and that occurs in outcrop areas connected to the regional flow system. Estimates exclude recharge to outcrops areas that are isolated from the regional flow system (erosional remnants), which generally results in ground-water discharge to area streams.

Streamflow losses provide a consistent source of recharge to the Madison and Minnelusa aquifers. Most streams generally lose their entire flow in crossing these outcrops (loss zones), up to "threshold" rates that are unique for each stream. Streamflow recharge is calculated directly for 11 streams by applying estimated loss thresholds (from previous investigations) to available records of daily streamflow obtained from continuous-record gaging stations located upstream from loss zones. Availability of daily records ranges from 1992-98 for one station to 1950-98 for two stations. Daily streamflow records are extrapolated, when necessary, using correlations with long-term gages, to develop annual estimates of streamflow recharge for 1950-98.

Streamflow recharge is estimated for a number of smaller basins, using previously determined loss thresholds for miscellaneous-record sites. Synthetic records of daily streamflow for 1992-98 are developed for these basins, using drainage-area ratios applied to records for nearby continuous-record gaging stations, with recharge calculated directly by applying the loss thresholds. Recharge estimates are further extrapolated for 1950-91, based on the average percentage of streamflow recharge contributed by these basins during 1992-98, relative to overall streamflow recharge.

Streamflow recharge also is estimated for drainage areas with undetermined loss thresholds (ungaged basins) that are situated between larger basins with known thresholds. Recharge estimates for 1992-98 are based on estimates of annual streamflow derived using drainage-area ratios, relative to representative gaged streams. Recharge is assumed equal to 90 percent of annual streamflow, and estimates are again extrapolated for 1950-91, based on the average percentage of streamflow recharge contributed by these basins.

Precipitation recharge is estimated using relations between precipitation and basin yield for the Black Hills area. Streamflow records are available for numerous basins dominated by crystalline outcrops, where regional ground-water flow is considered negligible and basin yield represents the residual between precipitation and evapotranspiration. Streamflow records also are available for several streams, which are dominated by ground-water discharge from the Madison and/or Minnelusa aquifers. Basin yields for some of these streams are quite similar to yields in crystalline basins; however, presumed incongruences in contributing surface- and ground-water areas result in dissimilar yields for several streams.

Because of apparent differences in yield characteristics, positive correlations between annual yield efficiency (ratio of basin yield to precipitation) and precipitation are used in developing a systematic approach for estimating recharge efficiency. These relations are used to compute yield efficiencies for missing years of record between 1950 and 1998. Average yield efficiencies for this period are used to generate a map of generalized average yield efficiency for the Black Hills area. A simplifying assumption is made that yield efficiency can be used as a surrogate for recharge efficiency to the Madison and Minnelusa aquifers. An exponential equation for adjusting average yield efficiency, based on the ratio of annual to average precipitation, is used to predict annual yield (or recharge) efficiency. A geographic information system (GIS) algorithm is used to compute annual recharge, based on comparison of 1,000-by-1,000-meter grids for average precipitation, annual precipitation, and average yield efficiency. This method is used to estimate annual precipitation recharge for 1931-98, based on precipitation records for this period. Estimates of precipitation recharge for 1931-49 are used to estimate streamflow recharge for the same period, based on correlations between the two variables for 1989-98.

Yield efficiency, which is used as a surrogate for the efficiency of precipitation recharge, is highly variable in the Black Hills area and ranges from an average of just over 2 percent in the south to in excess of 30 percent in the north. Accordingly, average precipitation recharge ranges from about 0.4 inch in the southern Black Hills to 8.7 inches in the northwestern Black Hills.

Combined streamflow and precipitation recharge averaged about 344 ft^3/s for 1931-98. Streamflow recharge averaged about 93 ft^3/s, or 27 percent of combined recharge, and precipitation recharge averaged about 251 ft^3/s, or 73 percent of combined recharge. Combined recharge ranged from about 62 ft^3/s in 1936 to 847 ft^3/s in 1995. The lowest recharge amounts generally occurred during the 1930's; however, a more prolonged period of low recharge occurred during 1947-61. Recharge during 1931-61 is below average for most years, and recharge during 1962-98 is above average for many years. Recharge during the 1990's is higher than for any other period.

Precipitation recharge is consistently larger than streamflow recharge; however, the relative proportion of streamflow recharge increases as combined recharge decreases. The minimum value for combined recharge (about 62 ft^3/s for 1936) consists of 49.5 and 50.5 percent, respectively, from streamflow and precipitation recharge. This compares with 21.7 and 78.3 percent, respectively, for the maximum recharge value of about 847 ft^3/s in 1995.

For 1931-98, average precipitation recharge to the Madison aquifer is about 3.6 inches, compared with 2.6 inches for the Minnelusa aquifer. Because the outcrop area of the Minnelusa Formation is larger, however, recharge volumes are nearly identical. Streamflow recharge to the Madison aquifer is presumed slightly larger than for the Minnelusa aquifer, primarily because of preferential recharge resulting from an upgradient location. Considering both precipitation and streamflow recharge, the Madison aquifer receives about 55 percent of combined recharge, relative to about 45 percent for the Minnelusa aquifer. Relative recharge proportions, however, have considerable temporal variability and very large spatial variability, depending on outcrop patterns.

The western flank of the Black Hills is almost entirely dominated by precipitation recharge, because of the large outcrop areas of Madison Limestone and Minnelusa Formation and absence of perennial streams. Recharge along the southeastern flank of the Black Hills generally is dominated by streamflow recharge. The relative contribution from streamflow and precipitation recharge is highly variable along the northern and northeastern flanks of the Black Hills.

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SUPPLEMENTAL INFORMATION

Table 17. Estimated average annual recharge for streams with continuous-record stations using two methods, water years 1950-98

[Shaded cells are used in final total; --, not determined]

Water year	Average annual recharge (cubic feet per second)														
	Battle Creek (basins 8 and 8A)			Boxelder Creek (basins 18 and 18A)			Grace Coolidge Creek (basin 10)			French Creek (basin 7)			Spring Creek (basin 14)		
	Calcu-lated	Estimated recharge regres-sion	Estimated stepwise regres-sion	Calcu-lated	Estimated recharge regres-sion	Estimated stepwise regres-sion	Calcu-lated	Estimated recharge regres-sion	Estimated stepwise regres-sion	Calcu-lated	Estimated recharge regres-sion	Estimated stepwise regres-sion	Calcu-lated	Estimated recharge regres-sion	Estimated stepwise regres-sion
1950	--	--	3.50	--	--	9.89	--	--	2.22	--	--	4.22	--	--	6.33
1951	--	--	3.36	--	--	8.14	--	--	2.34	--	--	3.87	--	--	5.91
1952	--	--	5.01	--	--	12.70	--	--	3.97	--	--	5.05	--	--	18.95
1953	--	--	3.84	--	--	11.46	--	--	2.27	--	--	4.33	--	--	11.93
1954	--	--	3.01	--	--	7.19	--	--	1.80	--	--	3.31	--	--	2.22
1955	--	--	2.87	--	--	7.28	--	--	1.71	--	--	3.53	--	--	.00
1956	--	--	3.06	--	--	6.60	--	--	1.98	--	--	3.21	--	--	3.74
1957	--	--	5.50	--	--	12.90	--	--	4.98	--	--	5.64	--	--	19.99
1958	--	--	3.44	--	--	7.60	--	--	2.48	--	--	3.63	--	--	6.41
1959	--	--	3.01	--	--	5.39	--	--	1.93	--	--	2.64	--	--	4.74
1960	--	--	2.97	--	--	5.55	--	--	1.82	--	--	2.63	--	--	4.58
1961	--	--	2.87	--	--	4.39	--	--	1.72	--	--	2.14	--	--	4.70
1962	4.43	--	5.65	--	--	16.39	--	--	4.54	--	--	6.36	--	--	16.78
1963	6.61	--	4.82	--	--	13.56	--	--	4.10	--	--	6.07	--	--	4.94
1964	5.61	--	3.76	--	--	11.78	--	--	2.59	--	--	5.17	--	--	4.68
1965	5.79	--	6.38	--	--	21.06	--	--	5.53	--	--	8.58	--	--	7.59
1966	3.94	--	3.80	--	--	12.22	--	--	2.31	--	--	4.85	--	--	9.11
1967	5.18	--	6.07	18.13	--	18.85	--	4.33	4.30	--	7.05	6.26	--	11.54	29.01
1968	3.84	--	3.57	9.57	--	9.95	--	2.97	2.53	--	4.22	4.60	--	7.28	4.62
1969	3.11	--	3.59	9.18	--	10.83	--	2.33	2.49	--	3.81	4.93	--	6.21	3.05
1970	3.89	--	3.76	16.76	--	14.73	--	3.18	2.32	--	6.14	6.19	--	9.45	4.89
1971	5.01	--	5.53	19.21	--	18.82	--	4.21	4.22	--	7.27	7.30	--	11.64	8.66
1972	5.59	--	5.27	18.18	--	18.45	--	4.68	4.56	--	7.24	8.20	--	12.08	.00
1973	5.56	--	4.27	16.79	--	17.08	--	4.63	3.33	--	6.86	7.80	--	11.64	1.98
1974	1.81	--	3.32	6.58	--	11.12	--	1.15	2.28	--	2.57	5.32	--	3.76	.00
1975	3.67	--	3.51	14.89	--	11.58	--	2.95	2.27	--	5.55	5.10	--	8.62	4.34
1976	5.16	--	4.73	15.18	--	16.38	--	4.25	4.12	--	6.27	7.68	--	10.65	5.04

Table 17. Estimated average annual recharge for streams with continuous-record stations using two methods, water years 1950-98–Continued

[Shaded cells are used in final total; --, not determined]

Water year	Average annual recharge (cubic feet per second)														
	Battle Creek (basins 8 and 8A)			Boxelder Creek (basins 18 and 18A)			Grace Coolidge Creek (basin 10)			French Creek (basin 7)			Spring Creek (basin 14)		
	Calculated	Estimated recharge regression	Estimated stepwise regression	Calculated	Estimated recharge regression	Estimated stepwise regression	Calculated	Estimated recharge regression	Estimated stepwise regression	Calculated	Estimated recharge regression	Estimated stepwise regression	Calculated	Estimated recharge regression	Estimated stepwise regression
1977	2.93	--	3.56	14.73	--	11.46	1.27	2.31	2.31	--	5.20	5.00	--	7.60	4.03
1978	4.46	--	4.81	15.84	--	16.59	3.90	3.65	3.72	--	6.14	6.99	--	9.93	7.54
1979	4.13	--	3.57	8.79	--	10.31	3.66	3.20	2.68	--	4.14	5.00	--	7.42	4.01
1980	2.72	--	3.29	5.94	--	7.74	1.17	1.92	2.32	--	2.79	3.80	--	4.76	4.36
1981	3.01	--	3.35	4.55	--	7.34	2.45	2.13	2.42	--	2.54	3.63	--	4.71	6.53
1982	4.14	--	4.14	10.14	--	16.85	3.89	3.24	2.57	--	4.50	6.79	--	7.84	8.79
1983	3.81	--	3.90	21.64	--	15.27	2.48	3.23	2.59	7.05	7.39	6.57	--	10.78	3.45
1984	4.89	--	4.41	19.63	--	15.52	3.97	4.11	3.42	6.86	7.32	6.86	--	11.60	5.03
1985	1.22	--	3.39	7.17	--	7.93	.82	.65	2.38	3.53	2.47	3.75	--	3.16	5.07
1986	4.32	--	4.28	13.10	--	13.55	2.03	3.47	2.33	3.63	5.36	4.52	--	8.94	20.21
1987	6.22	--	3.87	10.92	--	11.06	3.49	5.06	2.73	5.50	5.59	4.80	10.64	10.78	10.76
1988	.76	--	3.07	5.07	--	7.16	.61	.21	1.97	2.11	1.72	3.43	1.80	1.95	2.84
1989	.89	--	2.93	4.19	--	6.90	1.20	.30	1.80	1.02	1.55	3.36	.98	1.86	1.15
1990	5.09	--	3.47	6.18	--	7.71	3.40	3.96	2.60	3.65	3.86	3.81	6.76	7.91	7.80
1991	5.15	--	5.19	11.21	--	10.71	4.92	4.14	5.01	5.63	5.21	5.30	10.92	9.47	10.27
1992	3.72	--	3.30	7.57	--	6.52	2.98	2.82	2.34	4.48	3.64	3.21	7.46	6.53	6.02
1993	6.66	--	5.84	18.05	--	14.95	7.12	5.60	5.48	7.26	7.66	6.68	13.35	13.44	14.30
1994	5.21	--	4.28	17.53	--	11.87	3.27	4.34	3.32	6.02	6.91	5.22	11.63	11.41	13.14
1995	6.17	--	9.09	21.09	--	29.00	7.20	5.25	9.45	8.91	8.25	12.68	13.64	13.70	17.34
1996	8.10	--	7.48	25.55	--	26.42	6.45	7.02	6.39	10.92	10.26	10.16	18.02	17.52	17.36
1997	10.50	--	9.61	34.08	--	32.89	9.31	9.29	8.64	13.07	13.53	12.18	22.15	23.15	21.60
1998	8.26	--	6.71	28.30	--	20.18	7.57	7.22	6.69	12.12	11.05	9.25	18.89	18.53	13.67
Mean 1950-98	--	--	4.37	--	--	12.85	--	--	3.34	--	--	5.54	--	--	8.15
Mean 1967-98	4.54	--	4.60	14.24	--	14.24	--	3.68	3.61	--	5.75	6.14	--	9.56	8.34
Mean 1992-98	6.95	--	6.62	21.74	--	20.26	6.27	5.94	6.04	8.97	8.76	8.48	15.02	14.90	14.78

Table 17. Estimated average annual recharge for streams with continuous-record stations using two methods—Continued

[Shaded cells are used in final total; --, not determined]

Water year	Average annual recharge (cubic feet per second)														
	Bear Butte Creek (basins 37, 38, and 39)			Bear Gulch (basin 11)			Beaver Creek (basin 1)			Elk Creek (basins 20 and 21)			Total		
	Calculated	Estimated recharge regression	Estimated stepwise regression	Calculated	Estimated recharge regression	Estimated stepwise regression	Calculated	Estimated recharge regression	Estimated stepwise regression	Calculated	Estimated recharge regression	Estimated stepwise regression	Calculated	Estimated recharge regression	Estimated stepwise regression
1950	--	--	8.62	--	--	0.36	--	--	1.74	--	--	7.62	--	--	44.50
1951	--	--	7.72	--	--	.35	--	--	1.22	--	--	7.06	--	--	39.96
1952	--	--	9.61	--	--	.33	--	--	.81	--	--	7.26	--	--	63.67
1953	--	--	8.79	--	--	.36	--	--	1.81	--	--	7.72	--	--	52.51
1954	--	--	7.47	--	--	.35	--	--	1.17	--	--	6.79	--	--	33.32
1955	--	--	7.80	--	--	.36	--	--	1.51	--	--	7.15	--	--	32.21
1956	--	--	7.00	--	--	.34	--	--	.86	--	--	6.51	--	--	33.29
1957	--	--	10.15	--	--	.31	--	--	.39	--	--	7.19	--	--	67.05
1958	--	--	7.48	--	--	.33	--	--	.81	--	--	6.65	--	--	38.83
1959	--	--	6.21	--	--	.32	--	--	.29	--	--	5.82	--	--	30.35
1960	--	--	6.25	--	--	.33	--	--	.40	--	--	5.90	--	--	30.41
1961	--	--	5.56	--	--	.31	--	--	.00	--	--	5.34	--	--	27.04
1962	--	--	12.49	--	--	.35	--	--	1.64	--	--	8.47	--	--	72.67
1963	--	--	12.21	--	--	.35	--	--	1.80	--	--	8.47	--	--	56.32
1964	--	--	10.11	--	--	.38	--	--	2.39	--	--	8.53	--	--	49.39
1965	--	--	17.16	--	--	.38	--	--	3.07	--	--	10.53	--	--	80.28
1966	--	--	9.59	--	--	.38	--	--	2.34	--	--	8.35	--	--	52.95
1967	--	11.91	12.02	--	.35	.35	--	1.72	1.79	--	7.75	8.54	--	67.97	87.20
1968	--	9.04	9.04	--	.32	.36	--	.27	1.83	--	6.05	7.85	--	43.57	44.36
1969	--	7.47	9.74	--	0.32	0.37	--	0.20	2.23	--	5.12	8.31	--	37.76	45.53
1970	--	9.14	11.44	--	.35	.41	--	1.49	3.81	--	6.11	10.07	--	56.50	57.63
1971	--	11.55	14.87	--	.35	.39	--	1.90	3.04	--	7.54	9.96	--	68.68	72.79
1972	--	12.78	18.02	--	.35	.40	--	1.73	3.67	--	8.26	10.83	--	70.89	69.40
1973	--	12.73	13.69	--	.35	.43	--	1.49	4.53	--	8.23	11.33	--	68.29	64.45
1974	--	4.69	10.28	--	.31	.39	--	.00	2.89	--	3.48	8.98	--	24.35	44.57
1975	--	8.67	9.77	--	.34	.38	--	1.17	2.66	--	5.83	8.71	--	51.69	48.34
1976	--	11.87	13.41	--	.34	.40	--	1.22	3.57	--	7.73	10.53	--	62.67	65.85

Table 17. Estimated average annual recharge for streams with continuous-record stations using two methods—Continued

[Shaded cells are used in final total; --, not determined]

Water year	Average annual recharge (cubic feet per second)														
	Bear Butte Creek (basins 37, 38, and 39)			Bear Gulch (basin 11)			Beaver Creek (basin 1)			Elk Creek (basins 20 and 21)			Total		
	Calculated	Estimated recharge regression	Estimated stepwise regression	Calculated	Estimated recharge regression	Estimated stepwise regression	Calculated	Estimated recharge regression	Estimated stepwise regression	Calculated	Estimated recharge regression	Estimated stepwise regression	Calculated	Estimated recharge regression	Estimated stepwise regression
1977	--	7.08	9.83	--	.34	.38	--	1.14	2.51	--	4.89	8.55	--	46.22	47.64
1978	--	10.37	13.15	--	.34	.39	--	1.33	3.22	--	6.83	9.96	--	58.90	66.37
1979	--	9.65	9.31	--	.32	.37	--	.13	2.11	--	6.41	8.25	--	44.18	45.61
1980	--	6.65	7.71	--	.31	.34	--	.00	1.16	--	4.63	6.99	--	29.73	37.71
1981	--	7.25	7.22	--	.31	.34	--	.00	.86	--	4.99	6.69	--	29.49	38.37
1982	--	9.69	12.22	--	.32	.42	--	.36	4.22	--	6.43	10.65	--	46.67	66.65
1983	--	8.97	12.12	--	.36	.42	--	2.31	3.95	--	6.01	10.34	--	64.50	58.61
1984	--	11.28	12.60	--	.36	.40	--	1.97	3.40	--	7.37	10.04	--	68.53	61.69
1985	--	3.42	7.80	--	.31	.34	--	.00	1.05	--	2.73	6.88	--	21.14	38.60
1986	--	10.07	8.85	--	.33	.36	--	.87	1.94	--	6.66	7.90	--	53.14	63.96
1987	--	14.15	8.86	--	.33	.36	--	.50	1.83	--	9.07	7.94	--	62.61	52.21
1988	--	2.44	7.43	--	.31	.34	--	.00	1.13	--	2.15	6.81	--	14.61	34.19
1989	5.56	2.72	7.42	--	0.30	0.35	--	0.00	1.23	--	2.31	6.85	--	14.13	31.99
1990	6.76	11.71	7.33	0.33	.31	.34	--	.00	.88	--	7.63	6.78	--	46.65	40.70
1991	11.25	11.85	10.43	.29	.33	.30	.23	.55	.00	--	7.71	6.72	--	55.63	53.92
1992	5.03	8.78	6.86	.32	.32	.33	.33	.00	.49	4.67	5.89	6.22	35.87	39.27	35.30
1993	12.76	15.07	12.51	.34	.35	.33	.76	1.71	1.02	8.36	9.62	8.13	73.73	78.15	69.24
1994	14.24	11.98	9.34	.35	.35	.35	1.35	1.62	1.68	9.15	7.79	8.01	67.60	67.14	57.21
1995	21.52	14.03	22.56	.36	.36	.38	2.77	2.22	3.46	10.04	9.00	12.60	90.73	80.07	116.55
1996	18.12	18.17	19.31	.39	.37	.40	3.98	2.98	3.91	11.52	11.45	11.87	101.85	101.43	103.29
1997	25.60	23.30	24.22	.39	.40	.39	3.89	4.42	3.77	13.91	14.49	12.63	131.72	133.17	125.94
1998	15.27	18.50	16.14	.39	.38	.36	3.56	3.44	2.58	12.25	11.65	10.44	105.05	107.33	86.02
Mean 1950-98	--	--	10.81	--	--	0.36	--	--	2.01	--	--	8.40	--	--	55.85
Mean 1967-98	--	10.53	11.73	--	0.34	0.37	--	1.15	2.39	--	6.93	8.95	--	56.72	60.37
Mean 1992-98	16.08	15.69	15.85	0.36	0.36	0.36	2.38	2.34	2.42	9.99	9.98	9.99	86.65	86.65	84.79