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Streamflow Losses in the Black Hills of Western South Dakota

Water-Resources Investigations Report 98-4116

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

A Looking upstream

B Looking upstream

C Looking downstream

D Looking upstream

Inside cover: Sequence along Boxelder Creek from upstream to downstream showing A) full flow at site 35, located just upstream from loss zone; B) dry channel at base of Madison Limestone cliff, about one-half mile downstream; C) modest flow at site 36, resulting from springflow within loss zone; and D) complete loss of flow about one-half mile downstream. Photographs by D.G. Driscoll.

Front cover: Photograph showing John McFarland standing near whirlpool along loss zone in Boxelder Creek, 1998. Provided by Dr. P.H. Rahn.

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By Jon E. Hortness and Daniel G. Driscoll

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Bruce Babbitt, Secretary

U.S. Geological Survey

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
Area		
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer
Volume		
square foot (ft^2)	0.09290	square meter
cubic foot (ft^3)	0.02832	cubic meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot (acre-ft)	0.001233	cubic hectometer
Flow rate		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

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

$$°F = (1.8 \times °C) + 32$$

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: In Geological Survey reports dealing with surface-water supply, water year is the 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends; thus, the water year ending September 30, 1996, is called the "1996 water year."

Streamflow Losses in the Black Hills of Western South Dakota

By Jon E. Hortness *and* Daniel G. Driscoll

ABSTRACT

Losses occur in numerous streams that cross outcrops of various sedimentary rocks that are exposed around the periphery of the Black Hills of South Dakota. These streamflow losses are recognized as an important source of local recharge to regional bedrock aquifers. Most streams lose all of their flow up to some threshold rate. Streamflow is maintained through a loss zone when the threshold is exceeded. Streamflow records for 86 measurement sites are used to determine bedrock loss thresholds for 24 area streams, which have individual loss thresholds that range from negligible (no loss) to as much as 50 cubic feet per second. In addition, insights are provided regarding springflow that occurs in the immediate vicinity of selected loss zones.

Most losses occur to outcrops of the Madison Limestone and Minnelusa Formation. Losses to the Deadwood Formation probably are minimal. Losses to the Minnekahta Limestone generally are small; however, they are difficult to quantify because of potential losses to extensive alluvial deposits that commonly are located near Minnekahta outcrops.

Loss thresholds for each stream are shown to be relatively constant, without measurable effects from streamflow rates or duration of flow through the loss zones. Calculated losses for measurements made during high-flow conditions generally have larger variability than calculated losses for low-flow conditions; however, consistent relations between losses and streamflow have not been identified. Some of this variability results from the inability to account for tributary inflows and changes in storage. Calculated losses are shown to decrease, in some cases, during periods of extended flow through loss zones. Decreased "net" losses, however, generally can be attributed to springflow (ground-water discharge) within a loss zone, which may occur during prolonged periods of wet climatic conditions.

Losses to unsaturated alluvial deposits located adjacent to the stream channels are found to have significant effects on determination of bedrock losses. Large losses occur in filling initial storage in unsaturated alluvial deposits downstream from loss zones, when bedrock loss thresholds are first exceeded. Losses to alluvial deposits in the range of tens of cubic feet per second and alluvial storage capacities in the range of hundreds of acre-feet are documented.

Significant changes in loss thresholds for Grace Coolidge Creek, Spring Creek, and Whitewood Creek are documented. Introduction of large quantities of fine-grained sediments into these stream channels may have affected loss thresholds for various periods of time.

INTRODUCTION

The Black Hills area is an important resource center for the State of South Dakota. Not only do the Black Hills provide an economic base for western South Dakota through tourism, agriculture, the timber industry, and mineral resources, they also are an important source of water. Water originating from the area is used for municipal, industrial, agricultural, and recreational purposes throughout much of western South Dakota.

Population growth and resource development 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.

Streamflow losses are known to occur in Black Hills streams that cross the outcrops of various sedimentary rocks. Early expeditions to the Black Hills documented streamflow losses in various locations along the periphery of the Hills (Dodge, 1876). Although reducing surface flow, these losses are recognized as an important source of local recharge to regional bedrock aquifers (Downey and Dinwiddie, 1988).

Many streams generally lose their entire flow to “loss zones” during periods of base flow (Rahn and Gries, 1973). Until streamflow upstream from a loss zone exceeds the “threshold” rate, the entire flow of the stream becomes recharge to various bedrock aquifers. When streamflow upstream from the loss zone exceeds the bedrock loss threshold, some flow is sustained through the loss zone, and the loss rate (recharge) is equal to the threshold.

Purpose and Scope

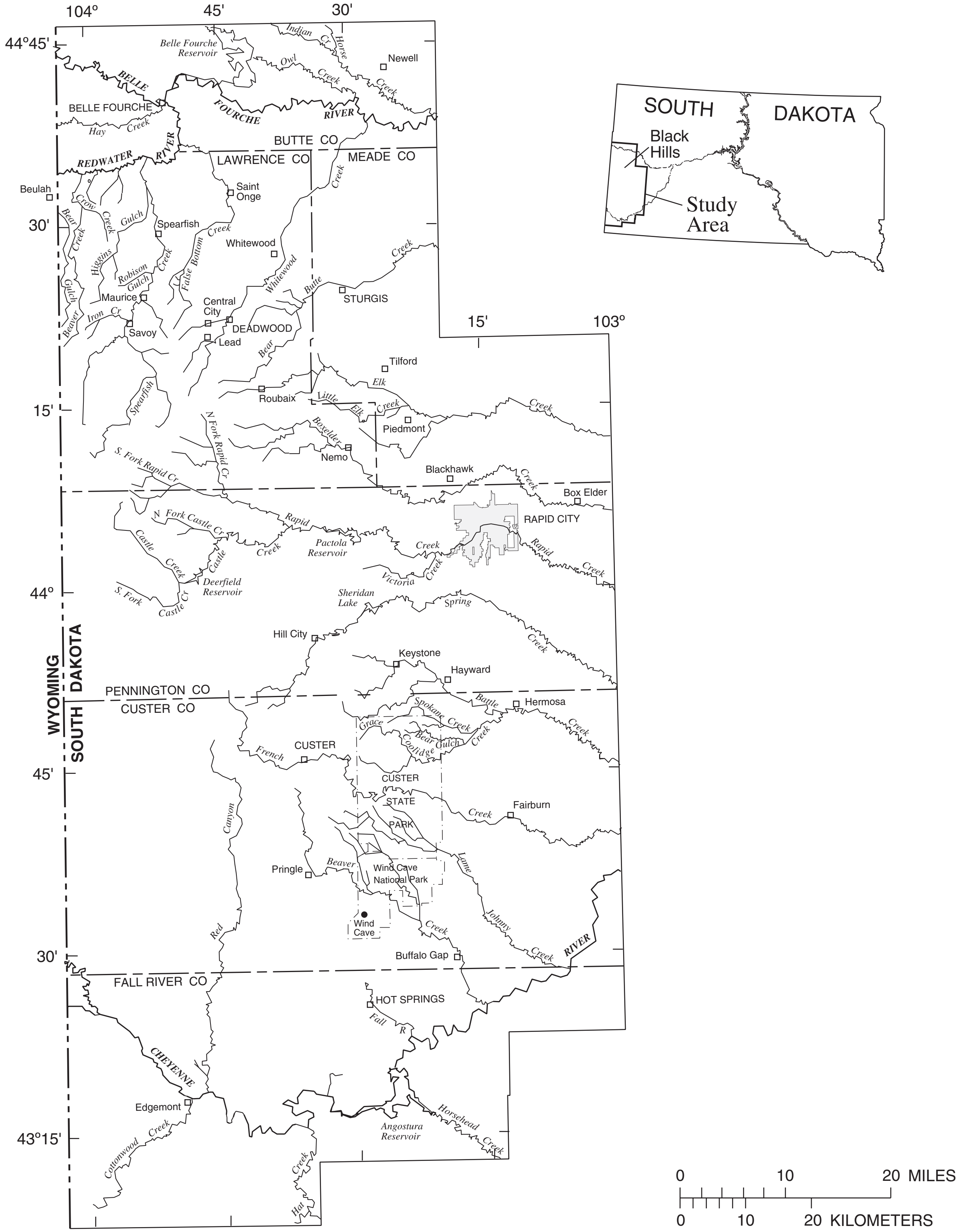
The purposes of this report are to: (1) summarize streamflow records pertinent to determination of loss rates; (2) present estimates of threshold loss rates to bedrock aquifers for selected streams; and (3) present an evaluation of whether loss thresholds are relatively constant or whether they are affected by factors such as streamflow rates or duration of flow through loss zones. Streamflow records through water year 1996 (WY96), which ended September 30, 1996, are considered in this report.

Estimates of loss thresholds are presented for 24 streams, which represent most of the larger, perennial streams in the Black Hills of South Dakota. A better understanding of streamflow losses will be an important contribution to future estimates of streamflow recharge to aquifers in the Black Hills area. Streamflow losses to the Madison Limestone and Minnelusa Formation are the primary consideration; however, losses to the Deadwood Formation and Minnekahta Limestone also are evaluated.

Description of Study Area

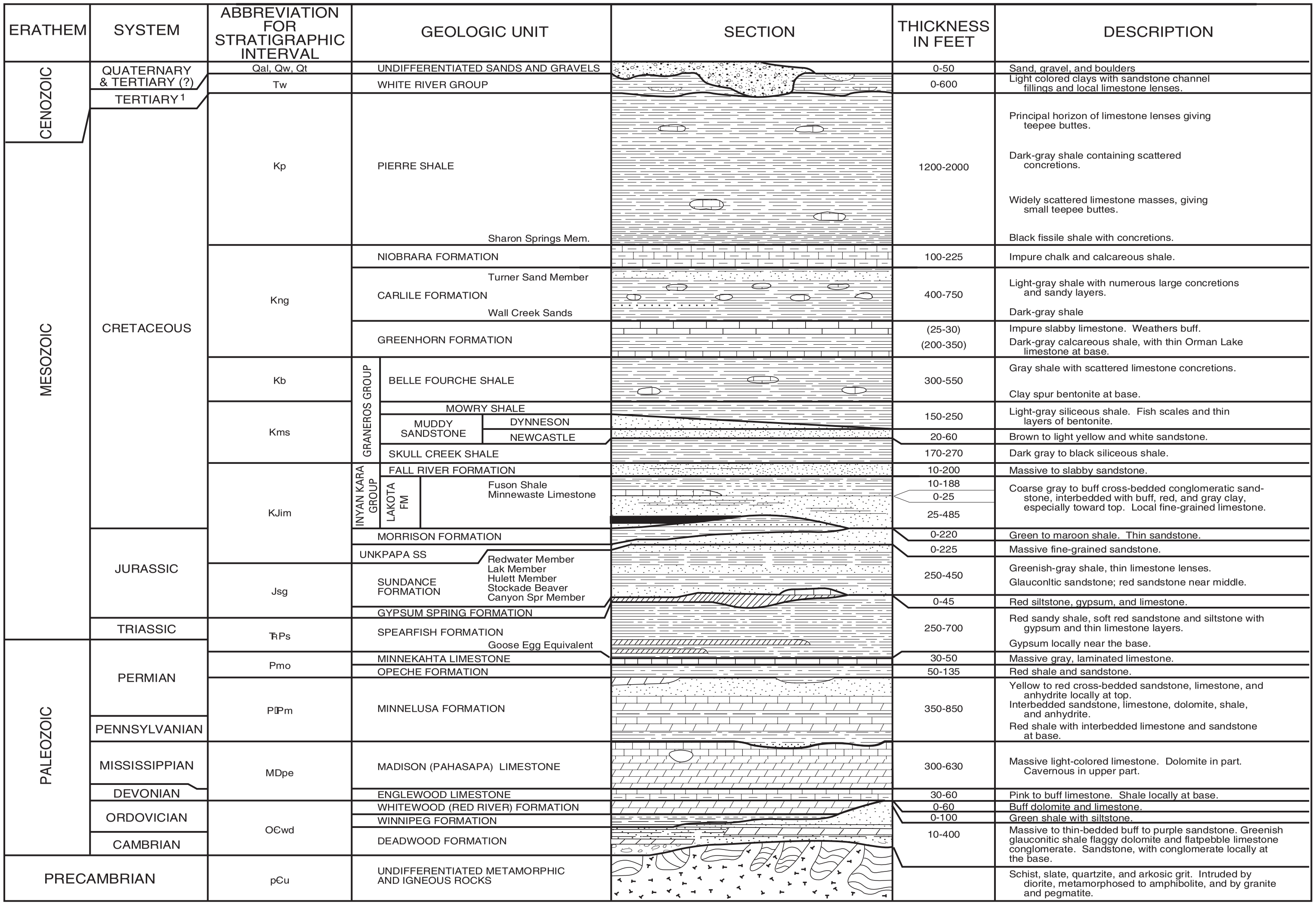
The study area consists of the topographically defined Black Hills and adjacent areas located in western South Dakota (fig. 1). The Black Hills area is an elongated, dome-shaped feature, about 125 mi long and 60 mi wide, which was uplifted during the Laramide orogeny (Feldman and Heimlich, 1980). Elevations range from about 7,200 ft above sea level, at the higher peaks to about 3,000 ft in the surrounding plains, resulting in an orographically induced microclimate characterized by generally greater precipitation and lower temperatures at the higher elevations. The overall climate of the area is continental, with generally low precipitation amounts, hot summers, cold winters, and extreme variations in both precipitation and temperatures (Johnson, 1933). Average annual precipitation for the Black Hills area (1961-90), is 21.90 in. (U.S. Department of Commerce, 1996), and ranges from 15.83 in. at Hot Springs (elevation = 3,560 ft) to 29.01 in. at Lead (elevation = 5,350 ft). The average annual temperature is 43.9 degrees Fahrenheit, and ranges from 48.6 degrees at Hot Springs to approximately 37 degrees near Deerfield Reservoir (elevation = 6,060 ft).

The oldest geologic units in the stratigraphic sequence are the Precambrian metamorphic and igneous rocks (fig. 2), which are exposed in the central core of the Black Hills, extending from near Lead to south of Custer. Surrounding the Precambrian core is a layered series of sedimentary rocks including limestones, sandstones, and shales that are exposed in roughly concentric rings around the uplifted flanks of the Black Hills (DeWitt and others, 1989). The generalized outcrop of the Madison Limestone, also known locally as the Pahasapa Limestone, is shown in figure 3. The generalized outer extent of the outcrop of the Inyan Kara Group, which approximates the outer extent of the Black Hills uplift, also is shown in figure 3. The bedrock sedimentary units typically dip away from the uplifted Black Hills at angles that approach or exceed 10 degrees near the outcrops, and decrease with distance from the uplift (fig. 4).



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

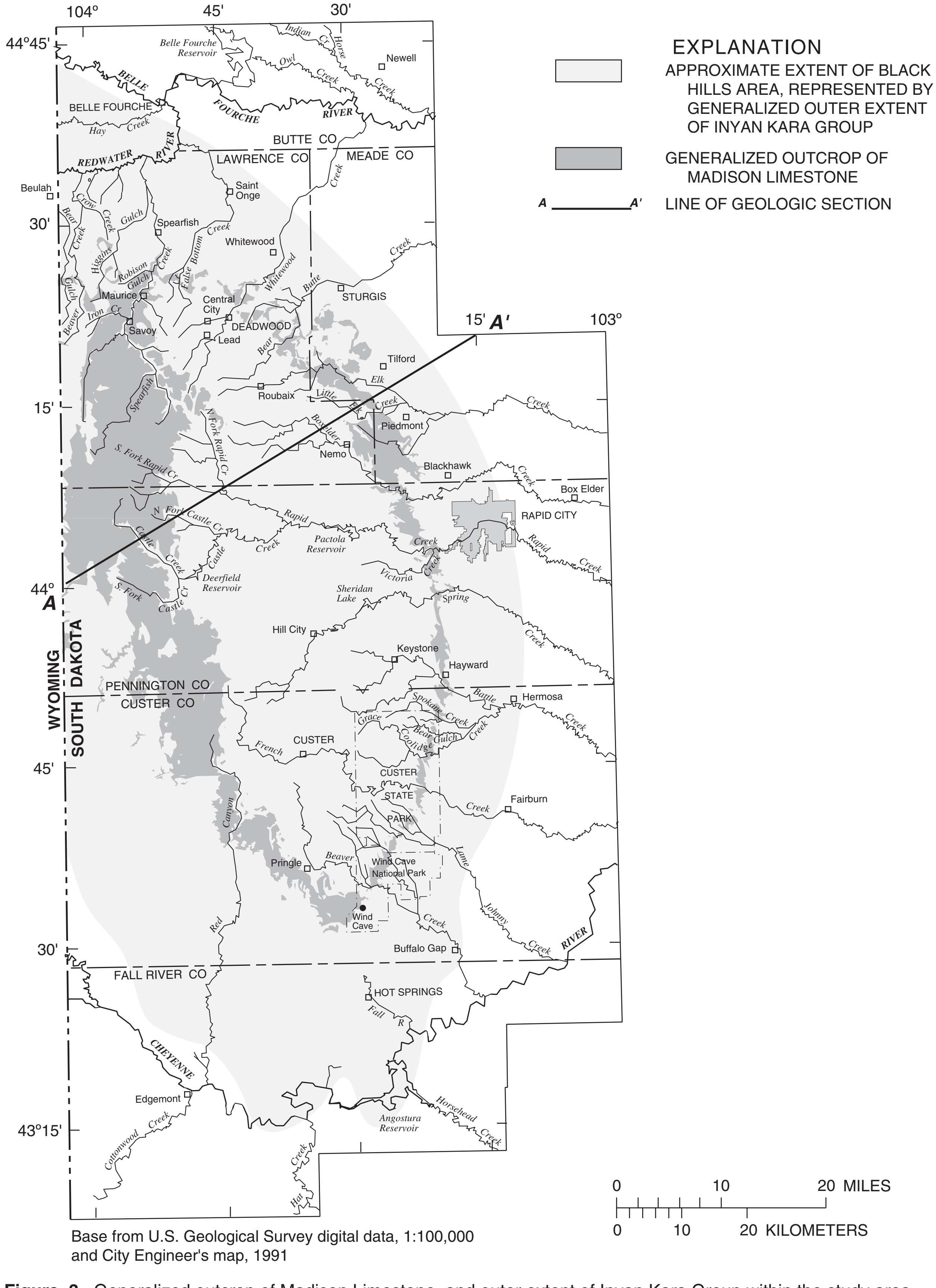
Figure 1. Area of investigation for the Black Hills Hydrology Study.



[1] Also may include intrusive igneous rocks

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

Figure 2. Stratigraphic section for the Black Hills.



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

Figure 3. Generalized outcrop of Madison Limestone and outer extent of Inyan Kara Group within the study area for Black Hills Hydrology Study.

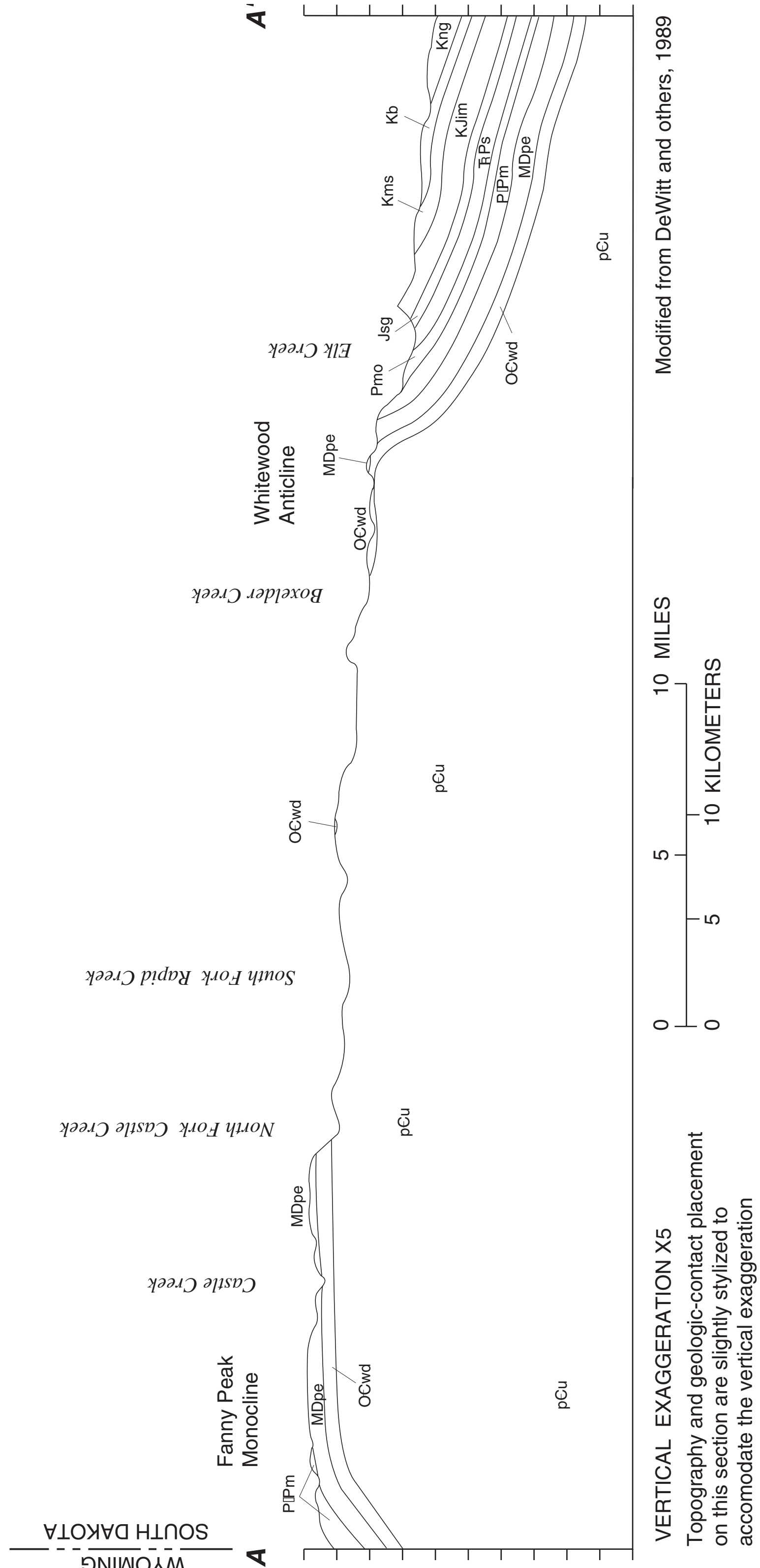


Figure 4. Geologic section A-A'. (Location of section is shown in figure 3. Abbreviations for stratigraphic intervals are explained in figure 2).

Many of the sedimentary units are aquifers, both within and beyond the study area. Recharge to these aquifers occurs from infiltration of precipitation upon the outcrops and, in some cases, from infiltration of streamflow (streamflow losses) (Greene, 1993; Kyllonen and Peter, 1987; Peter, 1985). Within the Paleozoic rock interval (fig. 2), 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 the aquifers are separated by minor confining layers, or by relatively low-permeability layers within the individual formations. Leakage between these aquifers is extremely variable (Greene, 1993; Peter, 1985). Within the Mesozoic rock interval, aquifers in the Inyan Kara Group are used extensively. Aquifers in various other units within the Mesozoic interval are used locally to lesser degrees. As much as 4,000 ft of Cretaceous shales form the upper confining unit to aquifers in the Mesozoic interval.

Artesian 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. If the water level, or potentiometric surface, is above the land surface, a flowing well will result. 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 Black Hills streams 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 units (fig. 2) on the western side of the study area. Most Black Hills streams generally lose all or part of their flow as they cross the outcrop of the Madison Limestone (Rahn and Gries, 1973). Karst features of the Madison Limestone, including sinkholes, collapse features, solution cavities, and caves, are responsible for the Madison's ability to accept recharge from streamflow. Large streamflow losses also occur in many locations within the outcrop of the Minnelusa Formation. Large artesian springs occur in many locations downgradient from loss zones, most commonly within or near the outcrop of the Spearfish

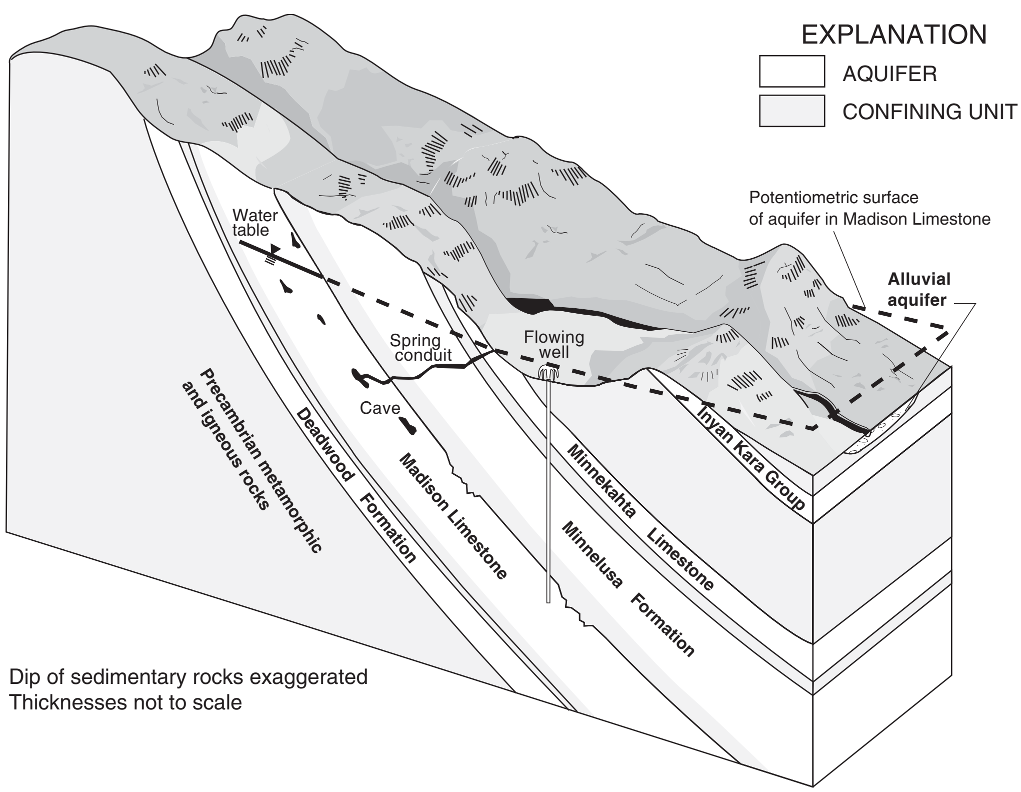


Figure 5. Schematic showing simplified hydrogeologic setting of the Black Hills area.

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).

Previous Investigations

Water losses from local Black Hills streams to outcrops of various sedimentary formations were first noted by Dodge (1876). At that time, it was believed that most losses occurred to the Minnelusa Formation and overlying sandstone units (Newton and Jenny, 1880). Beginning in the late 1930's, various attempts were made to seal loss zones, most often in an effort to benefit ranchers living downstream. The first documented attempt was performed by the U.S. Forest Service on Spring Creek in 1937. This, and additional attempts by the Works Progress Administration, led to several investigations of water losses to help in determining the need for, or success of, sealing projects (Gries, 1969).

An early study of streamflow losses was completed by the U.S. Soil Conservation Service (Brown, 1944). A limited number of streamflow measurements were used to estimate the following losses: 2 to 10 ft^3/s on Rapid Creek; 6 ft^3/s on Spring Creek; greater than 20 ft^3/s on Boxelder Creek; greater than 5 ft^3/s on Elk Creek; greater than 1 ft^3/s on Little Elk Creek; and greater than 5 ft^3/s on French Creek.

An investigation concerned only with streamflow losses from Boxelder Creek to the Madison Limestone (Crooks, 1968) estimated losses between 15 and 43 ft^3/s. Another study by Gries (1969) examined losses to the Madison Limestone and their relation to various springs in the Black Hills. This study produced the following estimated loss rates: Boxelder Creek, 12.5 ft^3/s; Rapid Creek, 6 ft^3/s; Battle Creek, 10 ft^3/s; and Grace Coolidge Creek, 24 ft^3/s. An additional study by Peter (1985) produced the following estimated loss rates for three streams: Boxelder Creek, 12 ft^3/s; Spring Creek, 7 ft^3/s; and Rapid Creek, 6.5 ft^3/s.

Most previous studies dealt with losses for three of the larger streams in the Rapid City area: Rapid Creek, Spring Creek, and Boxelder Creek. Rahn and Gries (1973) studied streamflow losses for the majority of streams in the Black Hills area and concluded that streamflow losses to outcrops of bedrock units totaled about 44 ft^3/s for the Black Hills area.

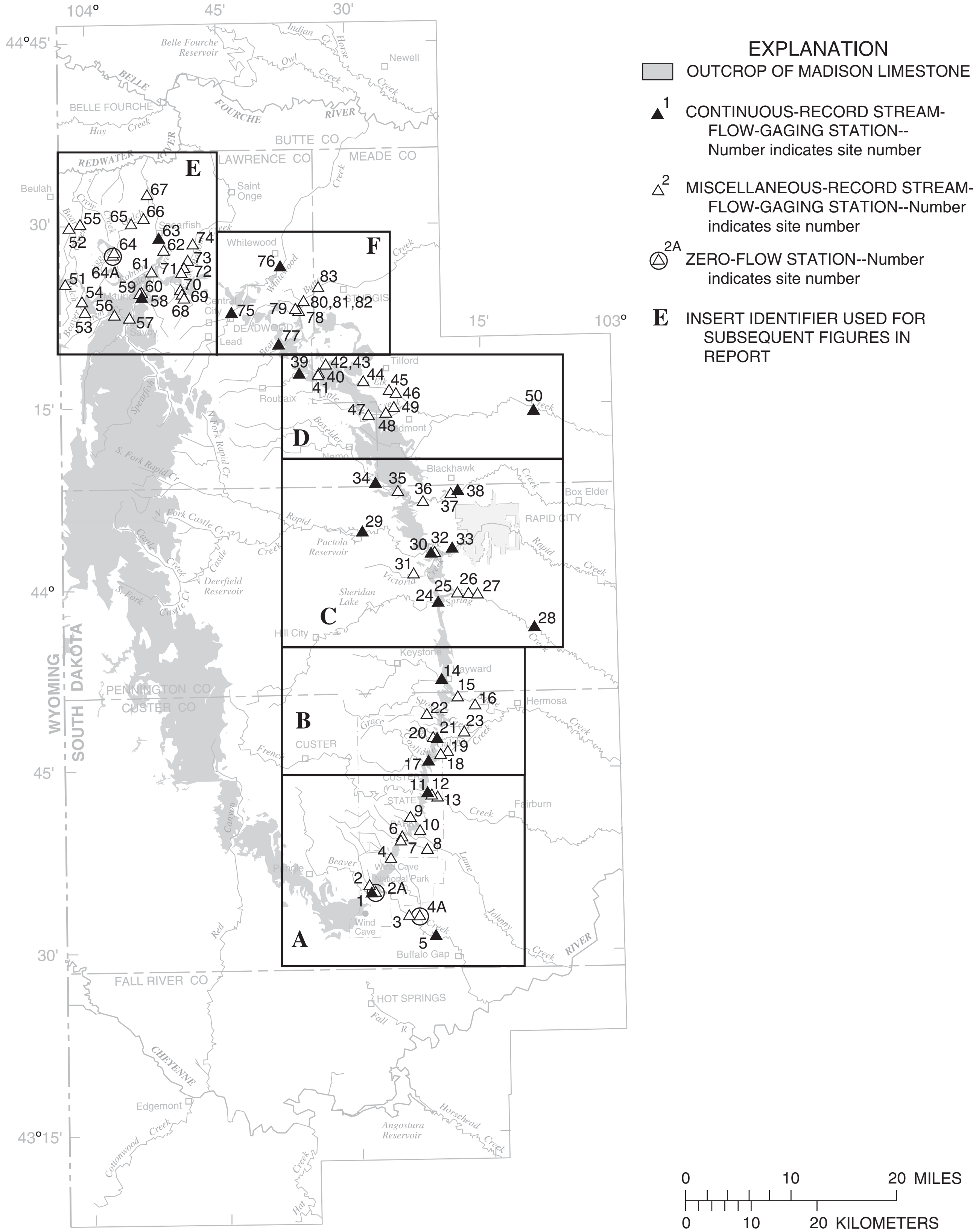
These previous studies have produced various hypotheses concerning water losses from Black Hills streams. Crooks (1968) and Gries (1969) hypothesized that loss rates decreased after extended periods of flow across the loss zones. Crooks and Gries also speculated that the water table in the Madison Limestone typically is below the level of the stream channels but may rise above the level of the channels during periods of high precipitation and streamflow. Gries identified ice formation in stream channels as a possible factor that could reduce loss rates and also hypothesized that streamflow loss rates may be proportional to streamflow up to a certain point, after which they remain stable. Peter (1985) concluded, however, that except during periods when the entire streamflow is lost, losses from Rapid Creek were not proportional to the streamflow.

METHODS

The general method for calculation of streamflow losses is to subtract flow at a downstream measurement site from flow at a measurement site located upstream of a loss zone. This calculation yields a positive value for losses and a negative value for gains. Streamflow records for both continuous-record and miscellaneous-record stations are considered, as described in the following discussion.

Measurement Sites

Streamflow records are considered for a total of 86 measurement sites located on 24 streams (fig. 6). Site information for these sites is presented in table 1. The sites listed in table 1 include 83 streamflow-gaging stations, for which 8- or 15-digit station identification numbers are assigned, along with "site numbers" that reference these stations to locations shown in figure 6. The 8-digit numbers are assigned according to the USGS downstream order system, in which numbering increases in a downstream direction. The 15-digit numbers are assigned according to the latitude-longitude system, in which the first 6 digits denote latitude north of the equator; the next 7 digits denote longitude west of the prime (Greenwich) meridian; and the last 2 digits are sequential numbers for sites located at the same latitude and longitude. Also included in table 1 are three measurement sites without station identification numbers, which are denoted by the letter "A" as part of the site number. All sites in table 1 are arranged in downstream order.



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

Figure 6. Location of streamflow-gaging stations relative to generalized outcrop of Madison Limestone.

Table 1. Measurement sites considered for calculation of streamflow losses

[C, continuous-record station; M, miscellaneous-record station; Z, zero-flow site (no records published but observations of zero flow have been made); --, undetermined]

Site number	Station identification number	Station name	Station type	Drainage area (square miles)	Location (degrees, minutes, seconds) Latitude	Longitude
		Cheyenne River Basin				
1	06402430	Beaver Creek near Pringle	C	45.8	43 34 53	103 28 34
2	433532103284800	Reaves Gulch above Madison outcrop, near Pringle	M	--	43 35 32	103 28 48
2A	([1])	Reaves Gulch above Beaver Creek	Z	--	43 35 01	103 28 12
3	433300103242100	Beaver Creek below Minnekahta outcrop, near Buffalo Gap	M	--	43 33 00	103 24 21
4	433745103261900	Highland Creek above Madison outcrop, near Pringle	M	--	43 37 45	103 26 19
4A	([1])	Highland Creek below Minnekahta outcrop	Z	--	43 32 59	103 23 10
5	06402470	Beaver Creek above Buffalo Gap	C	111	43 31 20	103 21 23
6	433930103250000	South Fork Lame Johnny Creek above Madison outcrop, near Fairburn	M	--	43 39 30	103 25 00
7	433910103251000	Flynn Creek above Madison outcrop, near Fairburn	M	--	43 39 10	103 25 10
8	433827103220900	South Fork Lame Johnny Creek below Minnelusa outcrop, near Fairburn	M	--	43 38 27	103 22 09
9	434105103240200	North Fork Lame Johnny Creek above Madison outcrop, near Fairburn	M	--	43 41 05	103 24 02
10	433958103225700	North Fork Lame Johnny Creek below Madison outcrop, near Fairburn	M	--	43 39 58	103 22 57
11	06403300	French Creek above Fairburn	C	105	43 43 02	103 22 03
12	434246103214300	French Creek at Madison/Minnelusa contact, near Fairburn	M	--	43 42 46	103 21 43
13	434244103205400	French Creek below Minnelusa outcrop, near Fairburn	M	--	43 42 44	103 20 54
14	06404000	Battle Creek near Keystone	C	66	43 52 21	103 20 10
15	435056103182300	Battle Creek at Madison/Minnelusa contact, near Hermosa	M	--	43 50 56	103 18 23
16	435013103162600	Battle Creek below Minnelusa outcrop, near Hermosa	M	--	43 50 13	103 16 26
17	06404998	Grace Coolidge Creek near Game Lodge, near Custer	C	25.2	43 45 40	103 21 49
18	06405400	Grace Coolidge Creek near Fairburn	M[2]	--	43 46 13	103 20 28
19	06405500	Grace Coolidge Creek (below Minnelusa outcrop) near Hermosa	M[2]	--	43 46 28	103 19 41
20	06405797	Bear Gulch above Hayward	M	--	43 47 37	103 21 17
21	06405800	Bear Gulch near Hayward	C	4.23	43 47 31	103 20 49
22	434929103215700	Spokane Creek above Madison outcrop, near Hayward	M	--	43 49 29	103 21 57
23	434800103174400	Spokane Creek below Madison outcrop, near Hayward	M	--	43 48 00	103 17 44
24	06407500	Spring Creek near Keystone	C	163	43 58 45	103 20 25
25	435930103181000	Spring Creek (Madison/Minnelusa contact) near Rapid City	M	--	43 59 30	103 18 10
26	435925103165600	Spring Creek above Minnekahta outcrop, near Rapid City	M	--	43 59 25	103 16 56

Table 1. Measurement sites considered for calculation of streamflow losses —Continued

[C, continuous-record station; M, miscellaneous-record station; Z, zero-flow site (no records published but observations of zero flow have been made); --, undetermined]

Site number	Station identification number	Station name	Station type	Drainage area (square miles)	Location	
					Latitude	Longitude
					(degrees, minutes, seconds)	
		Cheyenne River Basin—Continued				
27	06408000	Spring Creek near Rapid City	M[2]	171	43 59 20	103 15 55
28	06408500	Spring Creek near Hermosa	C	199	43 56 31	103 09 32
29	06411500	Rapid Creek below Pactola Dam	C	320	44 04 36	103 28 54
30	06412200	Rapid Creek above Victoria Creek, near Rapid City	C	355	44 02 48	103 21 06
31	440105103230700	Victoria Creek below Victoria Dam, near Rapid City	M	--	44 01 05	103 23 07
32	440251103204100	Victoria Creek at mouth, near Rapid City	M	--	44 02 51	103 20 41
33	06412500	Rapid Creek above Canyon Lake, near Rapid City	C	371	44 03 10	103 18 41
34	06422500	Boxelder Creek near Nemo	C	96	44 08 38	103 27 16
35	440756103244400	Boxelder Creek below Norris Peak Road, near Rapid City	M	--	44 07 56	103 24 44
36	06422650	Boxelder Creek at Doty School, near Blackhawk	M[2]	--	44 07 03	103 21 54
37	440741103184500	Boxelder Creek above Minnekahta outcrop, near Rapid City	M	--	44 07 41	103 18 45
38	06423010	Boxelder Creek near Rapid City	C	128	44 07 54	103 17 54
39	06424000	Elk Creek near Roubaix	C	21.5	44 17 41	103 35 47
40	441742103333300	Elk Creek above Meadow Creek, near Tilford	M	--	44 17 42	103 33 33
41	441738103333400	Meadow Creek above Elk Creek, near Tilford	M	--	44 17 38	103 33 34
42	441825103324400	Elk Creek trib (from North), near Tilford	M	--	44 18 25	103 32 44
43	441823103324100	Elk Creek below trib from North, near Tilford	M	--	44 18 23	103 32 41
44	441701103282700	Elk Creek below Madison outcrop, near Tilford	M	--	44 17 01	103 28 27
45	441614103253300	Elk Creek at Minnekahta outcrop, near Tilford	M	--	44 16 14	103 25 33
46	441557103244600	Elk Creek at I-90, near Tilford	M	--	44 15 57	103 24 46
47	441412103275600	Little Elk Creek below Dalton Lake, near Piedmont	M	--	44 14 12	103 27 56
48	441421103255800	Little Elk Creek below Madison outcrop, near Piedmont	M	--	44 14 21	103 25 58
49	441450103250200	Little Elk Creek at Minnekahta outcrop, near Piedmont	M	--	44 14 50	103 25 02
50	06425100	Elk Creek near Rapid City	C	190	44 14 25	103 09 03
		Belle Fourche River Basin				
51	06429920	Bear Gulch near Maurice	M	--	44 25 14	104 02 26
52	442952104015800	Bear Gulch below Minnekahta outcrop, near Beulah	M	--	44 29 52	104 01 58
53	06430520	Beaver Creek near Maurice	M	--	44 22 57	104 00 13
54	442347104004300	Beaver Creek below Beaver Crossing, near Maurice	M	--	44 23 47	104 00 43
55	443012104004300	Beaver Creek below Minnekahta outcrop, near Beulah	M	--	44 30 12	104 00 43
56	442242103565400	Iron Creek below Sawmill Gulch, near Savoy	M	--	44 22 42	103 56 54
57	06430865	Iron Creek near Lead	M	--	44 22 25	103 55 07
58	06430900	Spearfish Creek above Spearfish	C	139	44 24 06	103 53 40

Table 1. Measurement sites considered for calculation of streamflow losses —Continued

[C, continuous-record station; M, miscellaneous-record station; Z, zero-flow site (no records published but observations of zero flow have been made); --, undetermined]

Site number	Station identification number	Station name	Station type	Drainage area (square miles)	Location	
					Latitude	Longitude
					(degrees, minutes, seconds)	
		Belle Fourche River Basin—Continued				
59	06430910	Aqueduct Inlet below Maurice	M	--	44 24 32	103 53 52
60	442433103534400	Spearfish Creek below Homestake Diversion, below Maurice	M	--	44 24 33	103 53 44
61	06430950	Spearfish Creek below Robison Gulch, near Spearfish	M	--	44 26 14	103 52 32
62	442757103510600	Spearfish Creek below Madison outcrop, near Spearfish	M	--	44 27 57	103 51 06
63	06431500	Spearfish Creek at Spearfish	C	168	44 28 57	103 51 40
64A	([1])	Higgins Gulch above East Fork, near Spearfish	Z	--	44 27 44	103 56 58
64	442754103565000	Higgins Gulch below East Fork, near Spearfish	M	--	44 27 54	103 56 50
65	443012103544700	Higgins Gulch above Spearfish	M	--	44 30 12	103 54 47
66	443037103532400	Higgins Gulch at Spearfish	M	--	44 30 37	103 53 24
67	443237103525801	Higgins Gulch below I-90, near Spearfish	M	--	44 32 37	103 52 58
68	442405103485100	False Bottom Creek above Madison outcrop, near Central City	M	--	44 24 05	103 48 51
69	442419103490500	False Bottom Creek trib (1st West trib) near Central City	M	--	44 24 19	103 49 05
70	442440103491700	False Bottom Creek trib (2nd West trib) near Spearfish	M	--	44 24 40	103 49 17
71	442608103490500	False Bottom Creek below Madison outcrop, near Spearfish	M	--	44 26 08	103 49 05
72	442634103485000	Burno Gulch above False Bottom Creek, near Spearfish	M	--	44 26 34	103 48 50
73	06432180	False Bottom Creek (below Minnelusa outcrop) near Spearfish	M	--	44 27 09	103 48 22
74	442829103474600	False Bottom Creek at I-90, near Spearfish	M	--	44 28 29	103 47 46
75	06436170	Whitewood Creek at Deadwood	C	40.6	44 22 48	103 43 25
76	06436180	Whitewood Creek above Whitewood	C	56.3	44 26 32	103 37 44
77	06437020	Bear Butte Creek near Deadwood	C	16.6	44 20 08	103 38 06
78	442251103354400	Bear Butte Creek above Boulder Creek, near Sturgis	M	--	44 22 51	103 35 44
79	442301103360300	Boulder Creek above Bear Butte Creek, near Sturgis	M	--	44 23 01	103 36 03
80	442337103350600	Bear Butte Creek at Boulder Park, near Sturgis	M	--	44 23 37	103 35 06
81	442341103351200	Bear Butte Trib No. 1 at Boulder Park, near Sturgis	M	--	44 23 41	103 35 12
82	442341103350800	Bear Butte Trib No. 2 at Boulder Park, near Sturgis	M	--	44 23 41	103 35 08
83	442447103332800	Bear Butte Creek above Sturgis	M	--	44 24 47	103 33 28

[1]No station identification number assigned.

[2]Previously operated as continuous-record station.

Streamflow records for the 20 continuous-record and 63 miscellaneous-record stations presented in table 1 have been published in "Water Resources Data for South Dakota" (U.S. Geological Survey, 1967-97). Records of daily mean streamflow and individual measurements of streamflow and field water-quality parameters are published annually for continuous-record stations. Records of daily mean flow are derived by applying a rating curve (stage-versus-discharge relation) to continuous records of stage obtained from various types of recording devices (Kennedy, 1984). Measurements of streamflow and field water-quality parameters for the miscellaneous-record stations have been published for water years in which the measurements have been made. No records have been published for the three sites without station identification numbers (site numbers 2A, 4A, and 63A). Zero flow has been observed at these sites on occasions when measurements were made at an adjacent upstream or downstream station; however, flow has never been measured at these three sites.

A majority of the loss calculations are performed using individual streamflow measurements obtained from both types of stations. Many of the measurements considered were obtained specifically for the purpose of determining streamflow losses; however, individual measurements obtained at the continuous-record stations also are used for development of rating curves. All available "paired" measurements (made on the same day) for each of the 24 streams are summarized in subsequent sections. In some cases, daily streamflow records also are considered.

Water-Balance Equations

A variety of hydrogeologic conditions can occur along a typical downstream progression of a stream reach bracketing a loss zone, as schematically illustrated in figure 7. As a generality, a stream channel is situated within alluvial deposits overlying a bedrock unit that may, or may not, be an aquifer. A variety of interactions between the stream, alluvial deposits, and underlying bedrock units is possible within a given reach. Ideally, an upstream measurement site will be located within areas of metamorphic or igneous rocks, which generally have relatively low permeability and thus, minimal interactions with overlying alluvial deposits (fig. 7A). During steady flow conditions (when stream levels and alluvial water levels are near equilibrium), seepage between the stream and alluvial deposits also would be minimal. Similarly, if the underlying confining layer at a downstream measurement site is relatively impermeable (fig. 7I), interactions between the stream, alluvial deposits, and bedrock unit also will be minimal during equilibrium conditions.

The basic equation for conservation of mass states that the sum of outflows from a defined control volume must equal the sum of the inflows to the control volume, plus or minus any changes in storage (Streeter and Wylie, 1985). Depending on how the control volume is defined, a wide variety of inflows and outflows can occur within a stream reach that includes a loss zone. In order to quantify losses to bedrock aquifers, a control volume that includes the stream channel and adjacent alluvial deposits (fig. 8A) is first considered, in which case the appropriate water-balance equation is:

$$Str_i + A_i + P_{ca} + T_i + SF_b = Str_o + A_o + ET_{ca} + W_{ca} + Loss_b \pm \Delta Storage_{ca} \qquad (1)$$

where:

Str_i = stream inflow;
A_i = alluvial ground-water inflow;
P_{ca} = precipitation on the stream channel and alluvial area;
T_i = tributary inflow from surface streams;
SF_b = springflow from bedrock aquifers;
Str_o = stream outflow;
A_o = alluvial ground-water outflow;
ET_{ca} = evapotranspiration from the stream channel and alluvial deposits;
W_{ca} = withdrawals from the stream channel and alluvial deposits;
$Loss_b$ = losses to bedrock aquifers underlying the alluvial deposits; and
$\Delta Storage_{ca}$= changes in channel and alluvial storage.

Estimation of alluvial ground-water inflow (A_i) and outflow (A_o) is especially difficult; thus, it is more practical to consider only the immediate stream channel as the control volume (fig. 8B), which also simplifies the water-balance equation. Neglecting precipitation (P_c), evaporation (E_c), and withdrawals (W_c), which now apply only to the stream channel and generally are small, relative to streamflow losses, the water-balance equation can be simplified to:

$$Str_i + T_i + SF_t = Str_o + Loss_t \pm \Delta Storage_c \qquad (2)$$

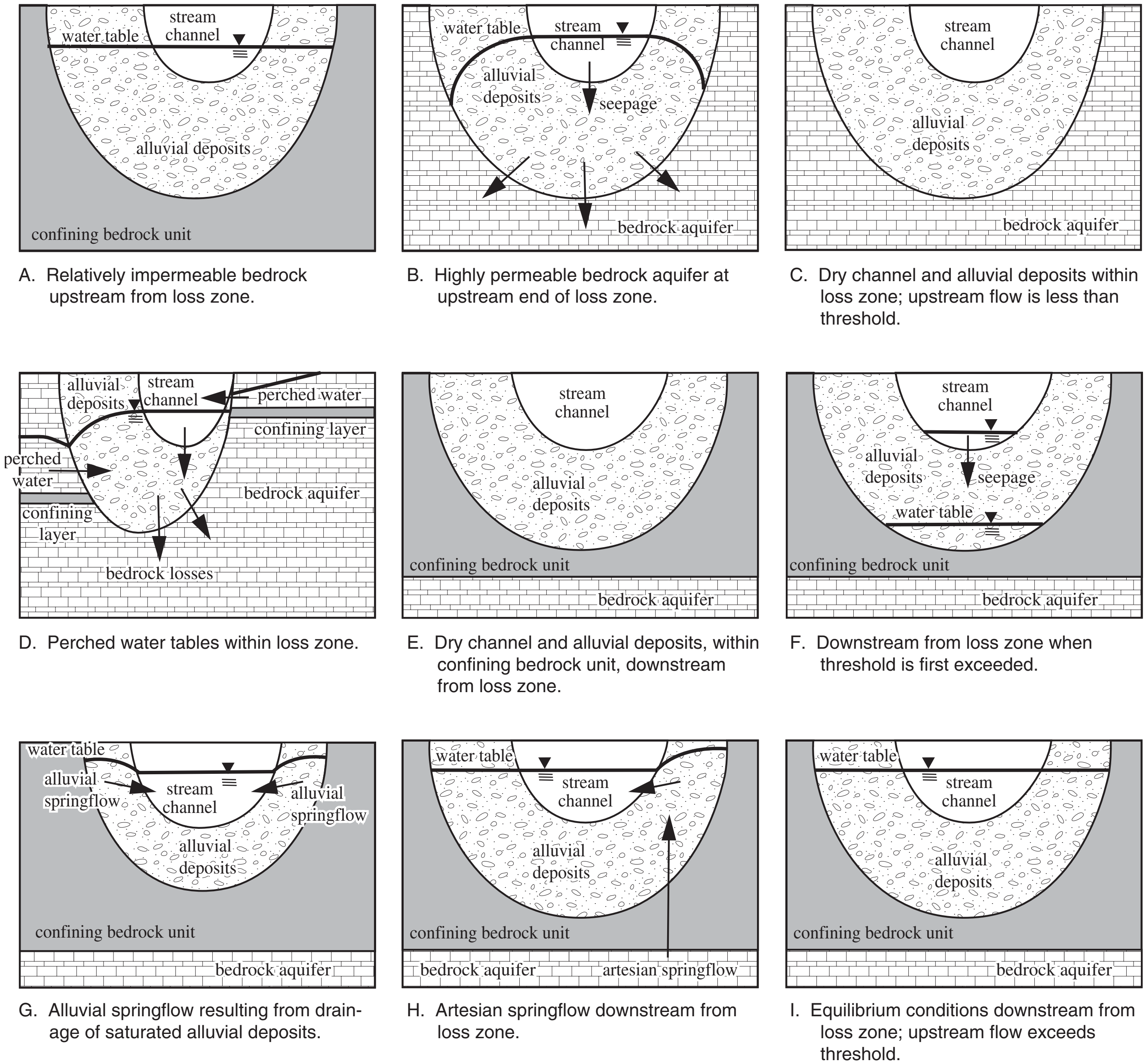


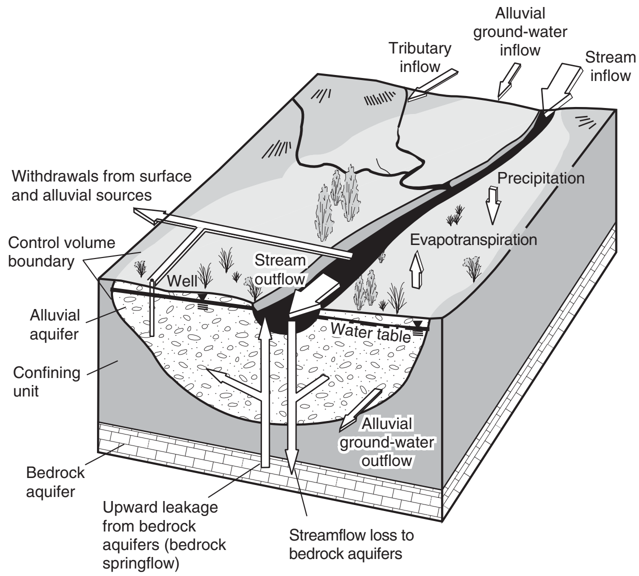
Figure 7. Schematic showing interactions between surface water, alluvial deposits, and bedrock aquifers for various hypothetical conditions.

The storage term ($\Delta Storage_c$) now includes only changes in channel storage; however, the loss term ($Loss_t$) now represents total losses, including losses to alluvial deposits (hereinafter referred to as alluvial losses), as well as losses to bedrock aquifers (referred to as bedrock losses). The springflow term (SF_t) also is changed to represent total springflow, which could include springflow from both alluvial and bedrock sources. Springflow from alluvial sources is considered, for purposes of this report, to include general (diffuse) seepage, as well as more localized spring discharge, that enters the stream. Neglecting changes in storage, which generally are addressed qualitatively, losses are calculated by modifying equation 2 to:

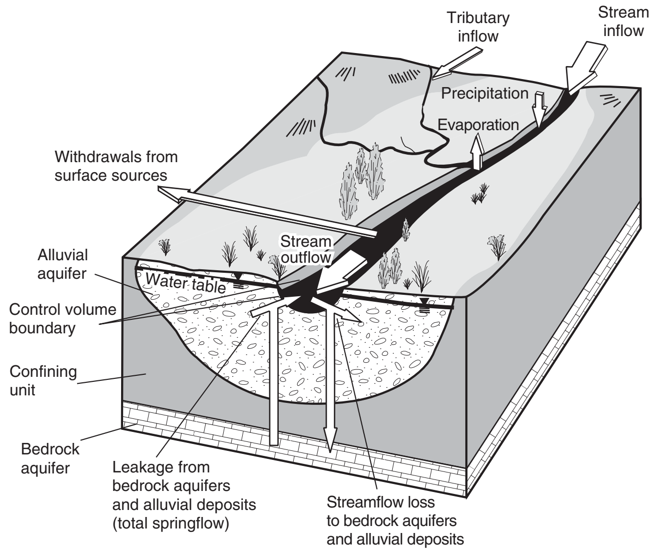
$$\mathrm{Loss_t = Str_i + T_i + SF_t - Str_o} \qquad (3)$$

When tributary inflows and springflow are negligible, the water-balance equation can be further simplified to:

$$\mathrm{Loss_t = Str_i - Str_o} \qquad (4)$$



A. Control volume that includes stream channel and alluvial deposits.



B. Control volume that includes only the immediate stream channel.

Figure 8. Schematic showing components of hydrologic budget used for determination of streamflow losses to bedrock aquifers, for two different control volumes.

Although equations 3 and 4 have been simplified, the loss term includes losses to both bedrock aquifers and alluvial deposits, as well as all errors associated with neglecting alluvial inflows and outflows, precipitation, evapotranspiration, withdrawals, and changes in storage. In many cases, neglecting various terms in equation 1 does not significantly affect calculation of bedrock losses. In some cases, however, outliers occur that apparently result from either an inability to account for significant terms, measurement inaccuracy, or unexplained variability in the hydrologic system. The largest complication is the inability to distinguish bedrock losses (losses from the stream and alluvium to bedrock aquifers) from alluvial losses (seepage from the stream channel to the alluvium). The existence of numerous streamflow measurements for many of the sites was invaluable for assessing potential sources of variability and inaccuracies in calculations of bedrock losses. Following is a discussion of how various factors can affect calculations of bedrock losses.

Factors Affecting Loss Calculations

The terms alluvial inflow (A_i) and outflow (A_o), precipitation (P_c), evaporation (E_c), and withdrawals (W_c) are excluded in all loss calculations in this report. These terms generally are small, relative to other terms, and development of reasonable estimates for these terms is impractical for the large number of measurements considered. Of these terms, alluvial inflow and outflow probably have the greatest potential to affect loss calculations. Using equations 3 and 4 implicitly assumes that alluvial inflow equals alluvial outflow; however, in some cases, relatively large differences could occur. The most likely scenario is that alluvial outflow would exceed alluvial inflow, because alluvial deposits generally increase in extent in a downstream direction. In this situation, bedrock losses would be overestimated.

Tributary inflow (T_i) and springflow (SF_t) are included, where feasible, in loss calculations. Changes in storage ($\Delta Storage$) are always excluded; however, in some cases, effects of changes in storage can be addressed qualitatively. All three of these factors can have a significant effect on loss calculations, as discussed in the following sections. The possible effects of measurement inaccuracy also are discussed.

Tributary Inflow

In many cases, measurement sites are located immediately upstream and downstream from outcrops of the Madison Limestone and Minnelusa Formation. In cases where the length of the stream channel is short, the additional tributary drainage area generally is small. Surface runoff from these outcrops generally is minimal, except immediately after exceptionally heavy precipitation (Miller and Driscoll, 1998). Most tributaries originating upstream from the Madison and Minnelusa generally lose all flow while crossing these outcrops. Thus, tributary inflow (T_i) can be neglected in many cases, but has been measured in other cases where relatively large tributaries are accessible. In some cases, inflows from specific tributaries are documented as zero. Failing to account for tributary inflows would result in underestimating losses.

Springflow

Springflow from both alluvial and bedrock sources (SF_t) can occur at various locations along a stream reach. Alluvial springflow (fig. 7G), which consists of drainage from saturated alluvial deposits into the stream channel, is the result of the water table in the alluvium being higher than the water level (stage) of the stream. This can be caused by various factors, which may include decreasing streamflow, a constriction in the alluvial area, or an area of decreased hydraulic conductivity in the alluvial deposits.

In addition to alluvial springflow, various forms of bedrock springflow can occur within a stream reach. The easiest form of bedrock springflow to account for is artesian springflow, which generally occurs downstream from a loss zone (fig. 7H), where artesian conditions can exist within a confined bedrock aquifer (fig. 5). Many artesian springs occur within dry channels and can be easily measured when the upstream loss zone is dry. In addition, many of the larger artesian springs have relatively constant discharge (Miller and Driscoll, 1998), which makes determination of springflow easier.

Bedrock springflow also can occur within a loss zone, which is more difficult to account for because the occurrence of such springs may be transient and discharges may be highly variable. For example, Rahn and Gries (1973) identified various springs within the loss zones of Boxelder and Elk Creeks, for which discharges during 1966-70 ranged from zero to more than 10 ft^3/s. Springs in Boxelder Creek have been shown, through dye tests, to be directly connected to the loss zone immediately upstream, with travel times of less than 1 day (Rahn and Gries, 1973). Most springs within loss zones probably result from water tables that are "perched" on low-permeability layers within a bedrock aquifer (fig. 7D), because a gradient from the stream to the underlying bedrock aquifer must exist for net losses to occur. Multiple spring reaches within a loss zone are possible if the channel intercepts a local water table in several locations.

It is not feasible, or necessary, to account for all springflow in loss calculations. Artesian springflow downstream from a loss zone, which generally is readily identifiable and measurable, can be included in calculations. Bedrock springflow within a loss zone is more difficult to account for, and generally is excluded, which results in calculation of a "net" loss rate. Alluvial springflow can be difficult to distinguish from bedrock springflow, and frequently is associated with changes in alluvial storage, which generally are addressed qualitatively, as discussed in a subsequent section.

Changes in Storage

Changes in storage ($\Delta Storage$) have the potential to cause large errors in loss calculations. Following is a discussion of how loss calculations are affected by changes in channel and alluvial storage.

Changes in Channel Storage

Changes in channel storage, that are related to channel dimensions, occur whenever streamflow and corresponding stage change within a given stream reach. Considering a hypothetical stream channel with no tributary inflows or streamflow losses; flow at every point along the channel is equal during steady (unchanging) flow conditions. During unsteady flow conditions, flow will vary throughout the channel because of changes in channel storage. For example, if simultaneous measurements are made at upstream and downstream sites during a rising stage, flow at the upstream site will exceed flow at the downstream site, because channel storage increases as stage increases. Conversely, downstream flow will exceed upstream flow for simultaneous measurements made during a falling stage. Thus, changes in channel storage can affect determination of bedrock losses, with maximum effects resulting from large changes in flow, and associated stage, in long stream reaches with wide channels.

It is not feasible to quantify changes in channel storage for the large number of stream reaches considered; however, two methods are used to minimize effects of changes in channel storage. First, when making a series of streamflow measurements for loss calculations, measurements generally are made from upstream to downstream, which minimizes effects of changes in storage. Dates and times of measurements are included in tables summarizing measurement data. Second, when possible, measurements are made during periods with relatively stable streamflow, which minimizes changes in channel storage. For streams with records of daily streamflow, the percent change in daily mean flow from the previous day to the day of the measurement is noted in the summary tables (percent change = [(current day - previous day) / previous day] x 100%).

Changes in Alluvial Storage

Changes in storage in alluvial deposits adjacent to stream channels can have large effects on loss calculations. For steady streamflow in a channel that is situated within saturated alluvial deposits with consistent cross-sectional and hydraulic characteristics, alluvial water levels at any point perpendicular to the stream generally would be approximately the same as adjacent stream stage (figs. 7A, 7I, and 8). Changes in streamflow result in changes in alluvial storage, which are related to changes in stage, alluvial (flood plain) width, channel length, and the hydraulic characteristics (effective porosity and hydraulic conductivity) of the alluvial deposits. Given sufficient time for the alluvial water level to re-equilibrate with stream stage, the "unit" change in alluvial storage (storage per unit of area) would be effective porosity times change in stage. For example, with 10 percent effective porosity, a 1.0 ft change in stage would eventually change alluvial storage by 0.1 ft^3 for each ft^2 of alluvial area. For increasing stage, streamflow losses occur in filling alluvial storage, which results in overestimation of bedrock losses. The resulting loss rate tends to decrease with time, as the gradient from the stream to the alluvium becomes progressively smaller. The opposite effect occurs during decreasing stage, as the gradient reverses and alluvial storage eventually is released to the stream channel, as alluvial springflow.

Effects of changes in alluvial storage generally are small, with the exception of losses that occur in saturating alluvial deposits along previously dry stream channels. Many streams lose all of their base flow when crossing outcrops of the Madison Limestone and Minnelusa Formation; thus, downstream alluvial deposits may be dry or nearly dry during much of the year. When streamflow first occurs in what previously was a dry channel, the gradient from the stream to alluvial deposits initially is downward. Thus, the alluvial loss rate initially is controlled by the infiltration capacity of the stream channel, but decreases as the gradient from the stream to the alluvium decreases. Furthermore, initial changes in alluvial storage are related to unsaturated alluvial thickness, rather than to changes in stream stage. Alluvial loss rates in the range of tens of cubic feet per second and storage capacities in the range of hundreds of acre-feet are documented in subsequent sections for several streams with extensive alluvial systems. It is possible to have large alluvial loss rates for periods of a week or more, until water levels in the alluvium equilibrate with stream levels.

It is not feasible to quantify changes in alluvial storage for the large number of stream reaches considered; however, a qualitative method for describing the extent of alluvial deposits based on the approximate width of the flood plain at measurement sites is presented in table 2. These descriptions also can provide useful insights regarding the potential magnitude of alluvial ground-water flow (A_i or A_o) at any site. Descriptions of alluvial extent for measurement sites are presented in table 3, along with other site information.

Table 2. Terms used to describe approximate extent of alluvial deposits

Term	Approximate extent of alluvial deposits
Very limited	Very limited flood plain apparent, typified by very narrow canyon (canyon walls less than about 100 ft apart).
Minor	Minor flood plain developed, typified by somewhat wider canyon (walls 100 to 300 ft apart).
Moderate	More extensive flood plain developed, typified by significantly wider canyon (walls 300 to 1,000 ft apart).
Extensive	Extensive flood plain developed, typified by canyon walls that are in excess of 1,000 ft apart or non-existent.

Table 3. Site information for measurement sites

[C, continuous-record station; M, miscellaneous-record station; Z, zero-flow site; S, staff gage read by observer; u/s, upstream; d/s, downstream; mi, miles; N/A, not applicable]

Site number	Station type/period of record (water years)	Station name	Hydrogeologic characteristics	
			Bedrock outcrop	Alluvial extent
		Beaver Creek and Tributaries		
1	C/1991-96	Beaver Creek near Pringle	Deadwood Formation, just u/s from Madison Limestone	very limited to minor
2	M/1995-96	Reaves Gulch above Madison outcrop, near Pringle	Deadwood Formation, just u/s from Madison Limestone	very limited
2A	Z/1995-96	Reaves Gulch above Beaver Creek	Madison Limestone, just u/s from confluence with Beaver Creek	very limited
3	M/1995-96	Beaver Creek below Minnekahta outcrop, near Buffalo Gap	Spearfish Formation, just d/s from Minnekahta Limestone	moderate to extensive
4	M/1995-96	Highland Creek above Madison outcrop, near Pringle	Deadwood Formation, just u/s from Madison Limestone	moderate
4A	Z/1995-96	Highland Creek below Minnekahta outcrop	Spearfish Formation, about 4.0 mi d/s from Minnekahta Limestone and 0.5 mi u/s from confluence with Beaver Creek	extensive
5	C/1991-96	Beaver Creek above Buffalo Gap	Inyan Kara Group	extensive
		Lame Johnny Creek and Tributaries		
6	M/1995-96	South Fork Lame Johnny Creek above Madison outcrop, near Fairburn	Precambrian rocks, just u/s from Deadwood Formation	very limited
7	M/1995-96	Flynn Creek above Madison outcrop, near Fairburn	Deadwood Formation, just u/s from Madison Limestone	very limited
8	M/1995-96	South Fork Lame Johnny Creek below Minnelusa outcrop, near Fairburn	Minnekahta Limestone, just d/s from Minnelusa Formation	moderate
9	M/1995-96	North Fork Lame Johnny Creek above Madison outcrop, near Fairburn	Precambrian rocks, just u/s from Deadwood Formation	very limited to minor
10	M/1995-96	North Fork Lame Johnny Creek below Madison outcrop, near Fairburn	White River Group, just d/s from Madison Limestone	moderate
		French Creek		
11	C/1982-96	French Creek above Fairburn	Deadwood Formation, just u/s from Madison Limestone	minor
12	M/1982-86 M/1996	French Creek at Madison/Minnelusa contact, near Fairburn	Minnelusa Formation, just d/s from Madison Limestone	minor
13	M/1982-84 M/1991-96	French Creek below Minnelusa outcrop, near Fairburn	Minnekahta Limestone, just d/s from Minnelusa Formation	moderate to extensive
		Battle Creek and Tributaries		
14	C/1945-47 C/1962-96	Battle Creek near Keystone	Deadwood Formation, just u/s from Madison Limestone	minor
15	M/1996	Battle Creek at Madison/Minnelusa contact, near Hermosa	Madison Limestone, just u/s from Minnelusa Formation	very limited
16	M/1995-96	Battle Creek below Minnelusa outcrop, near Hermosa	Spearfish Formation, just d/s from Minnekahta Formation	moderate

Table 3. Site information for measurement sites —Continued

[C, continuous-record station; M, miscellaneous-record station; Z, zero-flow site; S, staff gage read by observer; u/s, upstream; d/s, downstream; mi, miles; N/A, not applicable]

Site number	Station type/period of record (water years)	Station name	Hydrogeologic characteristics	
			Bedrock outcrop	Alluvial extent
		Battle Creek and Tributaries—Continued		
17	C/1977-96	Grace Coolidge Creek near Game Lodge, near Custer	Deadwood Formation, just u/s from Madison Limestone	minor to moderate
18	C/1978-80 M/1990-96	Grace Coolidge Creek near Fairburn	Minnelusa Formation, about 0.5 mi d/s from Madison Limestone	minor to moderate
19	C/1945-47 C/1978-80 M/1994-96	Grace Coolidge Creek (below Minnelusa outcrop) near Hermosa	Minnelusa Formation, just u/s from Minnekahta Limestone	minor to moderate
20	M/1989-90 M/1996	Bear Gulch above Hayward	Deadwood Formation, just d/s from outcrops of Precambrian rocks	minor
21	C/1989-96	Bear Gulch near Hayward	White River Group, about 0.3 mi d/s from Deadwood/Madison contact	minor
22	M/1995-96	Spokane Creek above Madison outcrop, near Hayward	within outcrops of Precambrian rocks, just u/s from Deadwood Formation	moderate
23	M/1995-96	Spokane Creek below Madison outcrop, near Hayward	Spearfish Formation, about 1 mi d/s from Minnekahta Limestone	moderate
		Spring Creek		
24	C/1945-47 C/1987-96	Spring Creek near Keystone	Precambrian rocks, about 0.5 mi u/s from Madison Limestone	minor
25	M/1996	Spring Creek (Madison/Minnelusa contact) near Rapid City	Madison Limestone, just u/s from Minnelusa Formation	minor
26	M/1996	Spring Creek above Minnekahta outcrop, near Rapid City	Minnelusa Formation, just u/s from Minnekahta Limestone	moderate to extensive
27	S/1903-06 S/1945-47 M/1990-95 S/1996	Spring Creek near Rapid City	Spearfish Formation, about 0.5 mi d/s from Minnekahta Limestone	extensive
28	C/1949-96	Spring Creek near Hermosa	Cretaceous shales, about 4.5 mi d/s from Minnekahta Limestone	extensive
		Rapid Creek and Victoria Creek		
29	C/1946-96	Rapid Creek below Pactola Dam	Precambrian rocks, about 0.5 mi d/s from Pactola Dam	minor
30	C/1989-96	Rapid Creek above Victoria Creek, near Rapid City	Deadwood Formation, about 0.5 mi u/s from Madison Limestone and about 0.5 mi u/s from confluence with Victoria Creek	very limited
31	M/1993-96	Victoria Creek below Victoria Dam, near Rapid City	Precambrian rocks, about 1 mi u/s from Deadwood Formation	minor
32	M/1993-96	Victoria Creek at mouth, near Rapid City	Madison Limestone, just u/s from confluence with Rapid Creek	minor

Table 3. Site information for measurement sites —Continued

[C, continuous-record station; M, miscellaneous-record station; Z, zero-flow site; S, staff gage read by observer; u/s, upstream; d/s, downstream; mi, miles; N/A, not applicable]

Site number	Station type/period of record (water years)	Station name	Hydrogeologic characteristics	
			Bedrock outcrop	Alluvial extent
		Rapid Creek and Victoria Creek—Continued		
33	C/1946-96	Rapid Creek above Canyon Lake, near Rapid City	Minnelusa Formation, about 0.5 mi d/s from Madison Limestone and 3.0 mi d/s from confluence with Victoria Creek	minor
		Boxelder Creek		
34	C/1945-47 C/1966-96	Boxelder Creek near Nemo	Deadwood Formation, about 3 mi u/s from Madison Limestone	minor
35	M/1993-96	Boxelder Creek below Norris Peak Road	Madison Limestone, just d/s from Deadwood Formation	minor
36	C/1978-80 M/1994-96 S/1996	Boxelder Creek at Doty School	Minnelusa Formation, about 0.5 mi d/s from Madison Limestone	moderate to extensive
37	M/1996	Boxelder Creek above Minnekahta outcrop	Opeche Formation, just u/s from Minnekahta Limestone	moderate to extensive
38	C/1978-96	Boxelder Creek near Rapid City	Within area of alluvial deposits, about 0.5 mi d/s from Minnekahta Limestone	extensive
		Elk Creek and Little Elk Creek		
39	C/1945-47 C/1992-96	Elk Creek near Roubaix	Precambrian rocks, just u/s from Deadwood Formation and about 0.5 mi u/s from Madison Limestone	moderate to extensive
40	M/1996	Elk Creek above Meadow Creek, near Tilford	Madison Limestone, about 1.5 mi d/s from Precambrian rocks	minor to moderate
41	M/1996	Meadow Creek above Elk Creek, near Tilford	Madison Limestone, just upstream from the confluence with Elk Creek	minor
42	M/1996	Elk Creek trib (from north), near Tilford	Madison Limestone, just upstream from the confluence with Elk Creek	minor
43	M/1996	Elk Creek below trib from north, near Tilford	Madison Limestone, about 2.5 mi d/s from Precambrian rocks	minor
44	M/1996	Elk Creek below Madison outcrop, near Tilford	Minnelusa Formation, just d/s from Madison Limestone	moderate
45	M/1996	Elk Creek at Minnekahta outcrop, near Tilford	Minnekahta Limestone, just u/s from area of extensive alluvial deposits	moderate to extensive
46	M/1994-96	Elk Creek at I-90, near Tilford	Within area of extensive alluvial deposits, about 0.5 mi d/s from Minnekahta Limestone	extensive
47	M/1996	Little Elk Creek below Dalton Lake, near Piedmont	Deadwood Formation, about 1 mi u/s from Madison Limestone	minor
48	M/1996	Little Elk Creek below Madison outcrop, near Piedmont	Minnelusa Formation, just d/s from Madison Limestone	minor
49	M/1996	Little Elk Creek at Minnekahta outcrop, near Piedmont	Minnekahta Limestone, just u/s from Spearfish Formation	moderate

Table 3. Site information for measurement sites —Continued

[C, continuous-record station; M, miscellaneous-record station; Z, zero-flow site; S, staff gage read by observer; u/s, upstream; d/s, downstream; mi, miles; N/A, not applicable]

Site number	Station type/period of record (water years)	Station name	Hydrogeologic characteristics	
			Bedrock outcrop	Alluvial extent
		Redwater River Tributaries		
50	C/1979-96	Elk Creek near Rapid City	Cretaceous shales, about 15 mi d/s from Minnekahta Limestone	extensive
51	M/1992-96	Bear Gulch near Maurice	Deadwood Formation, just u/s from Madison Limestone	very limited
52	M/1995-96	Bear Gulch below Minnekahta outcrop, near Beulah, WY	Spearfish Formation, just d/s from Minnekahta Limestone	moderate to extensive
53	M/1992-96	Beaver Creek near Maurice	Deadwood Formation, about 1.0 mi u/s from Madison Limestone	moderate
54	M/1995	Beaver Creek below Beaver Crossing, near Maurice	Deadwood Formation, just u/s from Madison Limestone	moderate
55	M/1995-96	Beaver Creek below Minnekahta outcrop, near Beulah, WY	Spearfish Formation, about 0.5 mi d/s from Minnekahta Limestone	moderate to extensive
56	M/1996	Iron Creek below Sawmill Gulch, near Savoy	Madison Limestone, just d/s from Deadwood Formation	moderate
57	M/1988-90 M/1996	Iron Creek near Lead	Deadwood Formation, just u/s from confluence with Spearfish Creek	minor
58	C/1989-96	Spearfish Creek above Spearfish	Deadwood Formation, about 3 mi u/s from Madison Limestone	minor
59	M/1995	Aqueduct Inlet below Maurice	Deadwood Formation, about 2.5 mi u/s from Madison Limestone	N/A
60	M/1994	Spearfish Creek below Homestake Diversion, below Maurice	Deadwood Formation, about 2.5 mi u/s from Madison Limestone	N/A
61	M/1988-96	Spearfish Creek below Robison Gulch, near Spearfish	Madison Limestone, about 0.25 mi d/s from Deadwood Formation	minor
62	M/1994-96	Spearfish Creek below Madison outcrop, near Spearfish	Minnelusa Formation, just u/s from Minnekahta Limestone	minor to moderate
63	C/1947-96	Spearfish Creek at Spearfish	Spearfish Formation, just d/s from Minnekahta Limestone	moderate
64A	M/1996	Higgins Gulch above East Fork, near Spearfish	Minnelusa Formation, just u/s from confluence with East Fork	minor
64	M/1996	Higgins Gulch below East Fork, near Spearfish	Minnelusa Formation, just d/s from confluence with East Fork	minor
65	M/1996	Higgins Gulch above Spearfish	Minnekahta Limestone, just d/s from Minnelusa Formation	minor to moderate
66	M/1996	Higgins Gulch at Spearfish	Within alluvial deposits overlying Spearfish Formation, about 0.5 mi d/s from Minnekahta Limestone	extensive
67	M/1996	Higgins Gulch below I-90, near Spearfish	Within alluvial deposits overlying Spearfish Formation, about 1.0 mi u/s from confluence with Spearfish Creek	extensive

Table 3. Site information for measurement sites —Continued

[C, continuous-record station; M, miscellaneous-record station; Z, zero-flow site; S, staff gage read by observer; u/s, upstream; d/s, downstream; mi, miles; N/A, not applicable]

Site number	Station type/period of record (water years)	Station name	Hydrogeologic characteristics	
			Bedrock outcrop	Alluvial extent
False Bottom Creek				
68	M/1995-96	False Bottom Creek above Madison outcrop, near Central City	Deadwood Formation, about 0.25 mi u/s from outcrop of Tertiary intrusive rocks	minor
69	M/1996	False Bottom Creek trib (1st West trib) near Central City	Tertiary intrusive rocks, just u/s from confluence with False Bottom Creek	very limited
70	M/1996	False Bottom Creek trib (2nd West trib) near Spearfish	Tertiary intrusive rocks, just u/s from confluence with False Bottom Creek	very limited
71	M/1995-96	False Bottom Creek below Madison outcrop, near Spearfish	Minnelusa Formation, just d/s from Madison Limestone	moderate
72	M/1996	Burno Gulch above False Bottom Creek, near Spearfish	Minnelusa Formation, just u/s from confluence with False Bottom Creek	minor to moderate
73	M/1989-90 M/1995-96	False Bottom Creek (below Minnelusa outcrop) near Spearfish	Minnekahta Limestone, just d/s from Minnelusa Formation	moderate
74	M/1996	False Bottom Creek at I-90, near Spearfish	Within area of alluvial deposits, about 0.75 mi d/s from Minnekahta Limestone	extensive
Whitewood Creek				
75	C/1982-95	Whitewood Creek at Deadwood	Deadwood Formation, about 1.0 mi u/s from Madison Limestone	very limited
76	C/1983-96	Whitewood Creek above Whitewood	Within or near outcrop of Minnekahta Limestone, just u/s from Spearfish Formation	moderate to extensive
Bear Butte Creek				
77	C/1989-96	Bear Butte Creek near Deadwood	Deadwood Formation, just u/s from Madison Limestone	very limited
78	M/1996	Bear Butte Creek above Boulder Creek, near Sturgis	Madison Limestone, about 0.5 mi u/s from Minnelusa Formation	minor
79	M/1996	Boulder Creek above Bear Butte Creek, near Sturgis	Madison Limestone, just u/s from confluence with Bear Butte Creek	minor
80	M/1996	Bear Butte Creek at Boulder Park, near Sturgis	Minnelusa Formation[1], just d/s from Madison Limestone	minor
81	M/1996	Bear Butte Trib No. 1 at Boulder Park, near Sturgis	Minnelusa Formation[1], about 0.2 mi from confluence with Bear Butte Creek	minor
82	M/1996	Bear Butte Trib No. 2 at Boulder Park, near Sturgis	Minnelusa Formation[1], about 0.1 mi from confluence with Bear Butte Creek	minor
83	M/1994, M/1996	Bear Butte Creek above Sturgis	Minnekahta Limestone, just d/s from Minnelusa Formation	moderate

[1]Station actually located within an isolated outcrop of Minnekahta Limestone, perched atop the Minnelusa Formation.

Measurement Accuracy

An inherent part of all streamflow measurements is that they are not 100 percent accurate. The relative accuracy of each individual measurement is rated by the hydrographer in terms of maximum probable error. The ratings are based on various measuring conditions and are expressed as a percentage of the measured streamflow (Buchanan and Somers, 1969). Measurements are rated as excellent (±2 percent), good (±5 percent), fair (±8 percent), or poor (more than ±8 percent). Most measurements are rated as "good," or within 5 percent of actual flow. Thus, actual streamflow for a measurement of 100 ft^3/s, which is rated good, would be expected to be between 95 and 105 ft^3/s. As a general rule, most measurements are more accurate than the rating implies, because the rating is based on maximum probable error.

Measurements are most accurate when made at the lowest possible streamflow. However, many high-flow measurements were made for this study to test the hypothesis that bedrock losses are proportional to streamflow. In some cases, measured streamflow during high-flow conditions was an order of magnitude larger than during low-flow conditions. Measurement error has the potential to be an important factor in these cases. In addition, variables such as changes in storage (associated with rapidly changing stage) and tributary inflow to a reach, are much more likely to be important factors during periods of high flows. Calculations using measurements made during high-flow conditions are subsequently shown to have more variability than those for moderate and low-flow conditions.

Daily streamflow records are subject to various inaccuracies associated with collection of stage records, development of rating curves, and changing channel conditions, in addition to inaccuracies associated with measurements of streamflow (Kennedy, 1984). Daily records are rated in terms of the accuracy of an entire year of record, using four accuracy classifications. A rating of “excellent” means that about 95 percent of the daily flows probably are within 5 percent of the actual flow; “good,” within 10 percent; “fair,” within 15 percent; and “poor” means that daily flows have less than “fair” accuracy. The rating is primarily dependent on the stability of stage-discharge relations, and the frequency and reliability of stage and discharge measurements (Novak, 1985). Records for any given day may be subject to larger errors than records for longer time spans, such as monthly and annual mean flows.

ANALYSIS OF STREAMFLOW LOSSES

This section of the report presents analyses of losses to bedrock aquifers for numerous streams in the Black Hills area. Losses are calculated by subtracting downstream flow from upstream flow (plus inflows, when applicable); thus, a positive residual represents a net loss and a negative residual represents a net gain through a given reach. Analyses are arranged by stream reach, according to the downstream order system that was described previously. A summary of estimated loss thresholds for all streams considered is presented in the concluding subsection of this section.

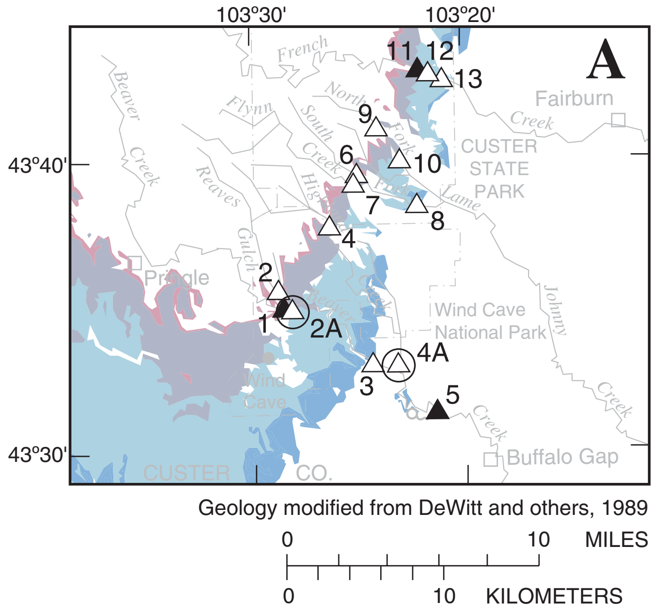
Beaver Creek and Tributaries

Streamflow losses are calculated for the main stem of Beaver Creek and two of its tributaries (Reaves Gulch and Highland Creek) using data for two continuous-record, three miscellaneous-record, and two zero-flow stations (fig. 9). Site information for these stations is presented in table 3.

Beaver Creek

Loss calculations for the main stem of Beaver Creek are presented in table 4, which includes measurements for sites 1, 2A, and 3 (fig. 9). Other than two notations of zero flow that were made at site 2A, no other tributaries within the reach were measured. Combined losses to the bedrock units along Beaver Creek are calculated as the sum of flow at sites 1 and 2A, minus flow at site 3. Because site 3 is located downstream from the Minnekahta Limestone (table 3), calculated losses may include losses to the Minnekahta, as well as, losses to the Madison Limestone and Minnelusa Formation. No attempt is made to differentiate between losses to the individual outcrops. The "Hydrograph changes/remarks" column in table 4 provides the percent change in daily mean flow from the previous day to the current day at site 1.

Losses are calculated as 5.14 ft^3/s on Aug. 10, 1995, and 5.08 ft^3/s on June 5, 1996. Measurements on these dates were made during periods of relatively stable streamflow, when flow had been sustained through the loss zone for sufficient periods of time for alluvial storage to be satisfied. Measurements made on April 22, 1996, result in a calculated loss of 7.24 ft^3/s; however, zero flow was recorded at the downstream station (site 3). Because it cannot be determined whether the loss threshold was exceeded, the calculated



Site Number	Station Name
1	Beaver Creek near Pringle
2	Reaves Gulch above Madison outcrop
2A	Reaves Gulch above Beaver Creek
3	Beaver Creek below Minnekahta outcrop
4	Highland Creek above Madison outcrop
4A	Highland Creek below Minnekahta outcrop
5	Beaver Creek above Buffalo Gap
6	South Fork Lame Johnny Creek above Madison outcrop
7	Flynn Creek above Madison outcrop
8	South Fork Lame Johnny Creek below Minnelusa outcrop
9	North Fork Lame Johnny Creek above Madison outcrop
10	North Fork Lame Johnny Creek below Madison outcrop
11	French Creek above Fairburn
12	French Creek at Madison/Minnelusa contact
13	French Creek below Minnelusa outcrop

EXPLANATION

DEADWOOD FORMATION

MADISON LIMESTONE

MINNELUSA FORMATION

MINNEKAHTA LIMESTONE

▲1 CONTINUOUS-RECORD STREAM-FLOW-GAGING STATION--Number indicates site number

△2 MISCELLANEOUS-RECORD STREAM-FLOW-GAGING STATION--Number indicates site number

2A ZERO-FLOW STATION--Number indicates site number

Figure 9. Insert A from figure 6, showing location of measurement sites and generalized outcrops for Beaver Creek and tributaries, Lame Johnny Creek, and French Creek. Outcrops shown may include other formations.

Table 4. Calculations of streamflow losses for Beaver Creek

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operations; --, no data available; >, potential loss greater than indicated because of zero flow at downstream site]

Date	Upstream station site 1		Upstream tributary site 2A		Downstream station site 3		Total loss, in ft^3/s (1 + 2A - 3)	Hydrograph changes[1]/ remarks
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s		
8-10-95	1000	8.26	1000	0	1245	3.12	5.14	-1%
4-22-96	0945	7.24	--	--	1210	0	>7.24	-9%/alluvial losses
6-05-96	0935	8.49	0935	0	1145	3.41	5.08	0%
						Mean loss[2]	5.11	
						Median loss[2]	5.11	

[1]Hydrograph changes calculated using daily mean streamflow at site 1: [(current day - previous day) / previous day] x 100%.
[2]Calculated using finite values only.

loss in table 4 is denoted with a greater than (>) symbol. The same protocol is followed in subsequent tables presenting loss calculations. Streamflow records show that daily mean flow at the upstream station (site 1) first exceeded 5 ft^3/s on April 14, with a maximum daily flow of 8.6 between April 14 and April 22 (U.S. Geological Survey, 1997). Thus, flow apparently had not been sufficient to satisfy initial alluvial storage between sites 1 and 3; however, storage apparently had been satisfied by June 5, 1996 (table 4). A more detailed analysis of alluvial storage conditions along Beaver Creek is presented within a subsequent analysis of losses for Highland Creek.

Using the calculated losses for Aug. 10, 1995, and June 5, 1996, the mean and median values are both 5.11 ft^3/s. Thus, the bedrock loss threshold for the main stem of Beaver Creek is estimated as 5 ft^3/s.

Reaves Gulch

Loss calculations for Reaves Gulch, a tributary to Beaver Creek, are presented in table 5, which includes measurements for sites 2 and 2A (fig. 9). The loss threshold can only be determined to be in excess of 0.2 ft^3/s, because only zero-flow measurements were obtained for the downstream station (site 2A). These losses occur entirely to the Madison Limestone (table 3).

Table 5. Calculations of streamflow losses for Reaves Gulch

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operation; >, potential loss greater than indicated because of zero flow at downstream site]

Date	Upstream station site 2		Downstream station site 2A		Total loss, in ft^3/s (2 - 2A)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	
8-10-95	0830	0.20	0845	0	>0.20
6-05-96	0835	.22	0900	0	>.22

Highland Creek

Loss calculations for Highland Creek, a tributary to Beaver Creek, are presented in table 6, which includes measurements for sites 4 and 4A (fig. 9). Calculated losses in table 6 consist of combined losses to outcrops of the Madison Limestone, Minnelusa Formation, and Minnekahta Limestone (table 3). Notations of zero flow were recorded on all dates at the downstream station (site 4A).

Table 6. Calculations of streamflow losses for Highland Creek

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operation; >, potential loss greater than indicated because of zero flow at downstream site]

Date	Upstream station site 4		Downstream station site 4A		Total loss, in ft^3/s (4 - 4A)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	
8-10-95	1135	3.40	1215	0	>3.40
4-22-96	1140	3.27	1210	0	>3.27
5-30-96	1400	6.74	1430	0	>6.74
6-05-96	1030	4.51	1120	0	>4.51
6-14-96	1000	4.25	1100	0	>4.25
9-03-96	1140	3.16	1230	0	>3.16

The loss threshold for Highland Creek cannot be determined using individual measurements because of the zero-flow measurements at the downstream station (site 4A). It is possible, however, to obtain additional insights by analyzing daily streamflow records that are available for the two continuous-record stations on Beaver Creek (sites 1 and 5). This analysis also provides insights regarding alluvial loss rates and storage volumes for Beaver Creek downstream from the loss zone.

Site 5 is located several miles downstream from the confluence of Beaver and Highland Creeks (fig. 9). Moderate to extensive alluvial deposits (table 3) are located throughout the reach, between the confluence and site 5. An artesian spring with relatively stable discharge of about 10 ft^3/s or larger is located about 1 mi upstream from site 5 and just downstream from an isolated outcrop of the Minnekahta Limestone (fig. 9). The reach from the loss zone downstream to the spring generally is dry, except during periods when upstream flow is sufficient to pass through the loss zone. Daily streamflow records for sites 1 and 5, along with other pertinent information for the period from May 1 through September 18, 1995, are presented in table 37 of the Supplemental Information section at the end of this report.

The daily mean streamflow for site 5 is shown in column 1 of table 37. An estimate of bedrock springflow, based on streamflow at site 5, is presented in column 2. Springflow is assumed equal to measured streamflow at site 5 through June 9, and is assumed equal to 16 ft^3/s through August 11, 1995. Flow immediately upstream from the spring reportedly ceased about noon on August 11 (S. Simpson, landowner, oral commun., 1995). Thus, subsequent to August 11, springflow was again assumed equal to streamflow at site 5, with the exception of August 26-28, when springflow was assumed equal to 14 ft^3/s. Measured streamflow at site 5 and estimated springflow for May 1 through September 18, 1995, are shown in figure 10.

Figure 10 also shows calculated flow upstream of the spring (table 37, column 3), which is determined by subtracting estimated springflow (column 2) from measured flow at site 5 (column 1). The reach above the spring apparently was dry through June 9, in spite of large measured flows at site 1 on Beaver Creek upstream from the loss zone, as shown in column 4 of table 37. The estimated flow of Beaver Creek just downstream from the bedrock loss zone, which is determined by subtracting the estimated bedrock loss threshold of 5 ft^3/s from measured flow at site 1, is shown in figure 11 and in column 5 of table 37.

Figure 11 also shows estimated tributary inflow between sites 1 and 5 (column 6 of table 37), which is determined by subtracting column 5 from column 3 of table 37. This calculation produces a negative value for tributary inflows (which actually represents alluvial losses) for the consecutive period of May 6 through June 23, 1995. This indicates that the alluvium probably was not saturated to stream level until about June 24. The volume of water required to saturate the alluvium to a level equal to the stream stage was at least 1,300 acre-ft, which is represented in figure 11 by the area between the zero-flow value and the negative inflows (alluvial losses) for May 6 through June 23. Estimated alluvial loss rates exceeded 20 ft^3/s for 15 consecutive days between May 30 and June 13.

After June 24, the flow of Beaver Creek downstream from the bedrock loss zone was essentially passed through the alluvial loss zone without large alluvial losses or substantial tributary inflows (fig. 11, table 37). Several moderate rises occurred, without any evidence of additional tributary inflow. Thus, it is unlikely that Highland Creek contributed much, if any, flow to Beaver Creek after June 24.

Estimated daily flows for the upstream station on Highland Creek (site 4) are presented in column 7 of

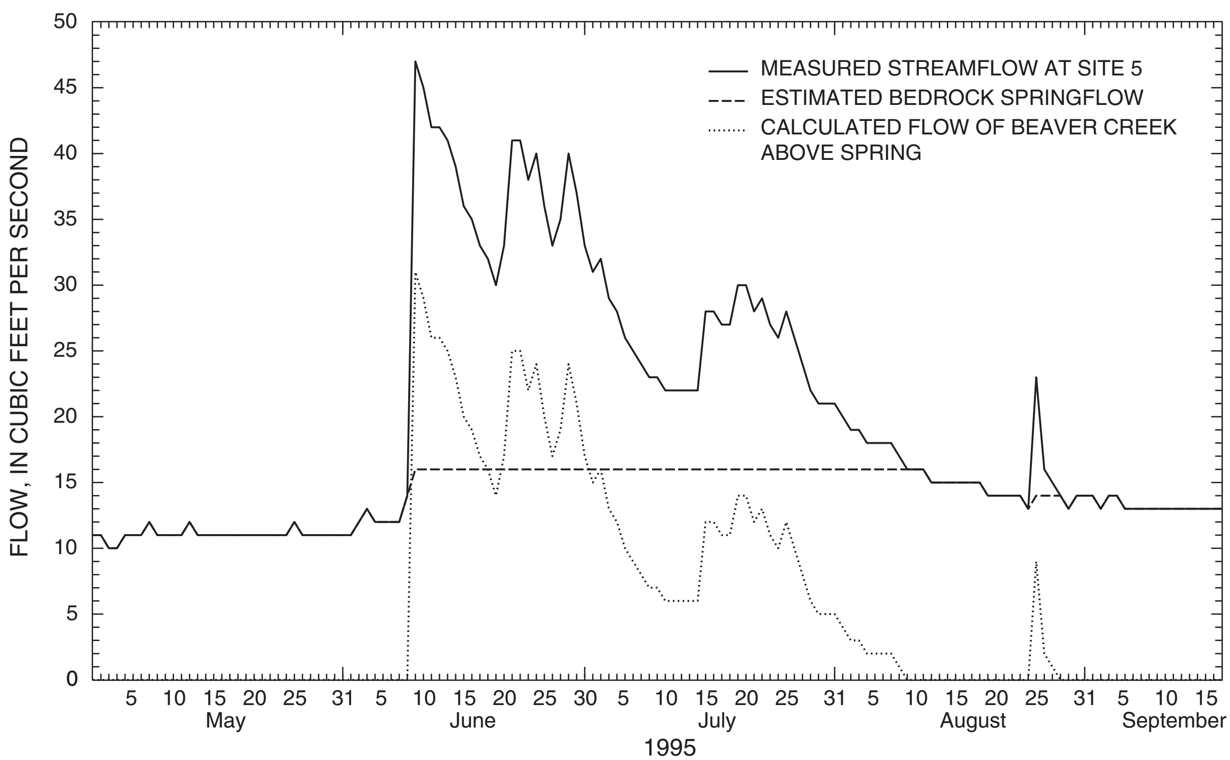


Figure 10. Hydrographs of measured daily streamflow at site 5 (Beaver Creek above Buffalo Gap), estimated bedrock springflow, and calculated flow above spring.

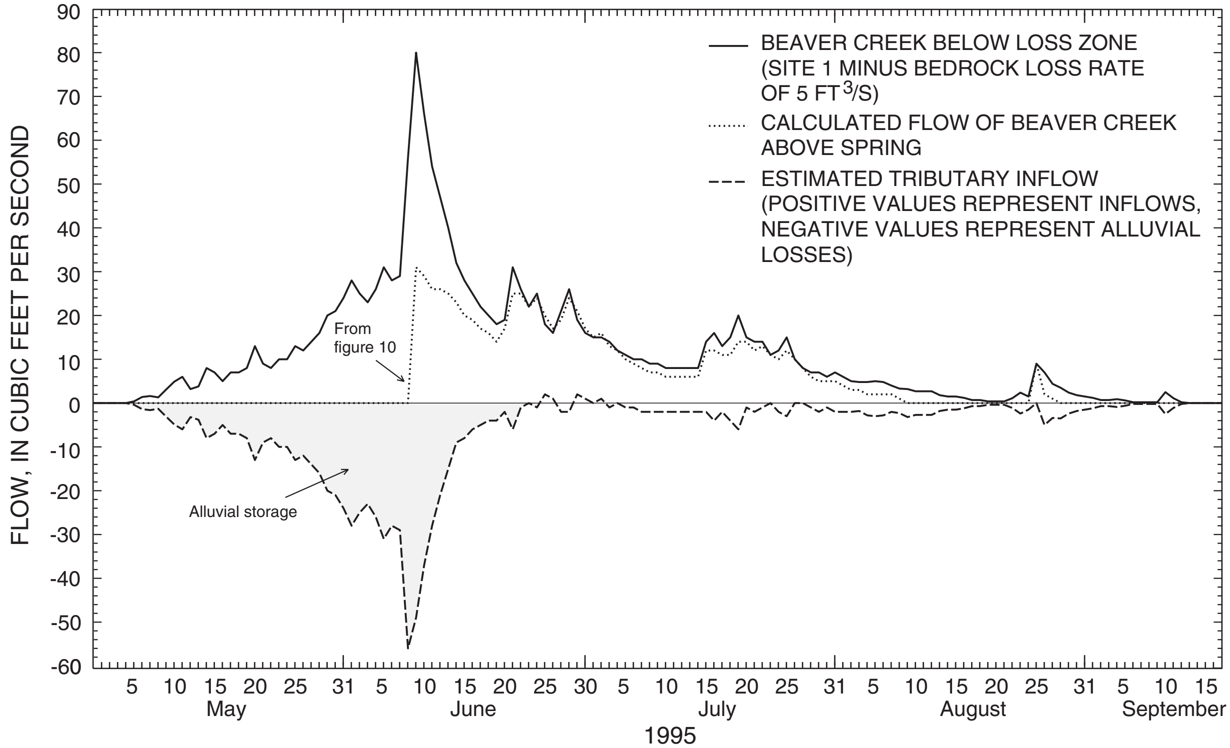


Figure 11. Hydrographs of calculated daily streamflow values used to estimate tributary inflow to Beaver Creek.

table 37. These estimates were derived using a linear regression analysis (fig. 12) of measured flow at site 4 as a function of mean daily flow in Beaver Creek at site 1 (table 7).

Estimated flows for Highland Creek for June 23 to June 30 averaged about 11 ft^3/s without evidence of substantial tributary inflow below the loss zone (fig. 11). Thus, it is estimated that the loss threshold for Highland Creek exceeds 10 ft^3/s. This estimate is considered poorer than those for most other streams because of the numerous assumptions and variables involved with this analysis.

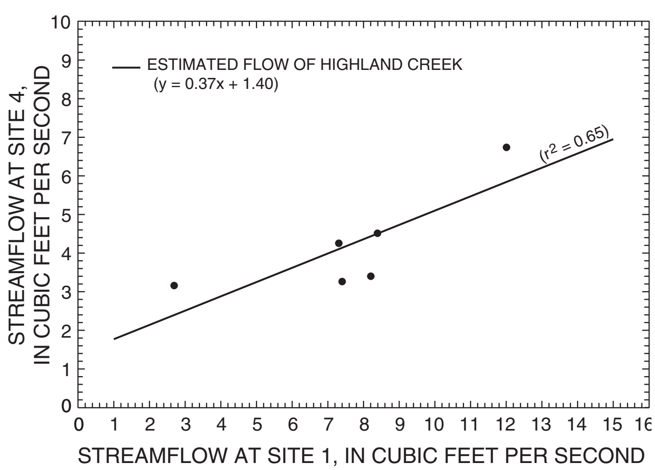


Figure 12. Regression plot of streamflow at site 4 (Highland Creek above Madison outcrop), as a function of streamflow at site 1 (Beaver Creek near Pringle), water year 1996.

Table 7. Flow data associated with the regression analysis of Highland Creek

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

Date	Beaver Creek at site 1	Highland Creek at site 4	
	Mean daily flow, in ft^3/s	Measured flow, in ft^3/s	Estimated flow[1], in ft^3/s
8-10-95	8.2	3.40	4.4
4-22-96	7.4	3.27	4.1
5-30-96	12	6.74	5.8
6-05-96	8.4	4.51	4.5
6-14-96	7.3	4.25	4.1
9-03-96	2.7	3.16	2.4

[1]Estimated flow for Highland Creek (site 4) as a function of flow at Beaver Creek (site 1), using the regression equation from figure 12.

Lame Johnny Creek and Tributaries

Losses are calculated for both the North and South Forks of Lame Johnny Creek (fig. 9). Calculations for the South Fork of Lame Johnny Creek include measurements for Flynn Creek, which joins the South Fork within the outcrop of the Madison Limestone.

South Fork Lame Johnny Creek (including Flynn Creek)

Loss calculations for the South Fork of Lame Johnny Creek are presented in table 8, which includes measurements for sites 6, 7, and 8 (fig. 9). The calculated losses in table 8 consist of combined losses to the Madison Limestone and Minnelusa Formation on South Fork Lame Johnny Creek, as well as losses to the Madison Limestone on Flynn Creek (table 3).

Combined losses are calculated as 1.47 ft^3/s for August 10, 1995 and 1.36 ft^3/s for May 22, 1996. These measurements were made at relatively low flows, which maximizes measurement accuracy. The losses of 3.4 ft^3/s for June 8, 1995, and 0.6 ft^3/s for June 30, 1995, are for higher flows, which decreases measurement accuracy. The mean and median values for all loss calculations are very similar at 1.7 and 1.4 ft^3/s, respectively. Because the median value is most representative of the losses for lower flows, which probably are accurate, the loss threshold is estimated as 1.4 ft^3/s.

North Fork Lame Johnny Creek

Loss calculations for the North Fork of Lame Johnny Creek are presented in table 9, which includes measurements for sites 9 and 10 (fig. 9). The majority of losses probably occur to the Madison Limestone with possible small losses to the Deadwood Formation (table 3). Determination of losses to the Minnelusa Formation is not possible because of overlying deposits of the White River Group near the downstream site. The mean and median for the two finite calculated loss values are both 2.31 ft^3/s. Thus, the loss threshold for the North Fork of Lame Johnny Creek is estimated as 2.3 ft^3/s.

Table 8. Calculations of streamflow losses for South Fork Lame Johnny Creek and Flynn Creek

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operations]

Date	Upstream station site 6		Upstream tributary site 7		Downstream station site 8		Total loss, in ft^3/s (6 + 7 - 8)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	
6-08-95	1552	8.54	1440	25.8	1720	30.9	3.4
6-30-95	0925	3.53	1040	12.3	1203	15.2	.6
8-10-95	1407	1.76	1505	7.17	1625	7.46	1.47
5-22-96	0855	.52	0925	2.04	1030	1.20	1.36
						Mean loss	1.7
						Median loss	1.4

Table 9. Calculations of streamflow losses for North Fork Lame Johnny Creek

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operation; >, potential loss greater than indicated because of zero flow at downstream site]

Date	Upstream station site 9		Downstream station site 10		Total loss, in ft^3/s (9 - 10)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	
6-20-95	1335	3.10	1445	1.00	2.10
5-22-96	1115	.20	1125	0	>.20
5-29-96	1000	2.62	1030	.10	2.52
				Mean loss[1]	2.31
				Median loss[1]	2.31

[1]Calculated using finite values only.

French Creek

Loss calculations for French Creek are presented in table 10, which includes measurements for sites 11, 12, and 13 (fig. 9, table 3). In many cases, it is possible to differentiate between losses to the Madison Limestone and Minnelusa Formation. In several cases, daily mean values are used for the upstream station, because individual measurements are not available.

The mean and median values for combined losses to the Madison Limestone and Minnelusa Formation are 14.9 and 14.5 ft^3/s, respectively (table 10). Losses for June 17, 1996, are excluded from the mean and median calculations because the daily mean flow on this date changed 86 percent from the previous day. Considering the results of mean and median calculations, the loss threshold for French Creek is estimated as 15 ft^3/s.

Measurements obtained at site 12 make it possible to differentiate between losses to the Madison and Minnelusa. Using median values, the loss threshold for the Madison is estimated as 11 ft^3/s and the threshold for the Minnelusa is estimated as 4 ft^3/s.

Data from two discontinued, continuous-record gages also were considered. Station 06403000, French Creek near Custer, was located approximately 9 mi upstream from site 11 and station 06403500, French Creek near Fairburn, was located approximately 5 mi downstream from site 13. Mean monthly values for these stations are available for WY45-47 (Miller and Driscoll, 1998); however, these values were not analyzed because of the large distance between the gages, which could cause large variability due to alluvial storage, tributary inflows, and other possible factors.

Battle Creek and Tributaries

Losses are calculated for the main stem of Battle Creek and its tributaries (Grace Coolidge Creek, Bear Gulch, and Spokane Creek). Bear Gulch and Spokane Creek are tributary to Grace Coolidge Creek, which is tributary to Battle Creek (fig. 13).

Battle Creek

Loss calculations for Battle Creek are presented in table 11, which includes measurements for sites 14, 15, and 16 (fig. 13, table 3). Calculations for Battle Creek are complicated by a series of bedrock springs with variable discharge that are located within the Minnelusa Formation, between sites 15 and 16 (Shortridge, 1953). Thus, losses are calculated only to the Madison Limestone, by subtracting flow at the intermediate station (site 15) from flow at the upstream station (site 14).

The mean and median loss rates to the Madison, for days with finite values, are calculated as 11.4 and 11.8 ft^3/s, respectively (table 11). The mean loss is affected by one smaller loss value (9.7 ft^3/s) calculated for July 3, 1996. Thus, the median is rounded to 12 ft^3/s and is considered the best estimate of the loss threshold to the Madison Limestone on Battle Creek.

It could not be determined if losses occur to the Minnelusa Formation or Minnekahta Limestone because of the springflow that occurs between sites 15 and 16. Springflow within the reach is calculated by subtracting flow at site 15 from site 16, which yields positive values for springflow (table 11). Springflow within this reach is more variable than for many other springs in the Black Hills area (Miller and Driscoll, 1998). Springflow is shown to respond rather quickly to changes in recharge conditions. Springflow decreased steadily after flow ceased through the loss zone on about August 1, 1995 (table 11). Then, as streamflow recharge increased, springflow increased from 5.30 ft^3/s on March 11, 1996 to about 10.5 ft^3/s on June 7, 1996. Springflow again began to decrease through July of 1996, as streamflow recharge decreased. A linear relation exists between springflow and streamflow at the upstream station (site 14), when the loss threshold was exceeded during WY96 (fig. 14). However, this relation probably would not be useful as a predictive tool, because springflow probably is affected by various other factors. For example, springflow following the protracted recharge period during WY96 is considerably larger than following the protracted recharge period during WY95 (table 11).

Grace Coolidge Creek and Tributaries

Losses are calculated for the main stem of Grace Coolidge Creek and two of its tributaries (Bear Gulch and Spokane Creek). Both tributaries join Grace Coolidge Creek downstream from the loss zone, so the inflows do not affect loss calculations for Grace Coolidge Creek (fig. 13).

Table 10. Calculations of streamflow losses for French Creek

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operation; --, no data available; >, potential loss greater than indicated because of zero flow at downstream site; u/s, upstream]

Date	Upstream station site 11		Intermediate station site 12		Downstream station site 13		Loss to Madison, in ft^3/s (11 - 12)	Loss to Minnelusa, in ft^3/s (12 - 13)	Total loss, in ft^3/s (11 - 13)	Hydrograph changes[1]/remarks
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s				
[2]7- -57	--	13.7	--	7.30	--	4.00	6.4	3.30	9.7	--
6-04-82	1600	90.4	1650	66.4	1845	55.4	24.0	11.0	35.0	+23%
11-08-82	1040	9.45	1110	.22	--	--	9.23	--	>9.45	-3%
5-24-83	1155	13.2	1250	4.59	1410	.10	8.6	4.49	13.1	-13%
6-16-83	1125	9.20	1215	.15	--	--	9.05	--	>9.20	-14%
10-05-83	1025	11.8	1110	.44	--	--	11.4	--	>11.8	-8%
5-10-84	1045	36.9	1150	25.8	1320	21.3	11.1	4.5	15.6	+3%
7-19-84	1425	21.8	1505	10.3	--	7.15	11.5	3.2	14.6	-27%
5-12-86	1430	15.4	1510	2.46	--	--	12.9	--	>15.4	-26%
6-05-91	1340	158	--	--	1810	144	--	--	14	-33%
6-12-91	1250	53.6	--	--	1510	43.7	--	--	9.9	-11%
6-27-91	1450	16.1	--	--	1640	10.2	--	--	5.9	-19%
5-11-93	1150	39.0	--	--	1435	24.4	--	--	14.6	-28%
6-15-93	1220	37.0	--	--	1400	24.6	--	--	12.4	-12%
7-20-93	1450	25.4	--	--	1545	11.5	--	--	13.9	-7%
9-01-93	1355	6.88	--	--	1500	0	--	--	>6.88	-8%
10-05-93	1315	5.84	--	--	1430	0	--	--	>5.84	-2%
4-12-94	1040	10.1	--	--	1200	0	--	--	>10.1	-4%
5-16-94	1310	23.7	--	--	1547	9.17	--	--	14.5	-23%
7-01-94	1145	2.99	--	--	1250	0	--	--	>2.99	-9%
8-26-94	1110	1.19	--	--	1230	0	--	--	>1.19	-20%

Table 10. Calculations of streamflow losses for French Creek —Continued

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operation; --, no data available; >, potential loss greater than indicated because of zero flow at downstream site; u/s, upstream]

Date	Upstream station site 11		Intermediate station site 12		Downstream station site 13		Loss to Madison, in ft^3/s (11 - 12)	Loss to Minnelusa, in ft^3/s (12 - 13)	Total loss, in ft^3/s (11 - 13)	Hydrograph changes[1]/remarks
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s				
11-22-94	1145	2.21	--	--	1210	0	--	--	>2.21	+36%
3-21-95	1440	9.09	--	--	--	0	--	--	>9.09	flow 300 yards u/s
4-27-95	1105	10.0	--	--	1500	0	--	--	>10.0	flow 1/4 mile u/s
6-30-95	1015	72.1	--	--	1340	54.3	--	--	17.8	-8%
7-10-95	0955	38.6	--	--	1150	23.5	--	--	15.1	-5%
8-18-95	--	[3]15	--	--	1205	.50	--	--	14	-6%
11-21-95	0915	8.53	--	--	1000	0	--	--	>8.53	-16%
1-23-96	1030	6.02	--	--	1130	0	--	--	>6.02	+9%
3-13-96	1005	33.8	--	--	1155	19.7	--	--	14.1	-28%
4-17-96	1130	31.1	--	--	1250	13.4	--	--	17.7	+35%
5-22-96	1315	15.7	1420	4.54	1450	.64	11.2	3.90	15.1	-6%
6-17-96	1200	139	--	--	1335	105	--	--	[4]34	+86%
7-19-96	0850	8.88	--	--	1000	0	--	--	>8.88	-13%
9-09-96	1200	11.2	--	--	1300	0	--	--	>11.2	-15%
						Mean loss[5]	11.5	5.1	15	
						Median loss[5]	11.2	4.2	14.3	

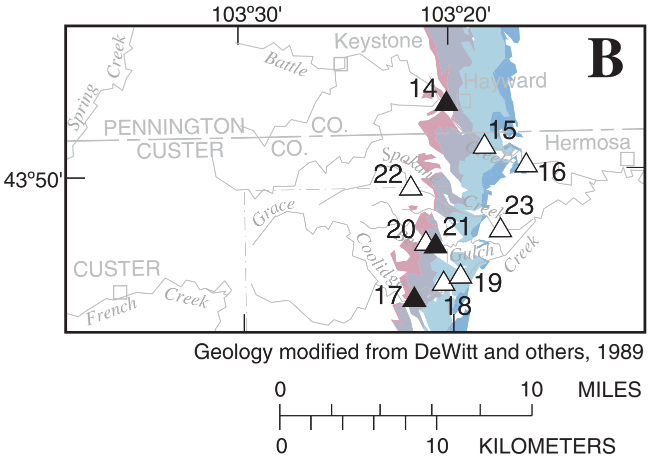
[1]Hydrograph changes calculated using daily mean streamflow at site 11: [(current day - previous day) / previous day] x 100%.
[2]Obtained from data for USGS pipeline survey for French Creek Water Project.
[3]Indicated value for this date is the daily mean.
[4]Excluded from mean and median calculations.
[5]Calculated using finite values only.

Table 11. Calculations of streamflow losses for Battle Creek

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operation; --, no data available; >, potential loss greater than indicated because of zero flow at downstream site]

Date	Upstream station site 14		Intermediate station site 15		Loss to Madison in ft^3/s, (14 - 15)	Downstream station site 16		Springflow[1], in ft^3/s (16 - 15)	Hydrograph changes[2]
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s		Time, in hours	Flow, in ft^3/s		
6-01-95	0740	89.4	--	--	--	1100	73.0	--	-10%
7-11-95	0845	23.2	--	--	--	1425	18.5	--	0%
8-01-95	0740	11.8	--	--	--	1015	8.63	--	+10%
9-05-95	0815	3.31	--	0	>3.31	0955	5.97	5.97	+3%
10-06-95	0810	5.93	--	0	>5.93	0925	5.77	5.77	-5%
11-20-95	1015	4.51	--	0	>4.51	1125	5.65	5.65	-4%
1-16-96	0925	3.29	--	0	>3.29	1050	5.27	5.27	+6%
3-11-96	0915	6.88	--	0	>6.88	1110	5.30	5.30	+2%
4-29-96	0730	10.5	1500	[3]0	>10.5	0915	6.39	6.39	0%
6-07-96	0820	49.8	1035	37.7	12.1	1210	48.2	10.5	-12%
6-14-96	0715	38.3	--	--		0900	36.1	--	-5%
6-19-96	1145	27.6	1350	15.9	11.7	1520	25.2	9.3	-12%
6-27-96	1200	17.3	1335	5.30	12.0	1500	13.6	8.3	-6%
7-03-96	1115	11.5	1305	1.80	9.7	1405	10.2	8.4	-8%
7-11-96	1145	8.90	1330	0	>8.90	1405	8.20	8.2	-7%
7-24-96	0745	4.68	--	0	>4.68	0900	7.28	7.28	+11%
				Mean loss[4]	11.4				
				Median loss[4]	11.8				

[1]Springflow originating within the Minnelusa outcrop between sites 15 and 16 is calculated as flow at downstream station minus intermediate station.
[2]Hydrograph changes calculated using daily mean streamflow at site 14: [(current day - previous day) / previous day] x 100%.
[3]Zero flow observed at 1500 hours on 4-28-96.
[4]Calculated using finite values only.



Site Number	Station Name
14	Battle Creek near Keystone
15	Battle Creek at Madison/Minnelusa contact
16	Battle Creek below Minnelusa outcrop
17	Grace Coolidge Creek near Game Lodge
18	Grace Coolidge Creek near Fairburn
19	Grace Coolidge Creek (below Minnelusa outcrop)
20	Bear Gulch above Hayward
21	Bear Gulch near Hayward
22	Spokane Creek above Madison outcrop
23	Spokane Creek below Madison outcrop

EXPLANATION

DEADWOOD FORMATION

MADISON LIMESTONE

MINNELUSA FORMATION

MINNEKAHTA LIMESTONE

▲21 CONTINUOUS-RECORD STREAMFLOW-GAGING STATION--Number indicates site number

△20 MISCELLANEOUS-RECORD STREAMFLOW-GAGING STATION--Number indicates site number

Figure 13. Insert B from figure 6, showing location of measurement sites and generalized outcrops for Battle Creek and tributaries. Outcrops shown may include other formations.

Grace Coolidge Creek

Loss calculations for the main stem of Grace Coolidge Creek are presented in table 12, which includes measurements for sites 17, 18, and 19 (fig. 13, table 3). Numerous meas7urements in table 12 can be used to calculate losses to the Madison Limestone; however, only two measurements can be used to calculate finite values for losses to the Minnelusa Formation. Those losses are very similar at 2.9 and 2.4 ft^3/s, respectively, and the mean and median are both 2.6 ft^3/s.

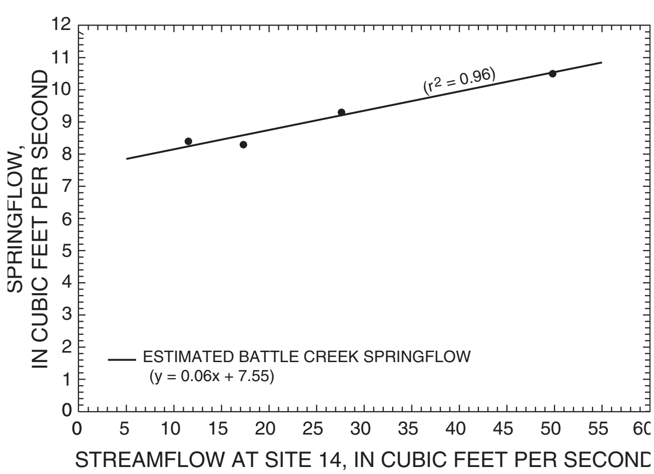


Figure 14. Regression plot of springflow in Battle Creek as a function of streamflow at site 14 (Battle Creek near Keystone), June 7 through July 3, 1996.

Losses to the Madison Limestone can be calculated for three days during WY96 (table 12). These values range from 15.8 to 21.6 ft^3/s and average 18.5 ft^3/s. This loss rate is consistently larger than for numerous measurements made during WY90-95, which range from 4.6 to 10.3 ft^3/s and average only 7.9 ft^3/s. Madison losses are calculated for two days in WY79; however, these losses are not used for calculating means and medians because these measurements were made on the second and third days of flow through the loss zone, with a high likelihood of large alluvial losses.

Additional insights can be gained by examination of continuous streamflow records that were collected at all three sites during WY78-79. Daily means for periods when flow occurred through the loss zone are presented tables 38 and 39 of the Supplemental Information section. Hydrographs for these periods are presented in figure 15. Loss calculations for WY79 are not very useful because of large alluvial losses during the two short periods when flow occurred through the loss zone. Flow through the loss zone did occur for an extended period during WY78, however. Means, medians, and the range of loss values are presented in table 13 for May 13 through June 6, 1978, excluding the period of May 18-20, because of a rapidly changing hydrograph.

Table 12. Calculations of streamflow losses for Grace Coolidge Creek

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operation; --, no data available; >, potential loss greater than indicated because of zero flow at downstream site]

Date	Upstream station site 17		Intermediate station site 18		Downstream station site 19		Loss to Madison, in ft^3/s (17 - 18)	Loss to Minnelusa, in ft^3/s (18 - 19)	Total loss, in ft^3/s (17 - 19)	Hydrograph changes[1]/ remarks
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s				
7-05-79	1200	46.0	1315	13.5	--	--	[2]32.5	--	--	-44%/2nd day of flow through
7-06-79	1030	29.5	0900	3.03	--	--	[2]26.5	--	--	-50%/3rd day of flow through
6-12-90	1420	15.0	1530	4.72	--	--	10.3	--	--	-12%
6-20-90	1235	7.57	1120	.03	--	--	7.54	--	--	-9%
6-12-91	1045	39.5	1200	34.9	--	--	4.6	--	--	-7%
5-10-93	1155	45.1	1055	38.5	--	--	6.6	--	--	-16%
6-14-93	1455	34.0	1450	23.7	--	--	10.3	--	--	-13%
9-07-93	1455	6.81	1545	0	--	--	>6.81	--	--	-14%
10-05-93	1000	4.64	0850	0	--	--	>4.64	--	--	-2%
11-17-93	1400	4.73	1500	0	--	--	>4.73	--	--	-4%
4-13-94	1240	3.11	1115	0	--	--	>3.11	--	--	+3%
6-29-94	1220	1.53	1320	0	--	--	>1.53	--	--	+7%
8-30-94	1350	.70	1410	0	--	--	>0.70	--	--	+28%
10-05-94	1620	1.51	1715	0	--	--	>1.51	--	--	+6%
3-22-95	1430	4.16	1525	0	--	--	>4.16	--	--	+5%
4-27-95	1410	5.43	1500	0	--	--	>5.43	--	--	-9%
5-23-95	1555	56.2	1730	47.4	--	--	8.8	--	--	-18%
7-27-95	1530	8.11	1635	.70	--	--	7.41	--	--	-12%
10-10-95	1015	5.41	1210	0	--	--	>5.41	--	--	-2%
12-05-95	1230	4.78	1300	0	--	--	>4.78	--	--	-4%

Table 12. Calculations of streamflow losses for Grace Coolidge Creek —Continued

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operation; --, no data available; >, potential loss greater than indicated because of zero flow at downstream site]

Date	Upstream station site 17		Intermediate station site 18		Downstream station site 19		Loss to Madison, in ft^3/s (17 - 18)	Loss to Minnelusa, in ft^3/s (18 - 19)	Total loss, in ft^3/s (17 - 19)	Hydrograph changes[1]/ remarks
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s				
1-22-96	1330	3.55	1400	0	--	--	>3.55	--	--	+13%
3-12-96	1200	4.35	0830	0	--	--	>4.35	--	--	-6%
4-30-96	1100	5.62	1200	0	--	--	>5.62	--	--	+5%
5-29-96	1210	93.8	1340	72.2	1445	69.3	21.6	2.9	24.7	-23%
6-04-96	1455	30.1	1555	14.3	1630	11.9	15.8	2.4	18.2	-9%
6-17-96	0910	19.3	1105	1.22	1145	0	18.1	>1.22	>19.3	-5%
7-22-96	1135	4.63	1200	0	--	--	>4.63	--	--	+2%
9-10-96	1135	4.66	1030	0	--	--	>4.66	--	--	0%
			Water years 1990-95			**Mean loss**[3]	7.9	--	--	
						Median loss[3]	7.5	--	--	
			Water year 1996			**Mean loss**[3]	18.5	2.6	21.4	
						Median loss[3]	18.1	2.6	21.4	

[1]Hydrograph changes calculated using daily mean streamflow at site 17: [(current day - previous day) / previous day] x 100%.
[2]Not used in calculation of mean and median losses, because of probable alluvial losses.
[3]Calculated using finite values only.

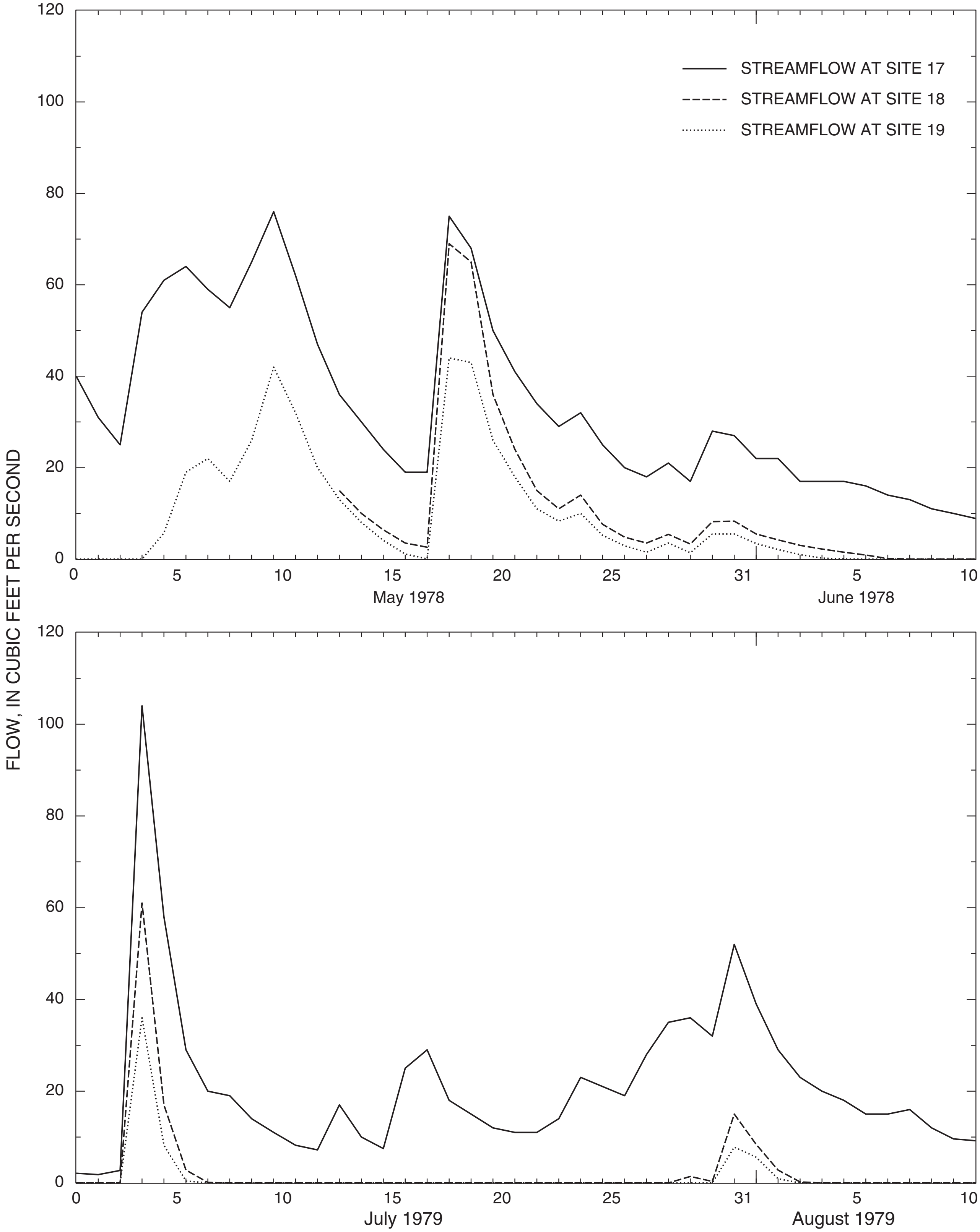


Figure 15. Daily hydrographs for site 17 (Grace Coolidge Creek near Game Lodge), site 18 (Grace Coolidge Creek near Fairburn), and site 19 (Grace Coolidge Creek below Minnelusa outcrop), water years 1978-79.

Table 13. Statistics for daily mean streamflow losses, in cubic feet per second, for Grace Coolidge Creek, May 13 through June 6, 1978 (May 18-20 are excluded[1])

Outcrop considered	Mean	Median	Minimum	Maximum
Loss to outcrops of Madison	17	17	14	21
Loss to outcrops of Minnelusa	2	2	.88	6
Total losses to outcrops of Madison and Minnelusa	19	19	16	23

[1]Period excluded because of rapidly changing hydrograph.

The total losses calculated using continuous records for WY78 (table 13) are very similar to calculations using individual measurements for WY96 (table 12). Calculated losses to the Madison for WY90-95 are consistently smaller than losses during WY78 and WY96. One possible explanation exists for these differences. Extremely large sediment yields were documented following the Galena Fire, which burned about one-half of the Grace Coolidge drainage area during July, 1988 (Whitesides, 1989). Deposition of fine-grained sediment within the channel may have reduced the permeability, causing a decrease in the loss rate. If so, the channel apparently has returned to a pre-burn condition. Future measurements would be useful to better quantify loss rates for Grace Coolidge Creek.

Because of the apparent changes in loss characteristics, measurements made during WY90-95 are excluded from determination of a loss threshold. Thus, loss thresholds for Grace Coolidge Creek are estimated as follows, using a combination of records from WY78 and WY96: Madison, 18 ft^3/s; Minnelusa, 3 ft^3/s; and total losses, 21 ft^3/s.

Bear Gulch

Loss calculations for Bear Gulch are presented in table 14, which includes measurements for sites 20 and 21. The Madison Limestone is exposed for a distance of only about 0.1 mi in the short reach between sites 20 and 21 (fig. 13). Thus, calculated losses in table 14 may include losses to the Deadwood Formation and White River Group, which also are exposed within the same reach (table 3). No attempt was made to differentiate between losses to each outcrop or to document potential losses downstream

Table 14. Calculations of streamflow losses for Bear Gulch

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operation; --, no data available; >, potential loss greater than indicated because of zero flow at downstream site]

Date	Upstream station site 20		Downstream station site 21		Total loss, in ft^3/s (20 - 21)	Hydrograph changes[1]
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s		
5-23-89	1100	0.12	--	[2]0	>0.12	0%
6-28-89	0930	.17	--	[2]0	>.17	0%
12-08-89	1410	.26	1245	.05	.21	0%
12-19-89	1530	.18	1550	0	>.18	0%
12-26-89	1600	.15	1545	0	>.15	0%
1-11-90	0930	.17	--	[2]0	>.17	0%
1-24-90	1445	.15	1500	0	>.15	0%
2-24-90	1400	.11	1245	0	>.11	0%
3-09-90	0930	.15	1145	0	>.15	0%
3-09-90	1530	.17	1145	0	>.17	0%
4-04-90	1600	.54	--	[2].05	.49	0%
5-02-90	--	.70	1010	.32	.38	-1%
5-23-90	1220	1.03	--	[2].76	.27	0%
6-04-96	1130	5.84	1235	5.36	.48	-25%
6-25-96	1405	1.59	1510	1.10	.49	-13%
				Mean loss[3]	0.39	
				Median loss[3]	0.43	

[1]Hydrograph changes calculated using daily mean streamflow at site 21: [(current day - previous day) / previous day] x 100%.
[2]Indicated value for this date is the daily mean.
[3]Calculated using finite values only.

from site 21. The mean and median loss values for Bear Gulch are nearly identical at 0.39 ft^3/s and 0.43 ft^3/s, respectively, thus the loss threshold is estimated as 0.4 ft^3/s.

Spokane Creek

Loss calculations for Spokane Creek are presented in table 15, which includes measurements for sites 22 and 23, as well as inflow from an unnamed tributary. The calculated losses consist of combined losses to the Madison Limestone and Minnelusa Formation, along with possible minor losses to the Deadwood Formation and Minnekahta Limestone (fig. 13, table 3).

The measurement made on May 24, 1995, at site 23 was affected by tributary inflows that were not measured; therefore, a loss is not calculated for this date. Measurements made on June 6 and June 18, 1996, were made about 1 mi upstream from site 23 and included measurements for the unnamed tributary between sites 22 and 23. The mean and median loss values are identical for these two measurements; thus, the loss threshold for Spokane Creek is estimated as 2.2 ft^3/s.

Spring Creek

Two continuous-record (sites 24 and 28) and three miscellaneous-record stations (sites 25, 26, and 27) are used to calculate losses for Spring Creek (fig. 16, table 3). One of the miscellaneous-record stations (site 27) includes daily staff gage readings obtained by an observer. Bedrock losses occur only in the reach between sites 24 and 27; however, site 28 is used for various comparisons with site 24 because continuous streamflow records are available for both sites.

Calculations of losses on Spring Creek are complicated by a variety of factors. Tributary inflows are relatively common and extensive alluvial deposits exist between sites 26 and 28 (table 3). In addition, highly variable springflow frequently occurs between sites 27 and 28. Initial insights regarding loss characteristics for Spring Creek can be obtained by comparing hydrographs of daily streamflow for WY91-96 for sites 24 and 28 (fig. 17), which are located at the extremities of the reach (fig. 16). An approximate threshold for combined losses to the Madison Limestone, Minnelusa Formation, and Minnekahta Limestone, which is estimated as 28 ft^3/s in subsequent discussions, also is shown in figure 17.

The effects of streamflow losses that occurred in saturating extensive alluvial deposits are readily apparent in figure 17A. During WY91, the approximate bedrock loss threshold was first exceeded at the upstream station (site 24) on May 11; however, no flow occurred at the downstream station (site 28) until May 19. Furthermore, the calculated loss rate between the two stations exceeded the approximate bedrock threshold until nearly the end of May (fig. 17A), which indicates that alluvial water levels probably had not reached an equilibrium with stream levels until that time. It is estimated that about 2,000 acre-ft of alluvial storage was filled during this period.

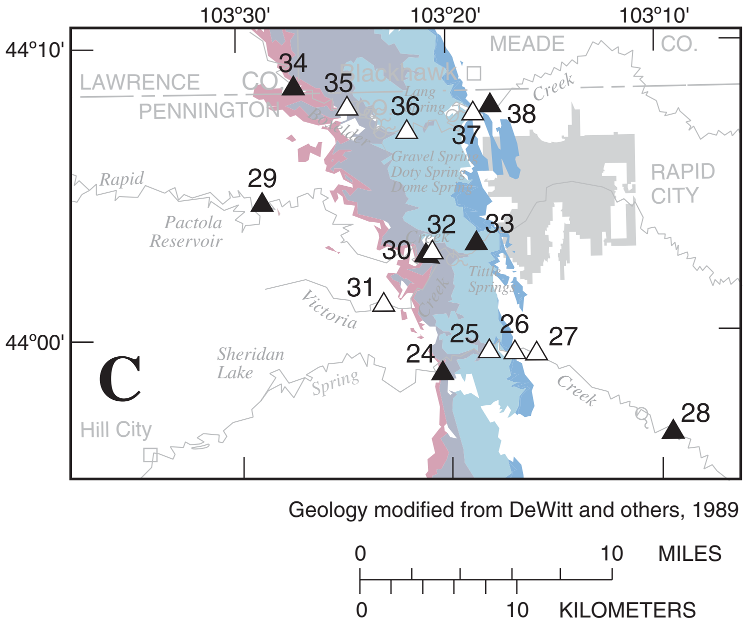
The effects of large tributary inflows also are apparent in figure 17A. The calculated loss rate during early June of WY91 shows a large negative value, when flow at the downstream station exceeded flow at the upstream station.

Table 15. Calculations of streamflow losses for Spokane Creek

[ft^3/s, cubic feet per second; --, no data available; est, estimated flow]

Date	Upstream station site 22		Upstream tributary[1] (unnamed)		Downstream station site 23		Total loss, in ft^3/s (22 - 23)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	
5-24-95	1425	7.28	--	([2])	1540	8.42	--
6-03-96	1115	7.14	--	0.47	1505	[3]5.52	2.09
6-18-96	1210	3.02	est	.2	1340	[3].90	2.3
						Mean loss	2.2
						Median loss	2.2

[1]Measurements from unnamed tributary flowing into Spokane Creek between sites 22 and 23.
[2]Tributary inflow was observed within the loss zone, but was not measured.
[3]Measurement made about 1 mi upstream from site 23, just downstream from outcrop of Minnekahta Limestone.



Site Number	Station Name
24	Spring Creek near Keystone
25	Spring Creek (Madison/Minnelusa contact)
26	Spring Creek above Minnekahta outcrop
27	Spring Creek near Rapid City
28	Spring Creek near Hermosa
29	Rapid Creek below Pactola Dam
30	Rapid Creek above Victoria Creek
31	Victoria Creek below Victoria Dam
32	Victoria Creek at mouth
33	Rapid Creek above Canyon Lake
34	Boxelder Creek near Nemo
35	Boxelder Creek below Norris Peak Road
36	Boxelder Creek at Doty School
37	Boxelder Creek above Minnekahta outcrop
38	Boxelder Creek near Rapid City

EXPLANATION

DEADWOOD FORMATION

MADISON LIMESTONE

MINNELUSA FORMATION

MINNEKAHTA LIMESTONE

▲30 CONTINUOUS-RECORD STREAMFLOW-GAGING STATION--Number indicates site number

△31 MISCELLANEOUS-RECORD STREAMFLOW-GAGING STATION--Number indicates site number

Figure 16. Insert C from figure 6, showing location of measurement sites and generalized outcrops for Spring, Rapid, Victoria, and Boxelder Creeks. Outcrops shown may include other formations.

The effects of variable springflow between sites 27 and 28 are apparent in figure 17B. Measured flow at site 28 was consistently about 2 ft^3/s at the beginning of WY92, but decreased steadily throughout the year, and reached a zero-flow condition by the end of WY92. The calculated loss rate shown in figure 17 does not account for springflow, which is readily apparent in figure 17B, where the calculated loss rate converges with flow at site 24, as flow at site 28 approaches zero.

The effects of alluvial storage, tributary inflows, and variable springflow also are apparent for WY93-96 (fig. 17C-F). Because of the cumulative effects of these factors, an accurate estimate of the bedrock loss threshold cannot be derived from the continuous streamflow records for sites 24 and 28. It is apparent, however, that during periods when upstream flow exceeds the threshold and losses are relatively stable, the loss rate is similar to the approximate threshold of 28 ft^3/s, which is estimated in subsequent discussions.

Insights regarding the possible source of springflow that originates upstream from site 28 also can obtained from figure 17. It cannot be determined if springflow from a bedrock source contributes to this springflow; however, it is hypothesized that drainage of alluvial storage does contribute. Springflow is shown to consistently respond to apparent changes in saturated volume of alluvial deposits, downstream from the bedrock loss zone. Flow at site 28 was zero prior to April of WY91 (fig. 17A); however, springflow was occurring in July of WY91, immediately after flow ceased to pass through the loss zone. Springflow decreased through the remainder of WY91 and ceased near the end of WY92 (fig. 17B). Similar responses are apparent after sustained periods of flow through the loss zone during WY93, 95, and 96. Springflow did not respond, however, to relatively large flows at site 24 during WY94 (fig. 17D), that were in excess of the approximate loss threshold, but apparently insufficient to increase flow at site 28. Observed flow conditions between sites 27 and 28 also support the hypothesis that the springflow originates from the alluvium. Flow near site 27 becomes zero as upstream flow declines to less than the loss threshold; however, flow can be observed immediately downstream from site 27. The length of the zero-flow reach then progressively increases with time, in a downstream direction.

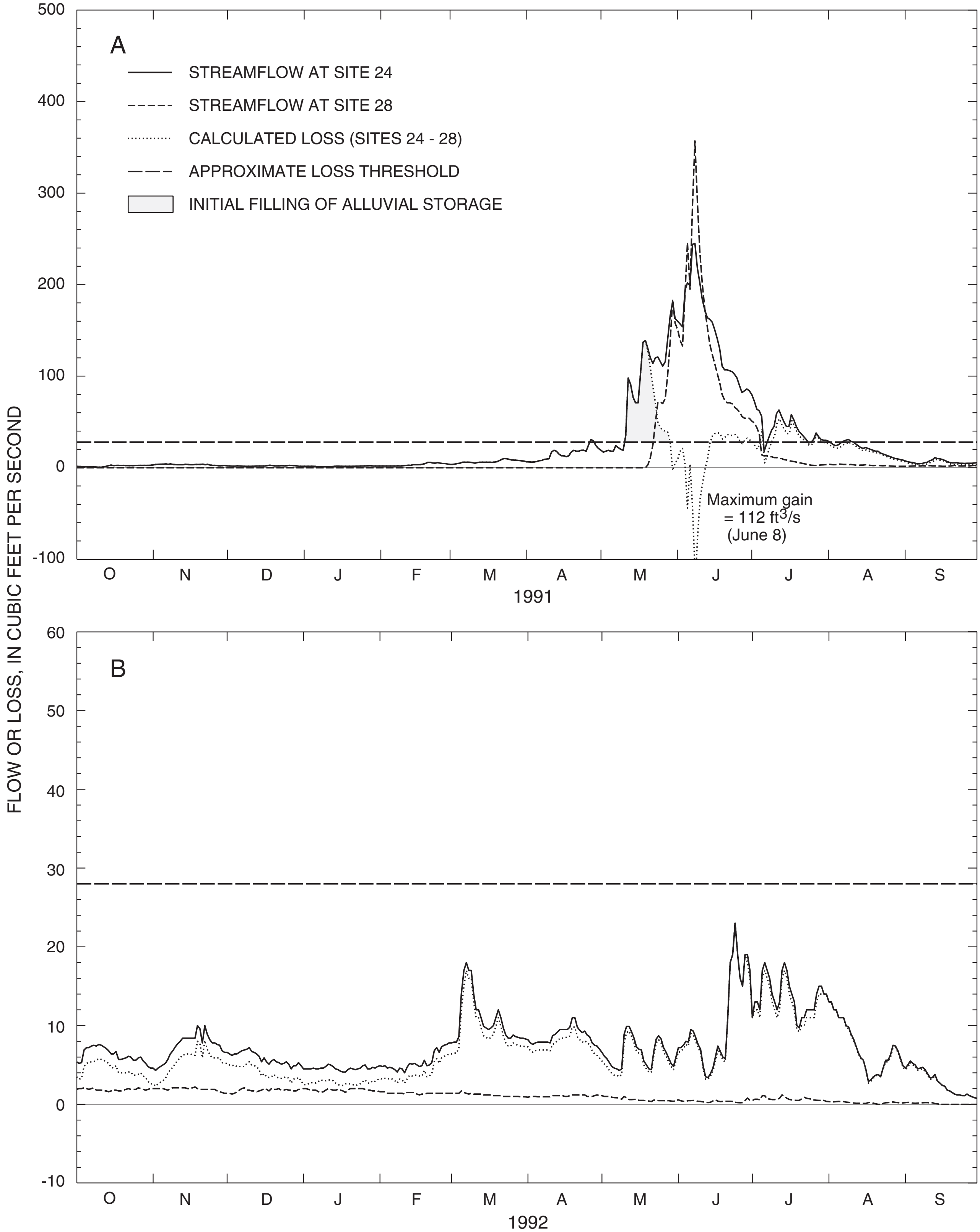


Figure 17. Daily hydrographs and calculated losses for site 24 (Spring Creek near Keystone) and site 28 (Spring Creek near Hermosa), water years 1991-96.

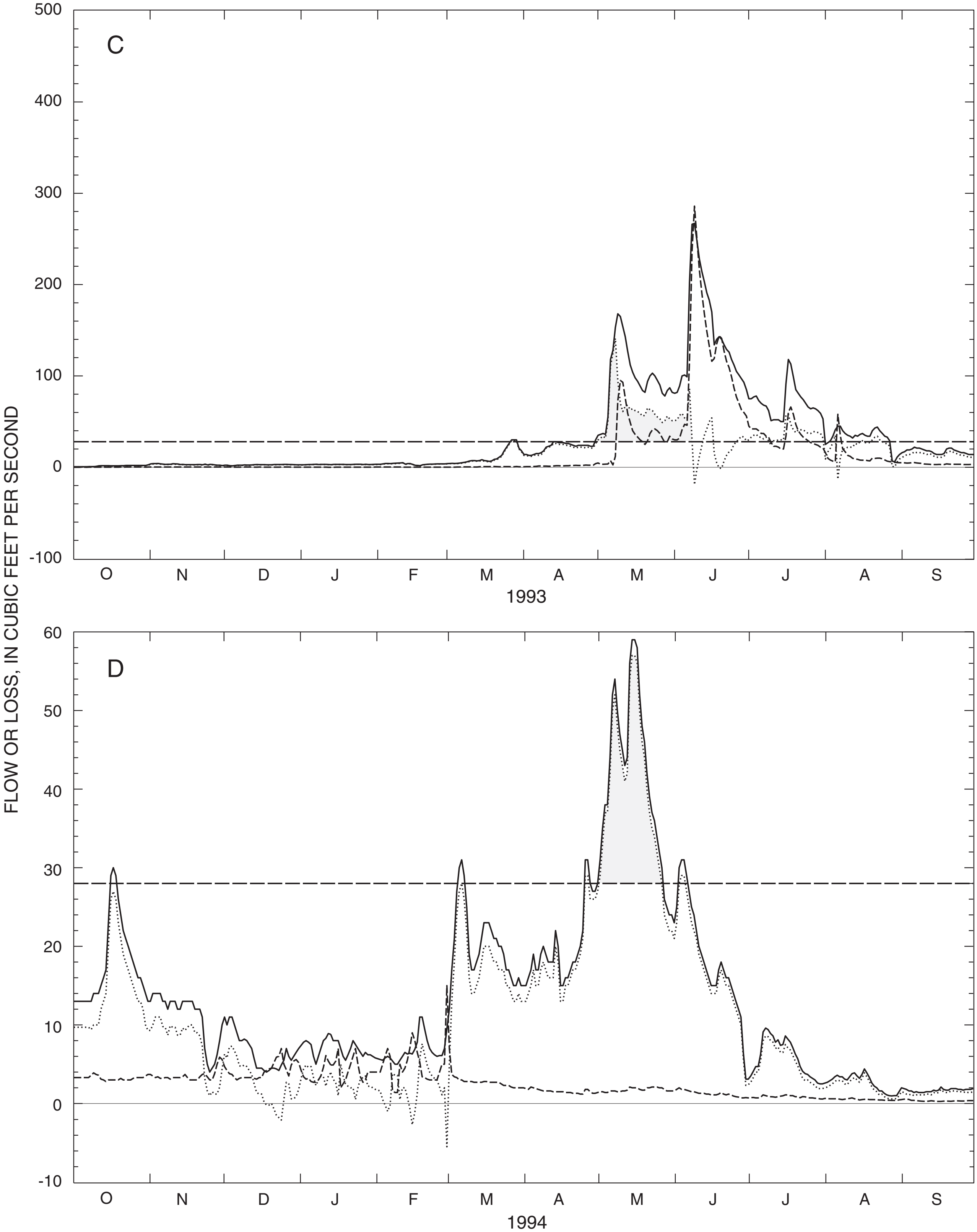


Figure 17. Daily hydrographs and calculated losses for site 24 (Spring Creek near Keystone) and site 28 (Spring Creek near Hermosa), water years 1991-96.--Continued

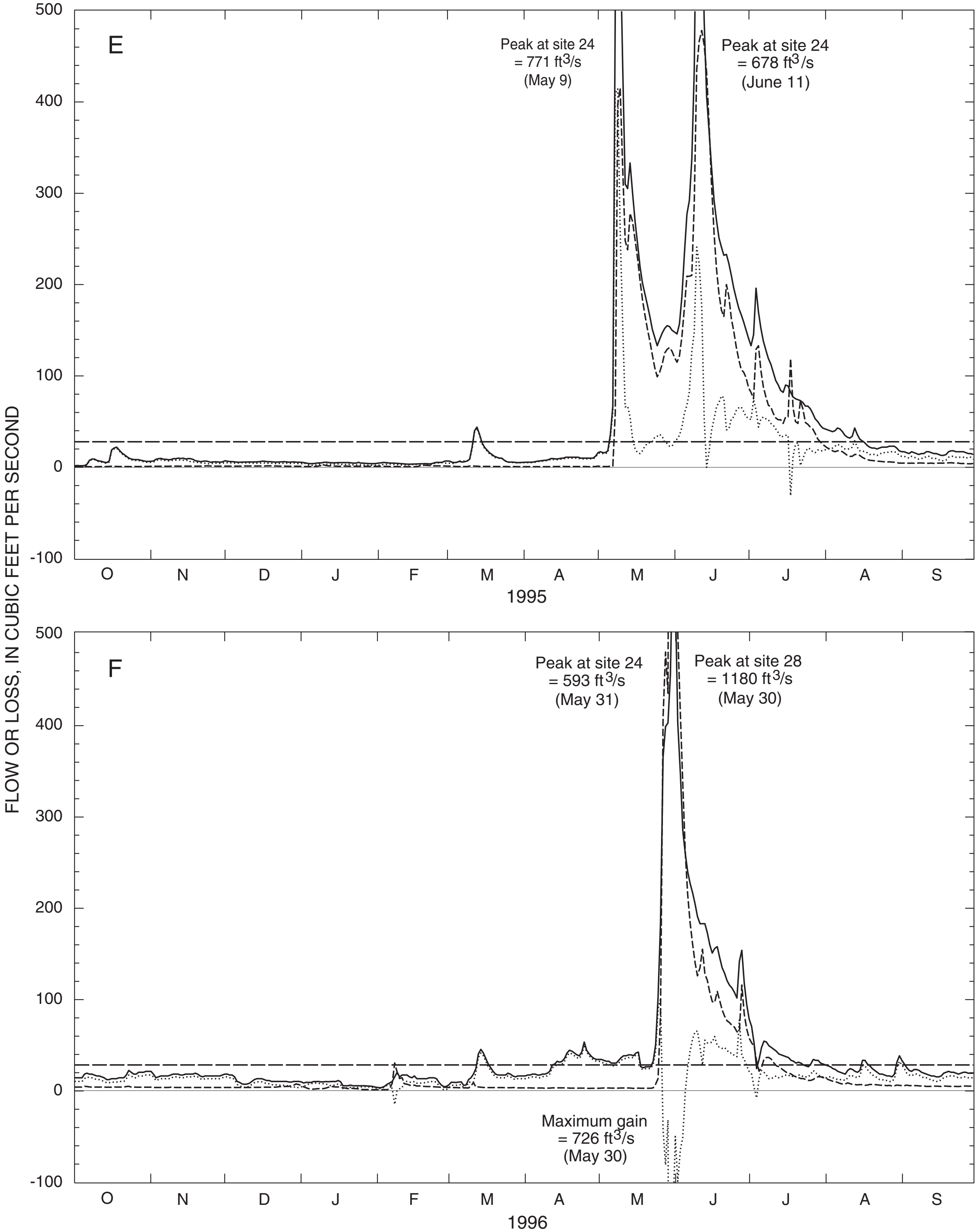


Figure 17. Daily hydrographs and calculated losses for site 24 (Spring Creek near Keystone) and site 28 (Spring Creek near Hermosa), water years 1991-96.--Continued

Loss calculations using individual measurements from sites 24, 25, 26, and 27 for WY90-96 are presented in table 16. Total bedrock losses between sites 24 and 27 are calculated for the entire period; however, losses to individual outcrops can be identified only for WY96, using measurements for sites 25 and 26. Because all bedrock losses probably occur between sites 24 and 27, measurements for site 28 are not included in table 16. Thus, effects from springflow and alluvial losses are reduced. After excluding various calculated losses for reasons footnoted in table 16, the mean and median total bedrock loss rates for WY90-96 are calculated to be 30 and 28 ft^3/s, respectively. The mean and median loss rates to each specific outcrop (Madison, Minnelusa, and Minnekahta) for WY96 also are shown in table 16. Alluvial losses between sites 26 and 27 may be large, relative to calculated losses to the Minnekahta Limestone. Alluvial losses probably are small, however, relative to total losses.

Hydrographs of daily streamflow for sites 24 and 27 for May 10 through September 30, 1996 are presented in figure 18. The hydrograph for site 24 is derived from daily staff-gage readings obtained by an observer, which are less accurate than data obtained from the continuous-recording gage, especially during unstable flow conditions. Calculated losses between sites 24 and 27, which represent total bedrock losses, are consistently in the range of the approximate loss threshold of 28 ft^3/s during the period of stable flow from about July 5 to August 5.

Brown (1944) reported two separate attempts to seal the loss zones along Spring Creek. Only minor decreases in streamflow losses were noted after an attempt made by the U.S. Forest Service in 1937. A more extensive attempt was carried out by the Works Progress Administration during 1939 and 1940, in which bentonite (approximately 100 tons) and rocks were placed in known loss areas. This effort apparently succeeded in significantly decreasing losses at that time. Powell (1940) estimated that the loss threshold was reduced from near 100 ft^3/s to about 6 ft^3/s, although documentation of measurement data is not available.

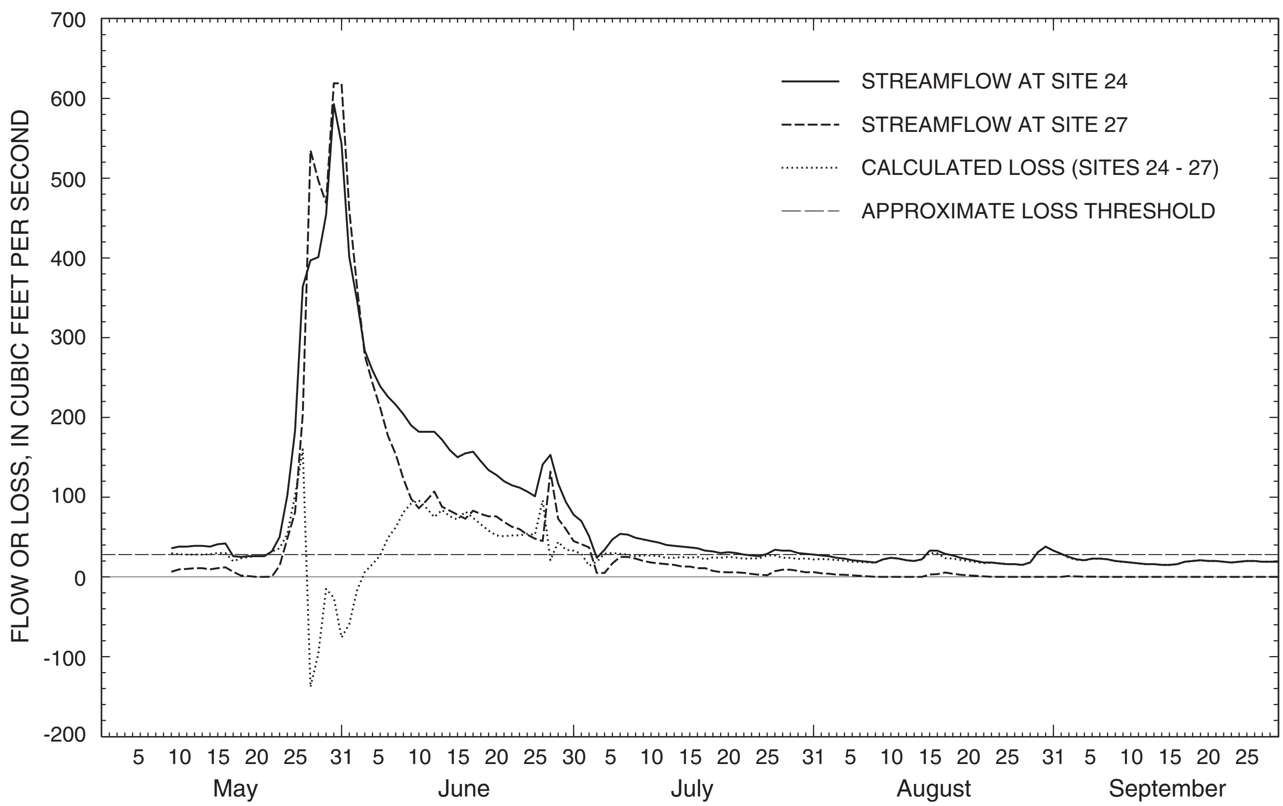


Figure 18. Daily hydrographs and calculated losses for site 24 (Spring Creek near Keystone) and site 27 (Spring Creek near Rapid City), water year 1996.

Table 16. Calculations of streamflow losses for Spring Creek, water years 1990-96

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operation; Mdsn, Madison; Mnls, Minnelusa; Mnkt, Minnekahta; --, no data available; >, potential loss greater than indicated because of zero flow at downstream site; est, estimated discharge]

Date	Upstream station site 24		Intermediate station site 25		Intermediate station site 26		Downstream station site 27		Loss to Mdsn, in ft^3/s (24 - 25)	Loss to Mnls, in ft^3/s (25 - 26)	Loss to Mnkt, in ft^3/s (26 - 27)	Total loss, in ft^3/s (24 - 27)	Hydrograph changes[1]/ remarks
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s					
6-07-90	--	[2]58	--	--	--	--	1600	7.50	--	--	--	50	0%/day 8 of flow through
6-11-90	1455	40.6	--	--	--	--	1405	0	--	--	--	>40.6	
5-12-91	--	[2]98	--	--	--	--	1305	36.2	--	--	--	62	+180%/day 2 of flow through
5-13-91	1532	89.2	--	--	--	--	1340	38.1	--	--	--	51.1	-7%/day 3 of flow through
5-16-91	--	[2]71	--	--	--	--	1215	12.5	--	--	--	58	0%/day 6 of flow through
5-17-91	--	[2]103	--	--	--	--	1100	56.7	--	--	--	46	+45%/day 7 of flow through
5-24-91	--	[2]121	--	--	--	--	1030	98.3	--	--	--	23	0%
5-29-91	--	[2]166	--	--	--	--	1610	155	--	--	--	11	+11%
5-29-91	--	[2]166	--	--	--	--	1855	147	--	--	--	19	+11%
6-13-91	0940	164	--	--	--	--	1140	133	--	--	--	[3]31	-5%
6-15-91	1429	157	--	--	--	--	1607	131	--	--	--	[3]26	-2%
5-14-93	1405	112	--	--	--	--	1240	66.0	--	--	--	[3]46	-12%
8-9-93	0940	37.1	--	--	--	--	0845	6.98	--	--	--	[3]30.1	-8%
3-04-94	--	[2]21	--	--	--	--	0840	0	--	--	--	>21	
5-6-94	1100	44.4	--	--	--	--	0925	0	--	--	--	>44.4	
5-16-94	1040	56.4	--	--	--	--	0930	14.5	--	--	--	41.9	0%/day 8 of flow through
6-23-94	0905	15.8	--	--	--	--	0830	0	--	--	--	>15.8	
7-26-94	0830	3.58	--	--	--	--	0710	0	--	--	--	>3.58	
8-29-94	1145	.99	--	--	--	--	1020	0	--	--	--	>0.99	

Table 16. Calculations of streamflow losses for Spring Creek, water years 1990-96 —Continued

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operation; Mdsn, Madison; Mnls, Minnelusa; Mnkt, Minnekahta; --, no data available; >, potential loss greater than indicated because of zero flow at downstream site; est, estimated discharge]

Date	Upstream station site 24		Intermediate station site 25		Intermediate station site 26		Downstream station site 27		Loss to Mdsn, in ft^3/s (24 - 25)	Loss to Mnls, in ft^3/s (25 - 26)	Loss to Mnkt, in ft^3/s (26 - 27)	Total loss, in ft^3/s (24 - 27)	Hydrograph changes[1]/ remarks
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s					
5-12-95	1430	279	--	--	--	--	1400	241	--	--	--	38	-29%/excessive flows
6-15-95	--	[2]368	--	--	--	--	1345	374	--	--	--	-6	-9%/excessive flows
7-25-95	0915	68.6	--	--	--	--	0720	41.9				[3]26.7	0%
8-19-95	--	[2]22	--	--	--	--	est	.1	--	--	--	22	-8%/trickle at site 27
8-22-95	--	[2]20	--	--	--	--	1335	0	--	--	--	>20	
4-03-96	0920	17.1	--	--	--	--	0735	0	--	--	--	>17.1	
4-16-96	--	[2]32	--	--	--	--	1200	0	--	--	--	>32	
4-23-96	--	[2]38	--	--	--	--	0940	0	--	--	--	>38	
5-02-96	0710	33.6	--	--	--	--	0847	2.97	--	--	--	[3]30.6	0%
5-13-96	0905	38.4	0820	18.1	1005	14.7	1025	10.5	20.3	3.4	4.2	[3]27.9	0%
5-21-96	0848	25.3	0845	4.21	1115	2.75	0955	.24	21.1	>4.21	2.51	>25.3	0%/zero flow observed below site 25
6-05-96	0930	258	--	--	--	--	1145	231	--	--	--	27	-9%/excessive flows
7-10-96	0925	47.9	1205	23.9	1400	24.8	1515	20.0	24.0	-.9	4.8	[3]27.9	-4%
8-19-96	1100	27.2	0945	8.72	1110	5.76	1300	3.51	18.5	2.96	2.25	[e]23.7	-7%
								Mean loss[4]	21.0	3.2	3.4	30	
								Median loss[4]	20.7	3.2	3.4	28	

[1]Hydrograph changes calculated using daily mean streamflow at site 24: [(current day - previous day) / previous day] x 100%.

[2]Indicated value for this date is the daily mean.

[3]Used in calculation of mean and median values for total losses to the bedrock. Other values excluded for various reasons, including: use of daily mean flow, flow at upstream station exceeding 200 ft^3/s (because of increased potential for tributary inflow), rapidly changing hydrograph, or less than 10 days of flow through loss zone.

[4]Calculated using finite positive values only. Total losses calculated using only selected values which are not excluded (see footnote 3).

Streamflow data for sites 24 and 27 indicate that the bedrock loss threshold during WY45-47 probably was less than the current threshold, because of the aforementioned sealing efforts. Hydrographs for the period of June 1945 through July 1947 for sites 24 and 27 (derived from daily staff-gage readings) are plotted in figure 19. Data for site 27 are missing during July of WY46 and October-November of WY47. Calculated losses that are plotted in figure 19 generally range from about 10 to 20 ft^3/s, during sustained periods of relatively stable losses, when upstream flow exceeds the loss threshold.

Loss calculations using individual measurements for sites 24 and 27 during WY45-47 are presented in table 17. Calculated losses represent total bedrock losses, in addition to possible alluvial losses. These losses are somewhat variable, ranging from 6.3 to 24 ft^3/s; however, the mean and median both equal 16 ft^3/s. Paired streamflow measurements made during 1967-70 (Rahn and Gries, 1973) indicate a loss threshold of about 24 ft^3/s.

It appears that sealing efforts initially succeeded in reducing bedrock losses along Spring Creek; however, the loss threshold has increased periodically since that time. The current loss threshold for Spring Creek is estimated to be 28 ft^3/s, with losses to the various outcrops estimated as follows: Madison, 21 ft^3/s; Minnelusa, 3.5 ft^3/s; and Minnekahta, 3.5 ft^3/s.

Table 17. Calculations of streamflow losses for Spring Creek, water years 1945-47

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operation; --, no data available; >, potential loss greater than indicated because of zero flow at downstream site]

Date	Upstream station site 24		Downstream station site 27		Total loss, in ft^3/s (24 - 27)	Hydrograph changes[1]
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s		
7-14-45	--	12.6	--	0.88	11.7	+18%
8-28-45	--	4.52	--	0	>4.52	0%
10-5-45	--	1.90	--	0	>1.90	0%
11-15-45	--	.63	--	0	>.63	0%
12-12-45	--	.08	--	0	>.08	0%
1-18-46	--	.52	--	0	>.52	0%
2-13-46	--	1.36	--	0	>1.36	+40%
3-11-46	--	2.77	--	0	>2.77	+12%
4-1-46	--	2.75	--	0	>2.75	-7%
4-19-46	--	5.33	--	0	>5.33	0%
5-3-46	--	233	--	247	[2]-14	+48%
5-14-46	--	61.8	--	45.6	16.2	-9%
6-2-46	--	143	--	122	21	-3%
6-25-46	--	145	--	121	24	-7%
7-15-46	--	119	--	94.5	24	-8%
7-30-46	--	44.7	--	32.3	12.4	-6%
8-20-46	--	18.4	--	8.33	10.1	-6%
10-13-46	--	21.4	--	6.53	14.9	0%
1-14-47	--	6.13	--	0	>6.13	-14%
2-11-47	--	7.14	--	0	>7.14	+14%
3-11-47	--	5.64	--	0	>5.64	0%
4-8-47	--	19.3	--	3.57	15.7	0%
5-2-47	--	23.8	--	7.87	15.9	0%
5-20-47	--	32.1	--	25.8	6.3	0%
				Mean loss[3]	16	
				Median loss[3]	16	

[1]Hydrograph changes calculated using daily mean streamflow at site 24: [(current day - previous day) / previous day] x 100%.

[2]Excluded from calculation of mean and median values.

[3]Calculated using positive, finite values only.

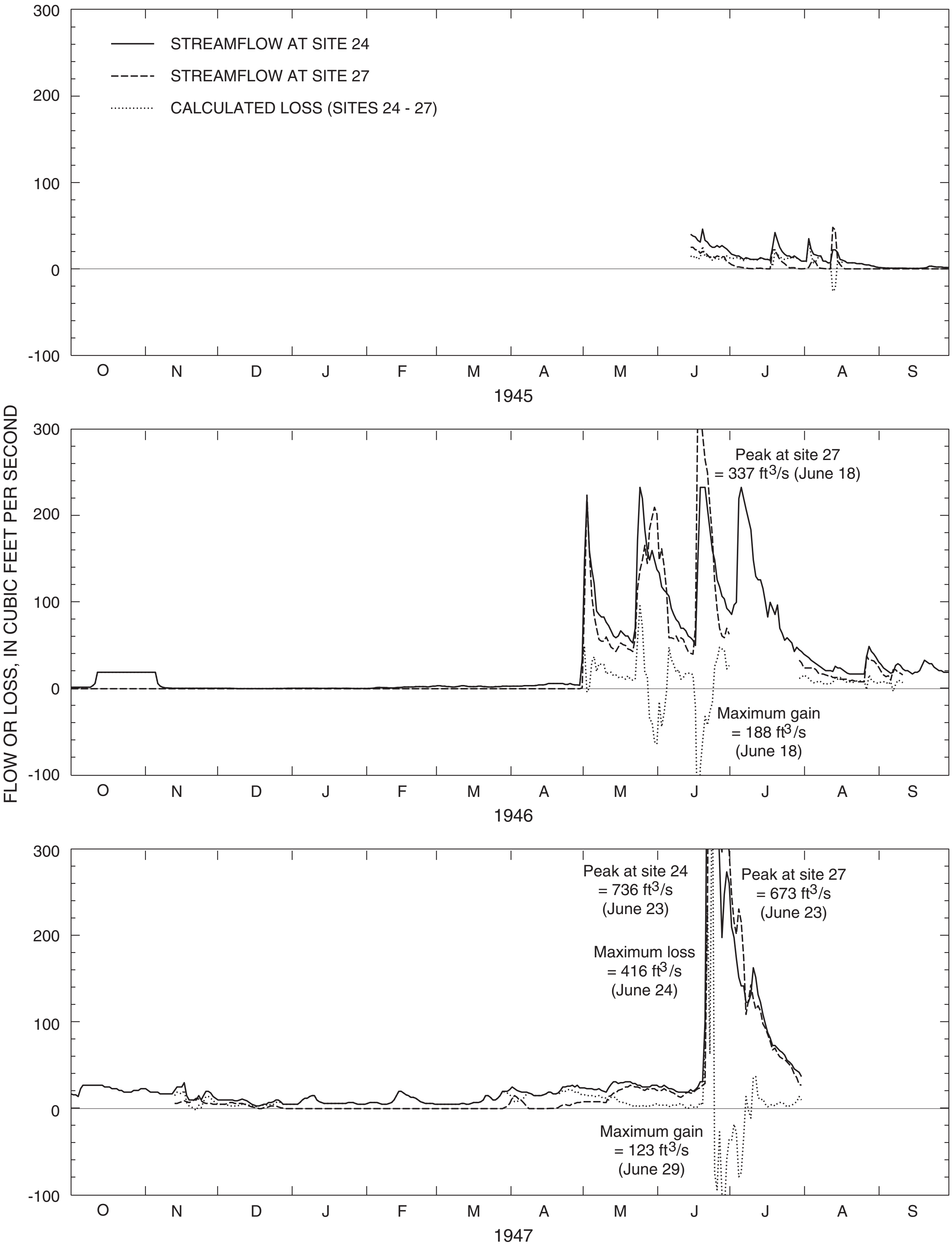


Figure 19. Daily hydrographs and calculated losses for site 24 (Spring Creek near Keystone) and site 27 (Spring Creek near Rapid City), water years 1945-47.