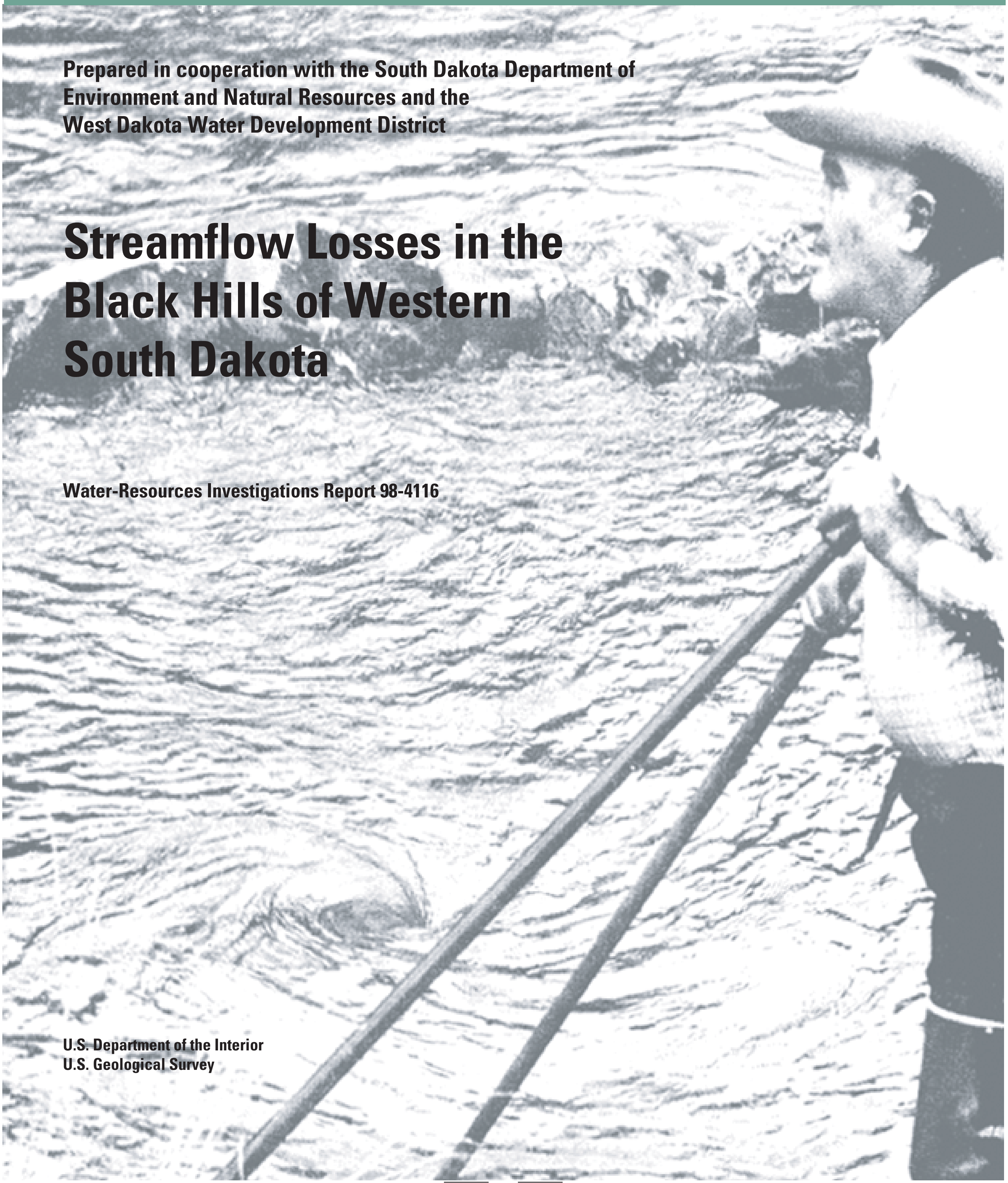
USGS
science for a changing world



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

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.

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

Streamflow Losses in the Black Hills of Western South Dakota

By Jon E. Hortness and Daniel G. Driscoll

Water-Resources Investigations Report 98–4116

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

U.S. Department of the Interior

Bruce Babbitt, Secretary

U.S. Geological Survey

Thomas J. Casadevall, Acting Director

Rapid City, South Dakota: 1998

For additional information write to:

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

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286

CONTENTS

CONTENTS—Continued

ILLUSTRATIONS

ILLUSTRATIONS—Continued

TABLES

TABLES—Continued

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

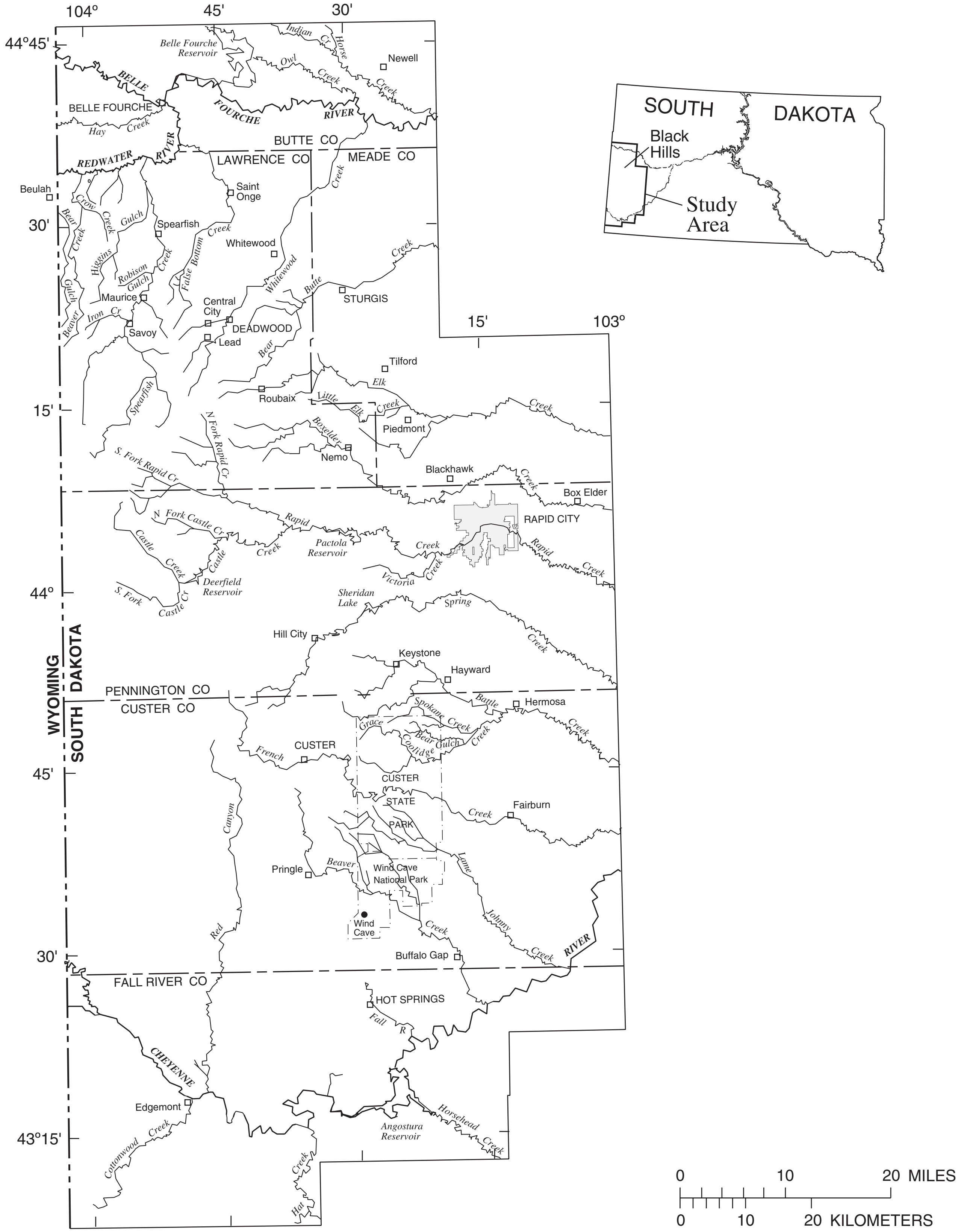
The purposes of this report are to: (1) summarize streamflow records pertinent to determination of loss rates; (2) present estimates of threshold loss rates to bedrock aquifers for selected streams; and (3) present an evaluation of whether loss thresholds are relatively constant or whether they are affected 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

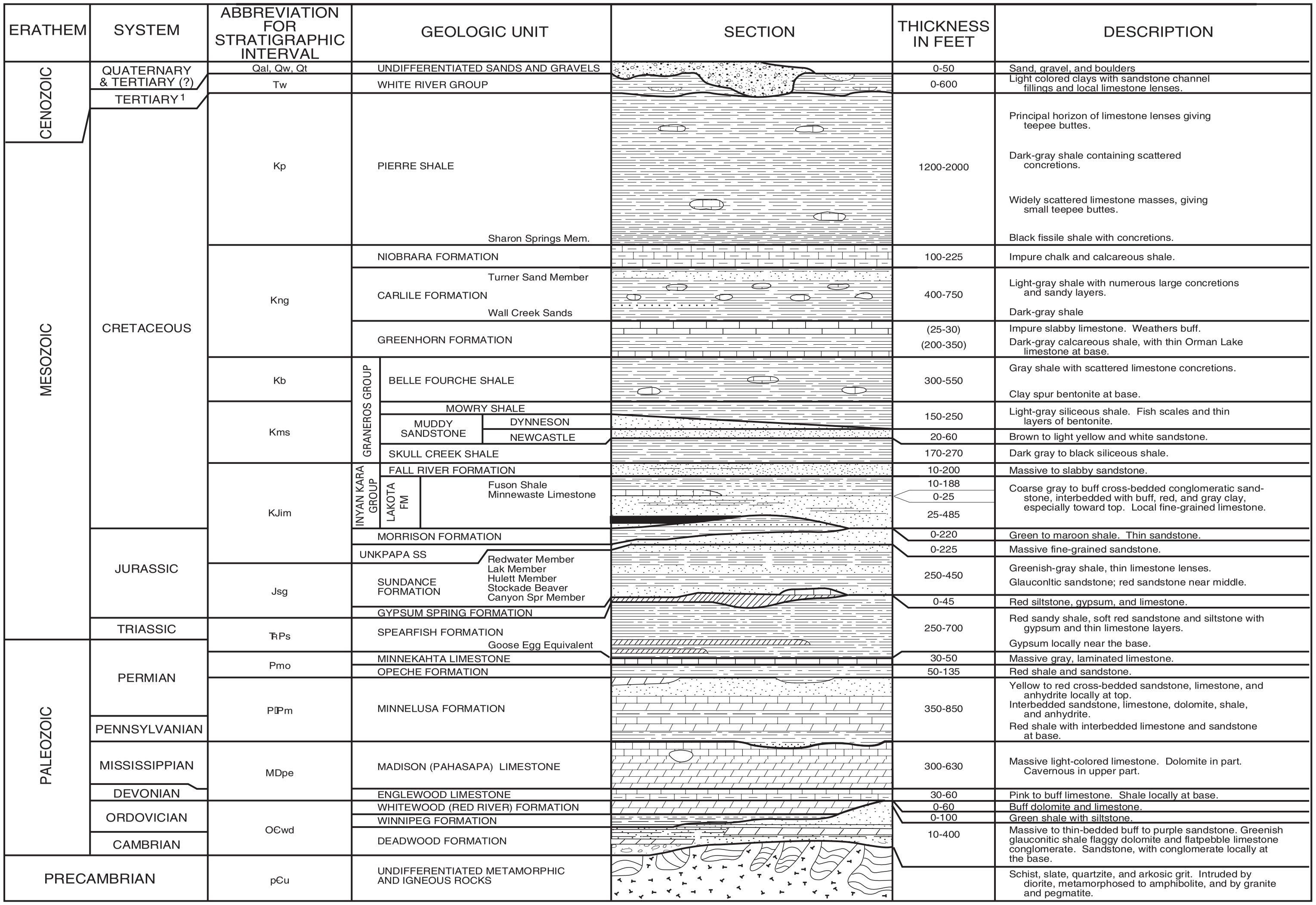
The study area consists of the topographically defined Black Hills and adjacent areas located in western South Dakota (fig. 1). The Black Hills area is an elongated, dome-shaped feature, about 125 mi long and 60 mi wide, which was uplifted during the Laramide orogeny (Feldman and Heimlich, 1980). Elevations 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.

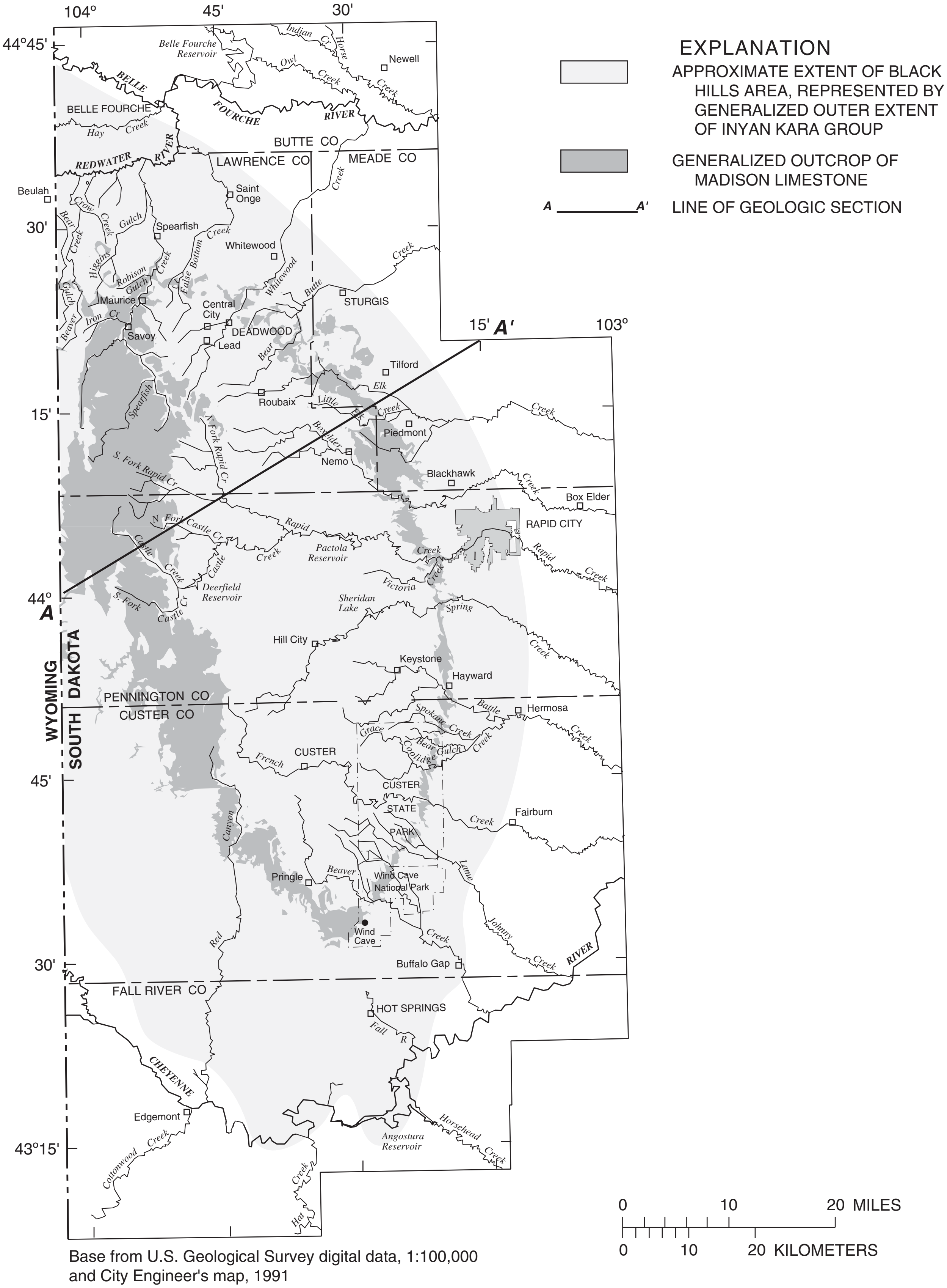


Figure 3. Generalized outcrop of Madison Limestone and outer extent of Inyan Kara Group within the study area for Black Hills Hydrology Study.

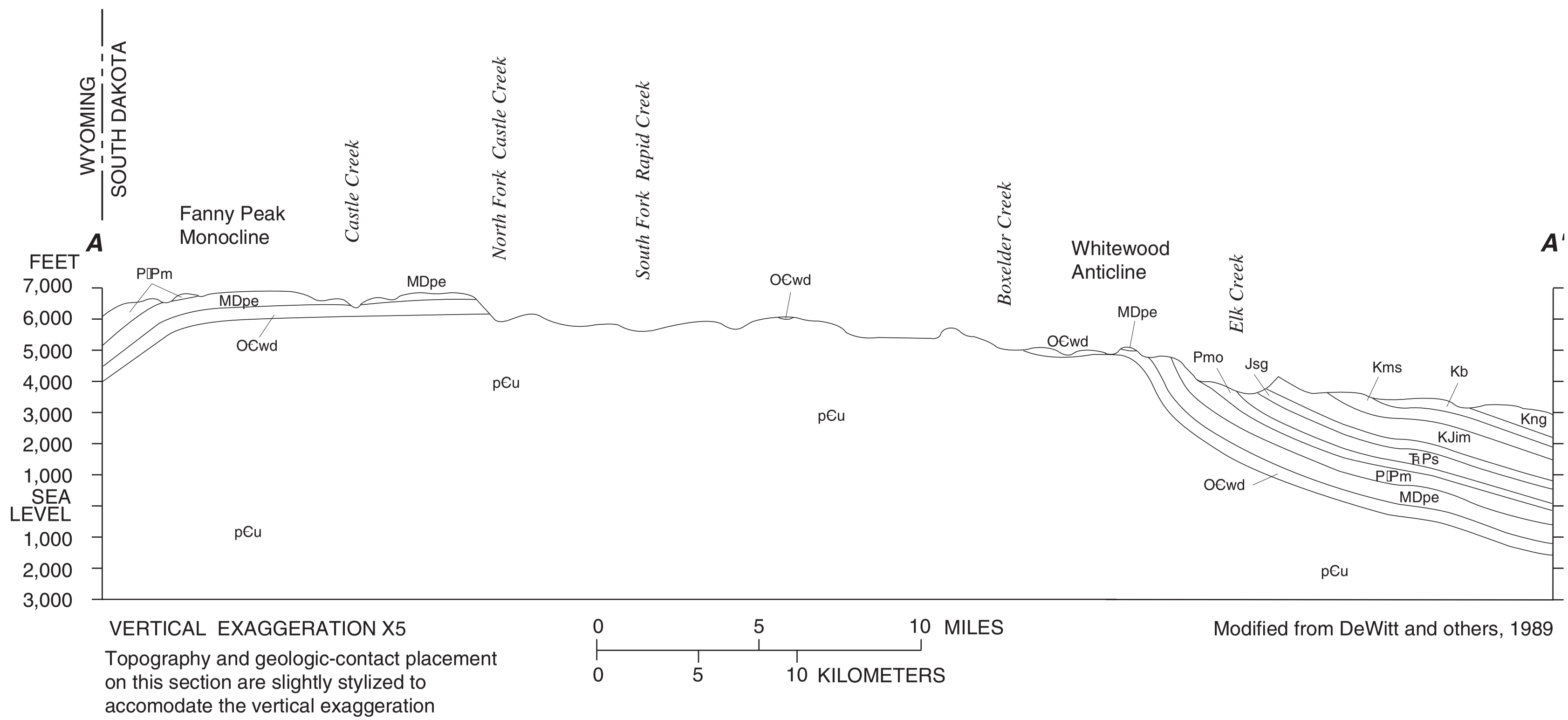


Figure 4. Geologic section A-A'. (Location of section is shown in figure 3. Abbreviations for stratigraphic intervals are explained in figure 2).

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

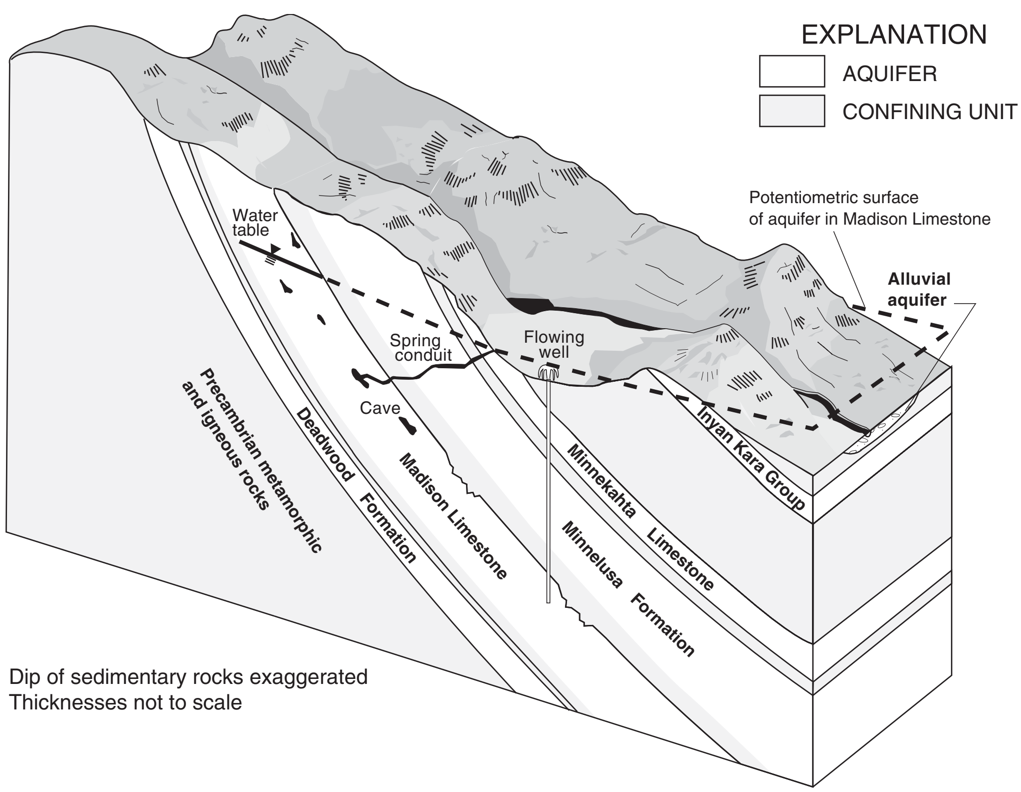


Figure 5. Schematic showing simplified hydrogeologic setting of the Black Hills area.

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.

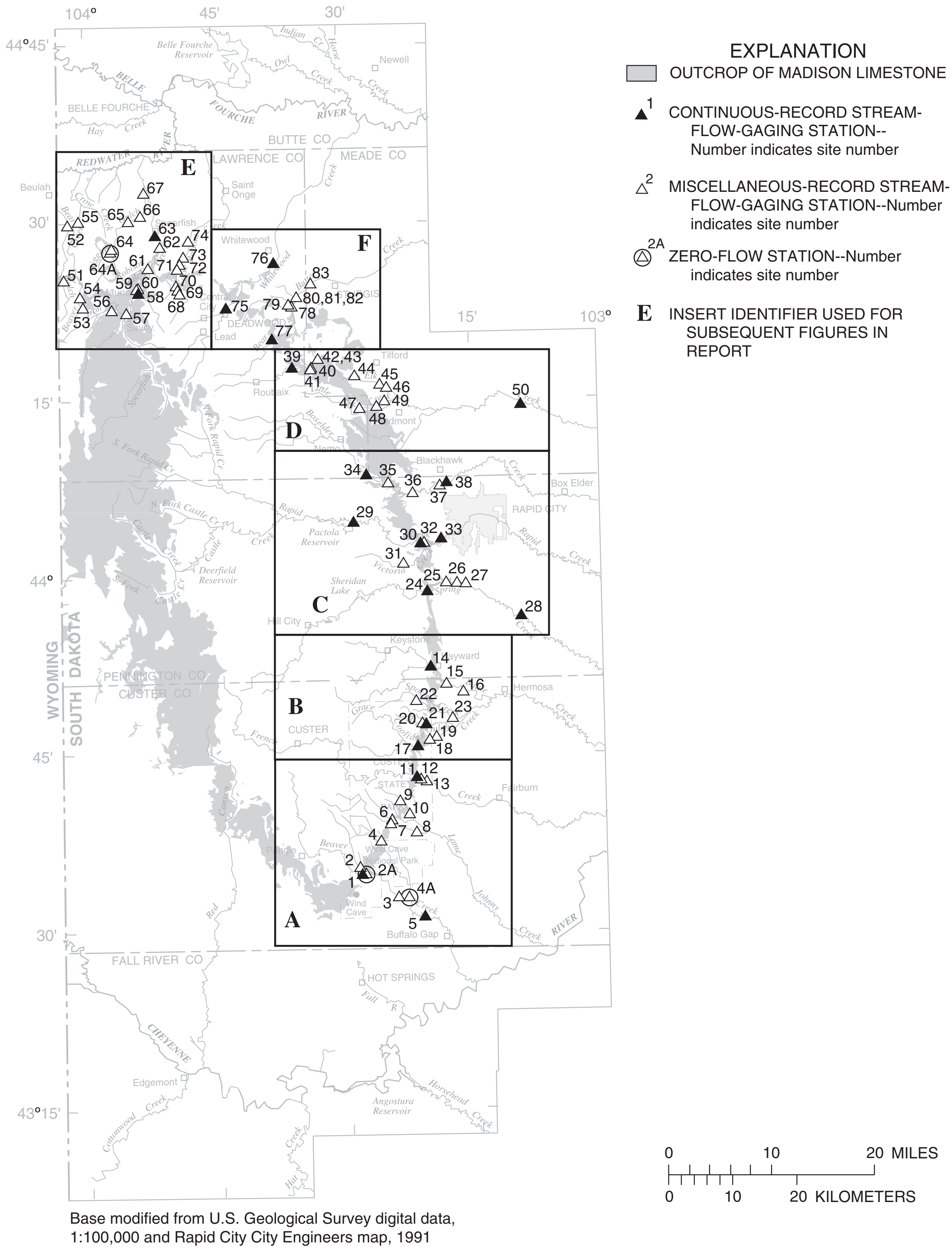


Figure 6. Location of streamflow-gaging stations relative to generalized outcrop of Madison Limestone.

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: Latitude (degrees, minutes, seconds)	Location: Longitude (degrees, minutes, seconds)
		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 (degrees, minutes, seconds) Latitude	Longitude
		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:

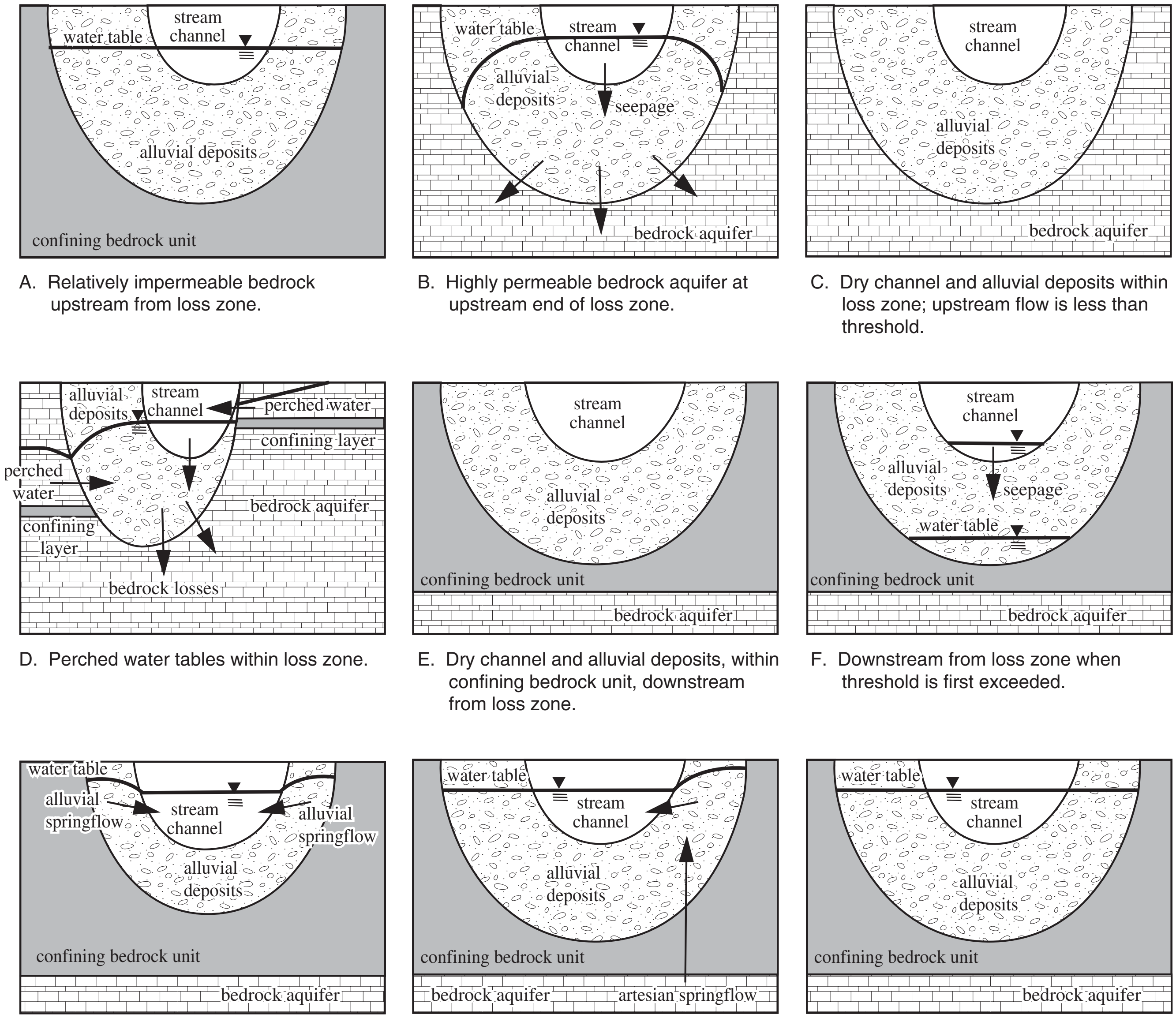
$$Str_i + A_i + P_{ca} + T_i + SF_b = Str_o + A_o + ET_{ca} + W_{ca} + Loss_b \pm \Delta Storage_{ca} \qquad (1)$$

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:

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



A. Relatively impermeable bedrock upstream from loss zone.

B. Highly permeable bedrock aquifer at upstream end of loss zone.

C. Dry channel and alluvial deposits within loss zone; upstream flow is less than threshold.

D. Perched water tables within loss zone.

E. Dry channel and alluvial deposits, within confining bedrock unit, downstream from loss zone.

F. Downstream from loss zone when threshold is first exceeded.

G. Alluvial springflow resulting from drainage of saturated alluvial deposits.

H. Artesian springflow downstream from loss zone.

I. Equilibrium conditions downstream from loss zone; upstream flow exceeds threshold.

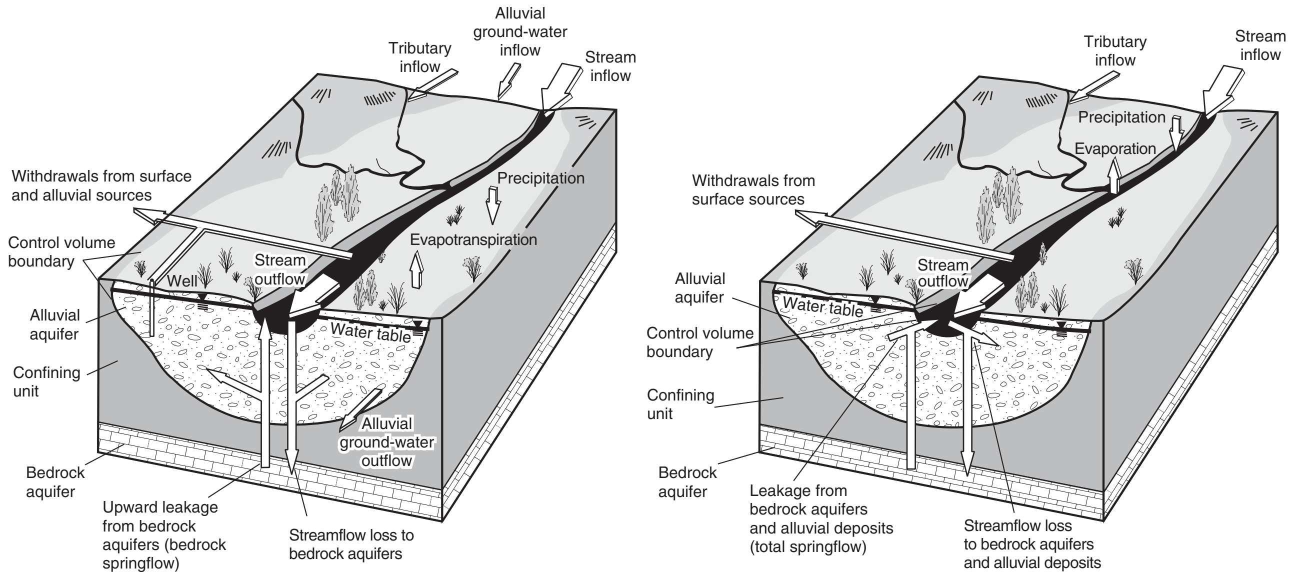
Figure 7. Schematic showing interactions between surface water, alluvial deposits, and bedrock aquifers for various hypothetical conditions.

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:

$$\mathrm{Loss}_t = \mathrm{Str}_i + \mathrm{T}_i + \mathrm{SF}_t - \mathrm{Str}_o \qquad (3)$$

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

$$\mathrm{Loss}_t = \mathrm{Str}_i - \mathrm{Str}_o \qquad (4)$$



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 ($\pm$2 percent), good ($\pm$5 percent), fair ($\pm$8 percent), or poor (more than $\pm$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.

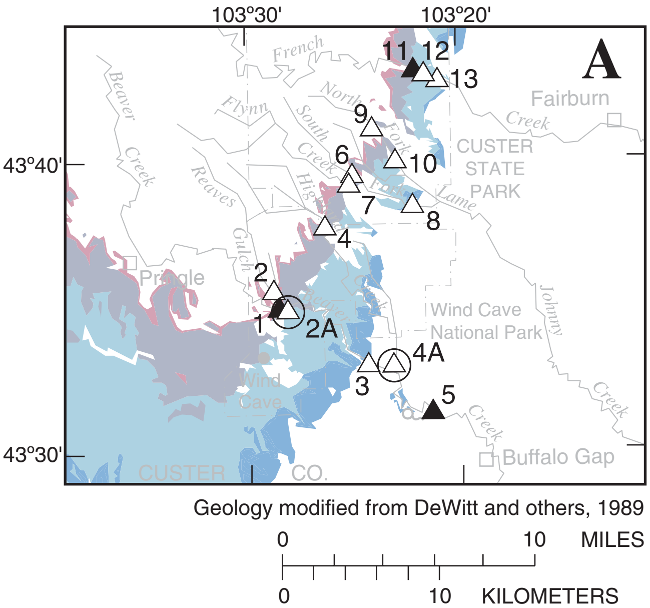
Beaver Creek and Tributaries

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 Madis on 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

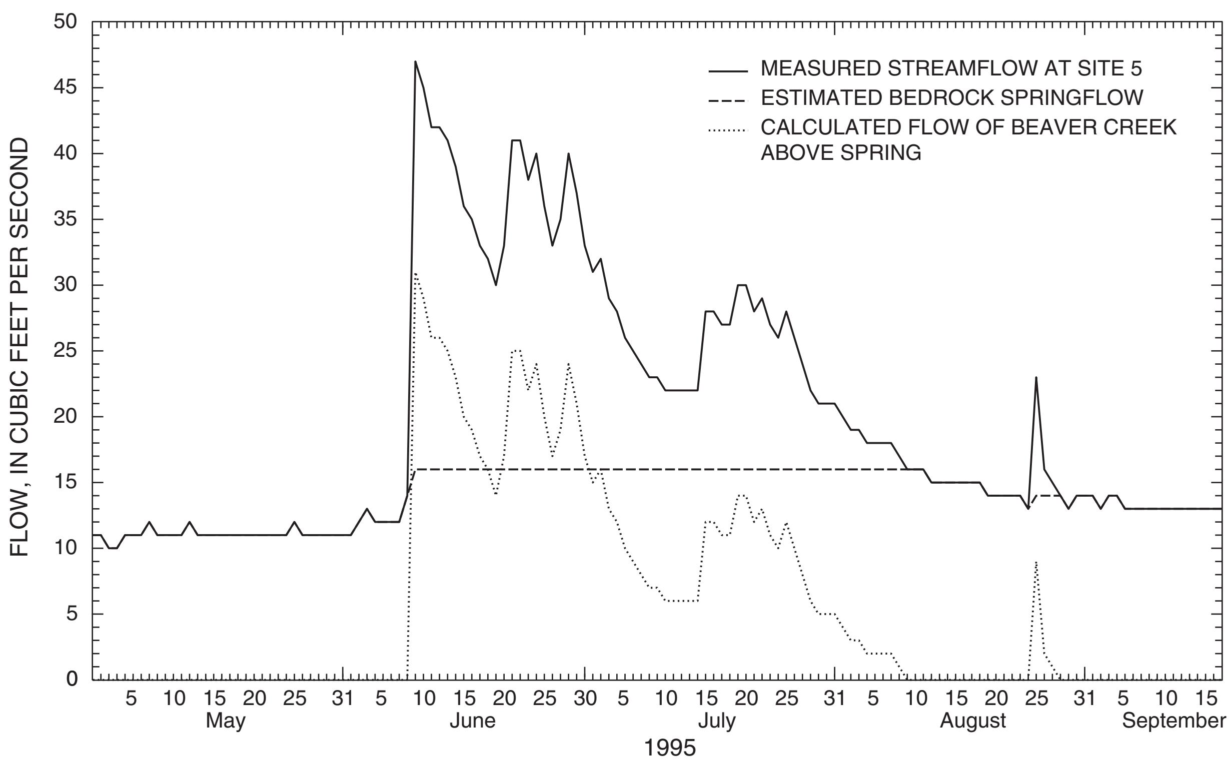


Figure 10. Hydrographs of measured daily streamflow at site 5 (Beaver Creek above Buffalo Gap), estimated bedrock springflow, and calculated flow above spring.

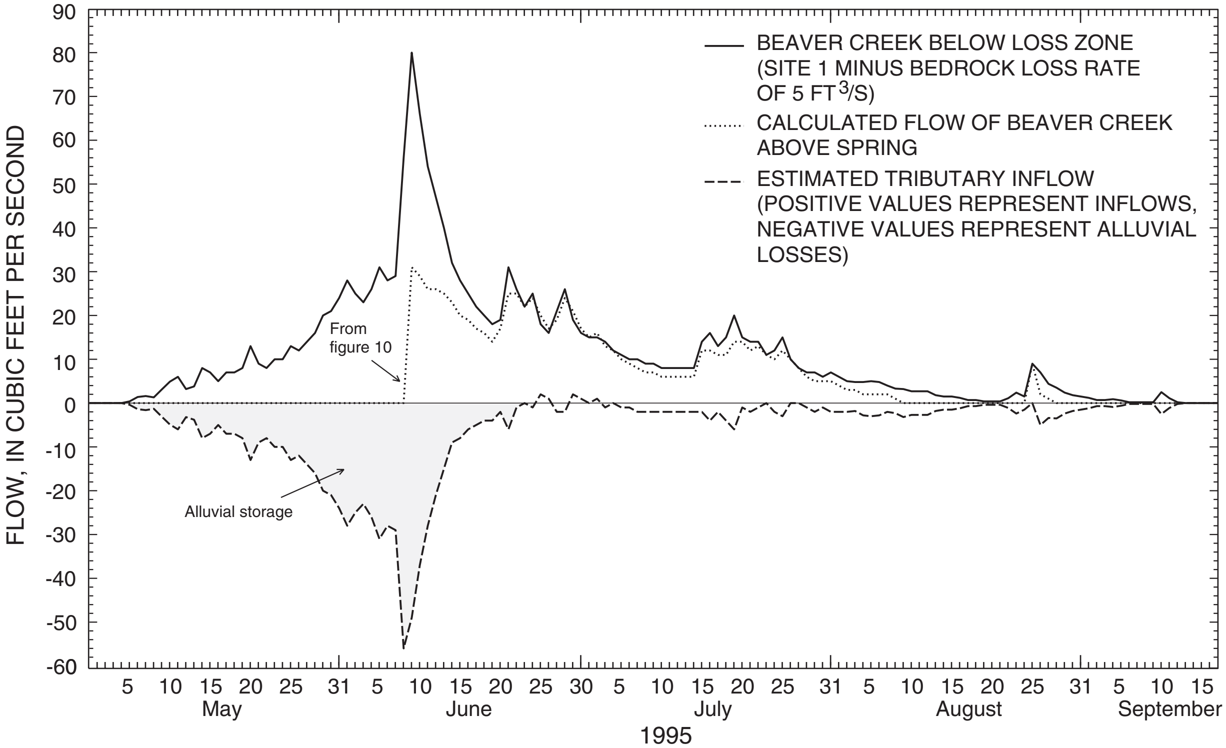


Figure 11. Hydrographs of calculated daily streamflow values used to estimate tributary inflow to Beaver Creek.

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.

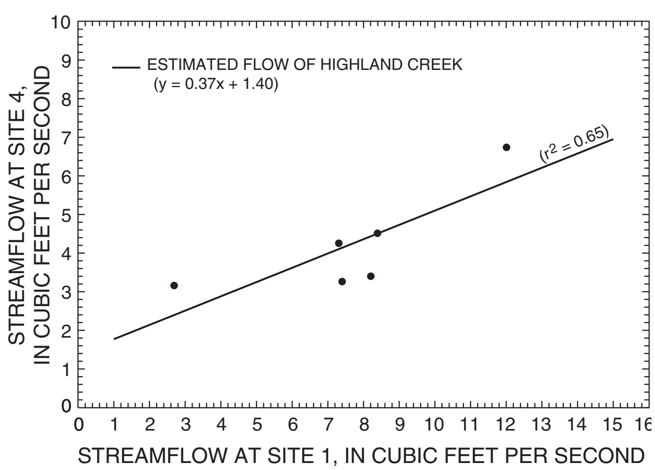


Figure 12. Regression plot of streamflow at site 4 (Highland Creek above Madison outcrop), as a function of streamflow at site 1 (Beaver Creek near Pringle), water year 1996.

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	

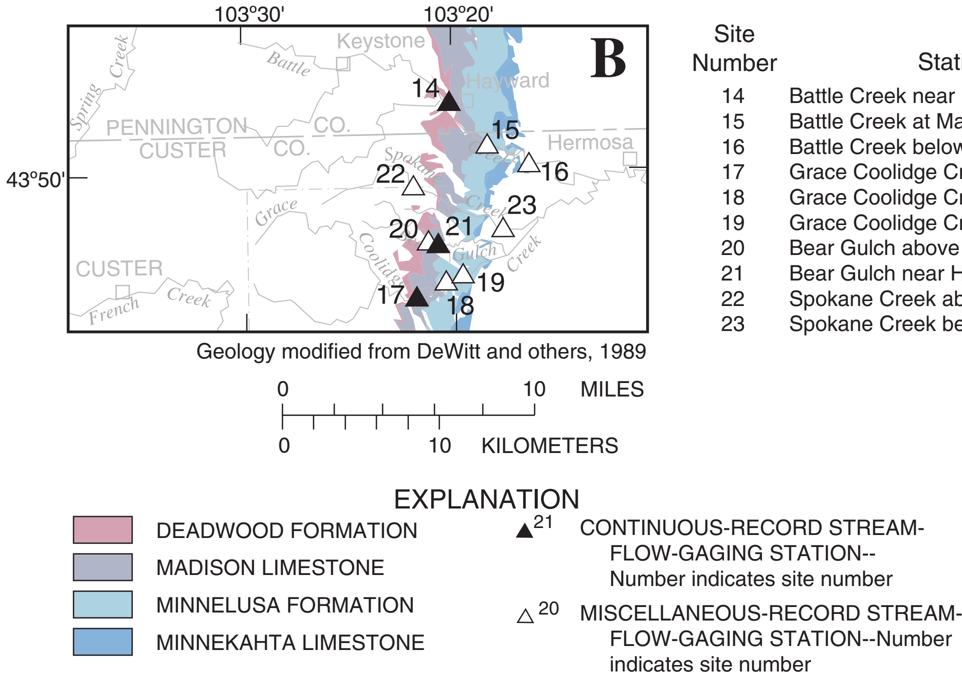
[1]Hydrograph changes calculated using daily mean streamflow at site 11: [(current day - previous day) / previous day] x 100%.
[2]Obtained from data for USGS pipeline survey for French Creek Water Project.
[3]Indicated value for this date is the daily mean.
[4]Excluded from mean and median calculations.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

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.

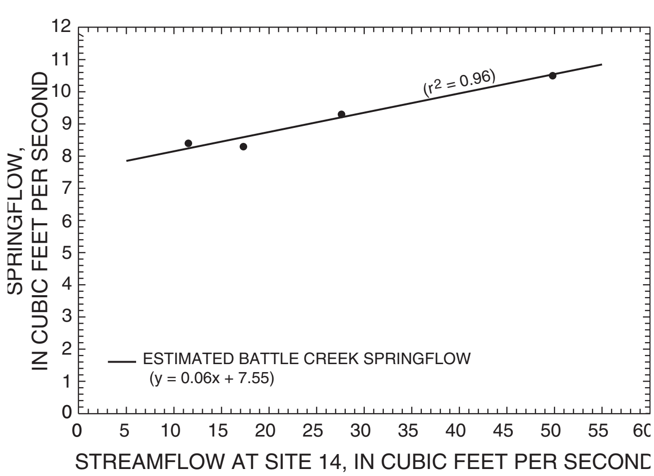


Figure 14. Regression plot of springflow in Battle Creek as a function of streamflow at site 14 (Battle Creek near Keystone), June 7 through July 3, 1996.

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.

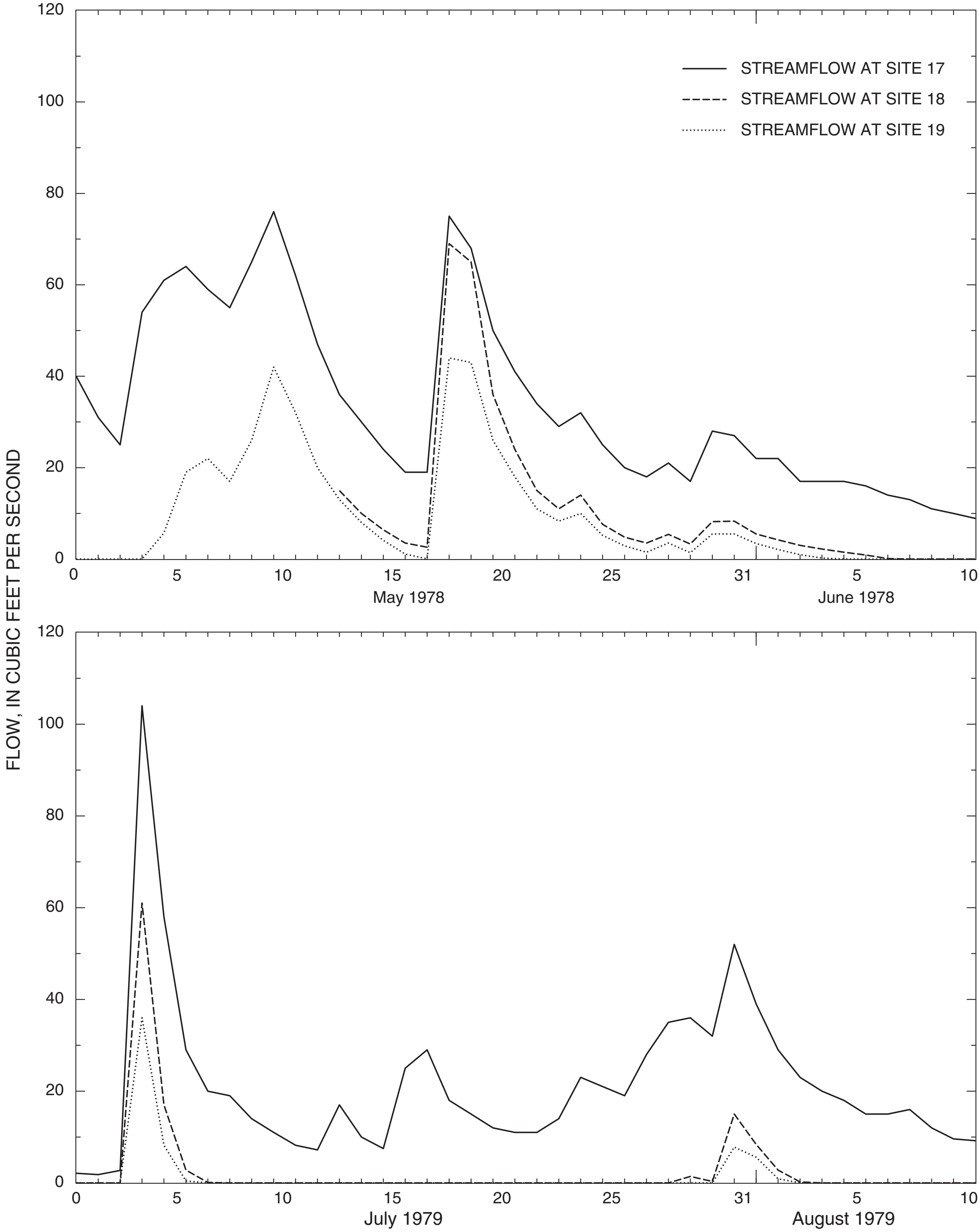


Figure 15. Daily hydrographs for site 17 (Grace Coolidge Creek near Game Lodge), site 18 (Grace Coolidge Creek near Fairburn), and site 19 (Grace Coolidge Creek below Minnelusa outcrop), water years 1978-79.

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.

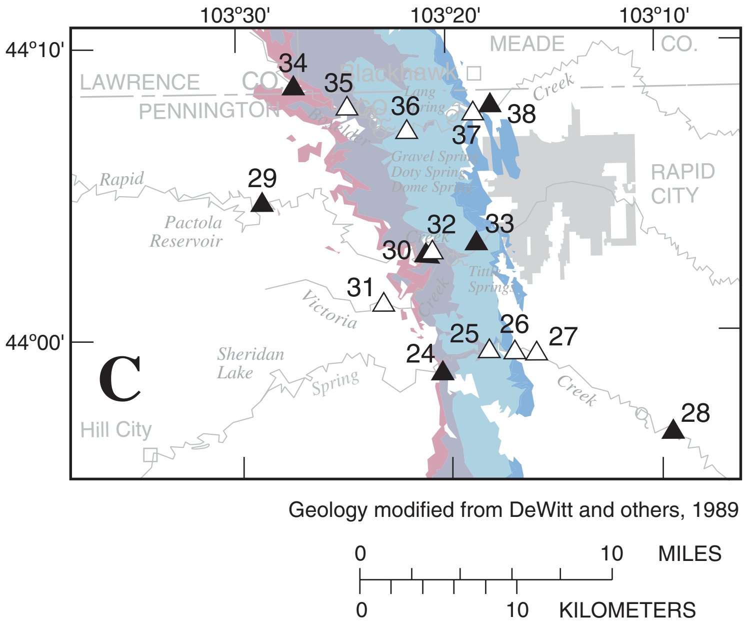
The effects of large tributary inflows also are apparent in figure 17A. The calculated loss rate during early June of WY91 shows a large negative value, when flow at the downstream station exceeded flow at the upstream station.

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 STREAM-FLOW-GAGING STATION--Number indicates site number

△31 MISCELLANEOUS-RECORD STREAM-FLOW-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.

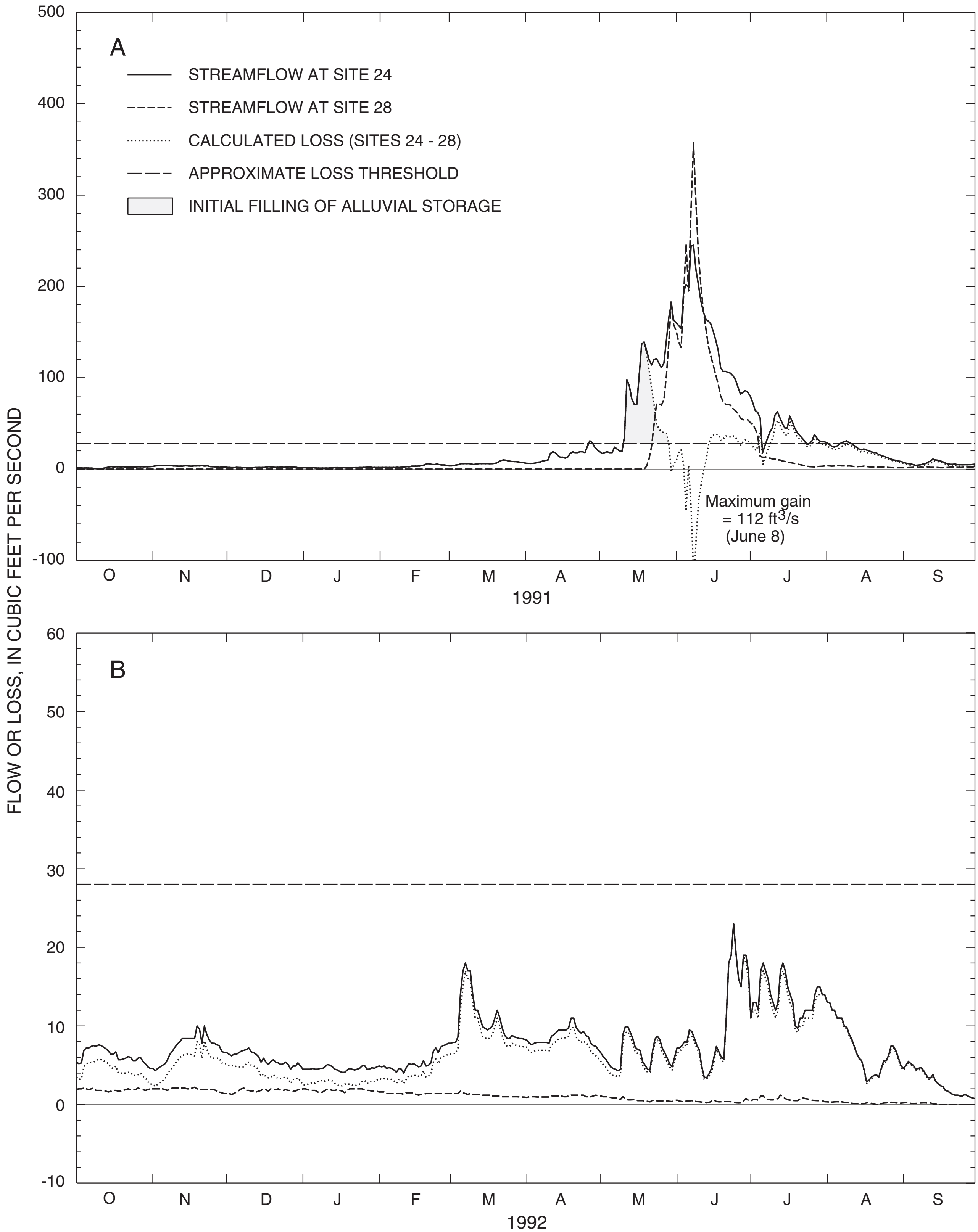


Figure 17. Daily hydrographs and calculated losses for site 24 (Spring Creek near Keystone) and site 28 (Spring Creek near Hermosa), water years 1991-96.

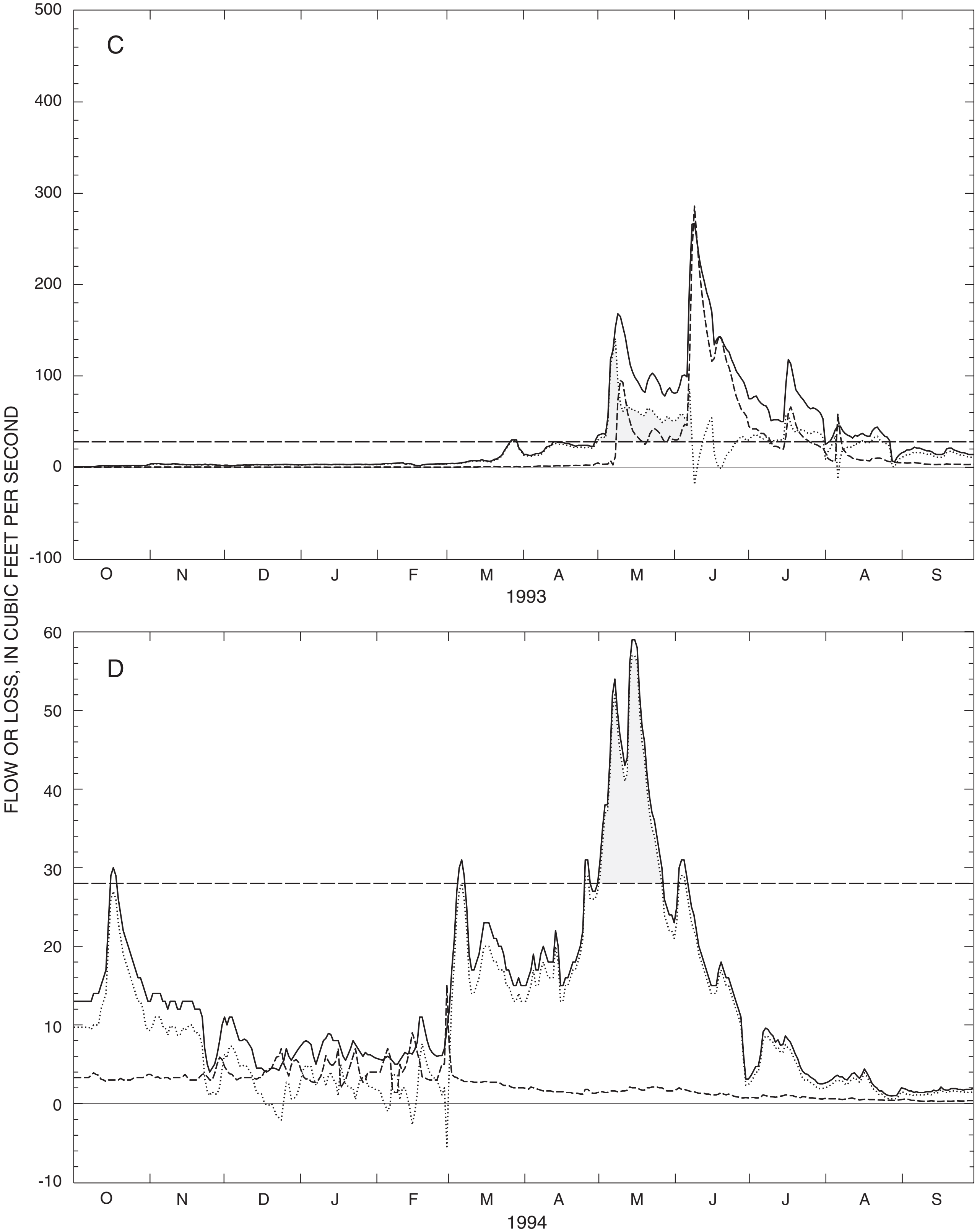


Figure 17. Daily hydrographs and calculated losses for site 24 (Spring Creek near Keystone) and site 28 (Spring Creek near Hermosa), water years 1991-96.--Continued

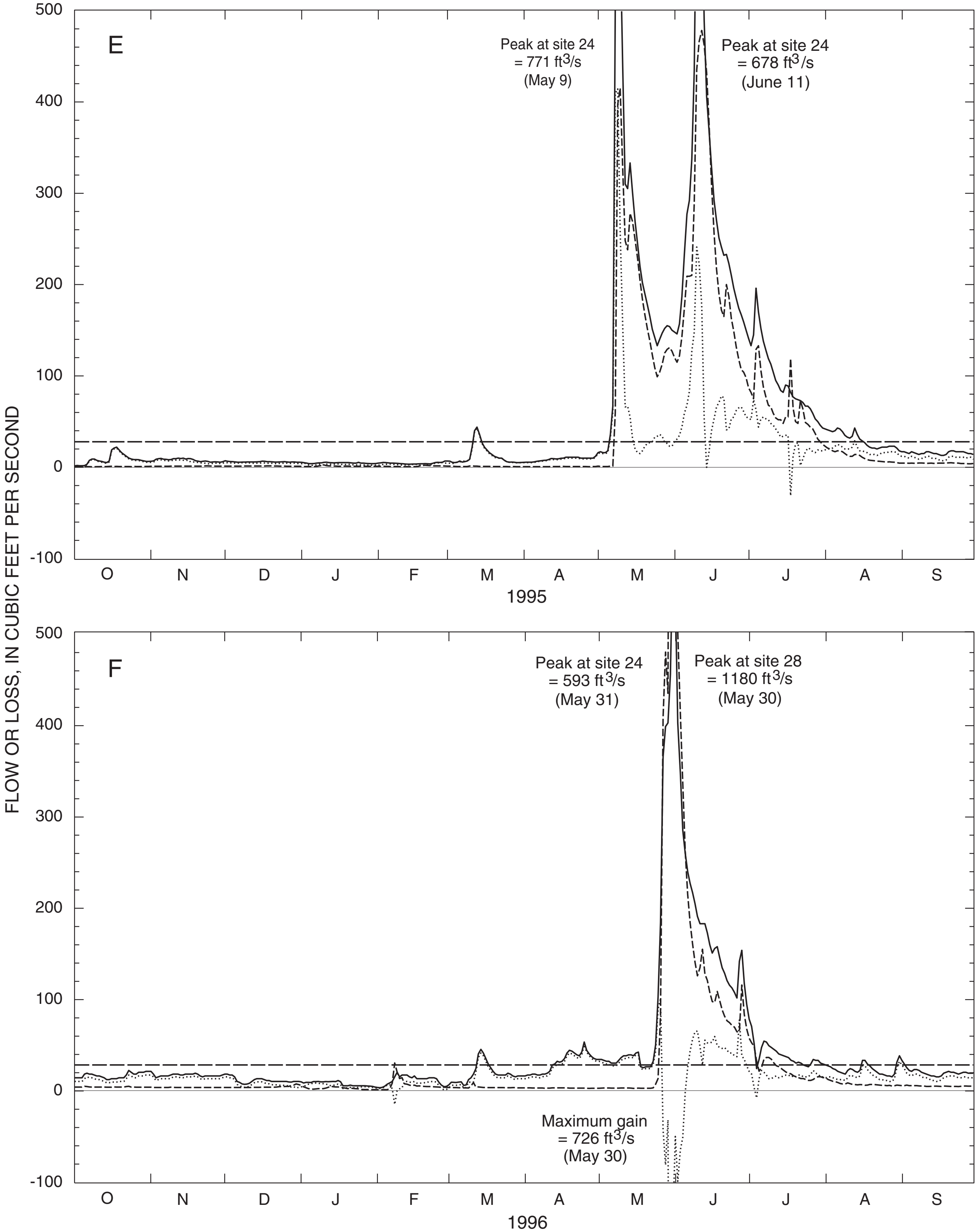


Figure 17. Daily hydrographs and calculated losses for site 24 (Spring Creek near Keystone) and site 28 (Spring Creek near Hermosa), water years 1991-96.--Continued

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.

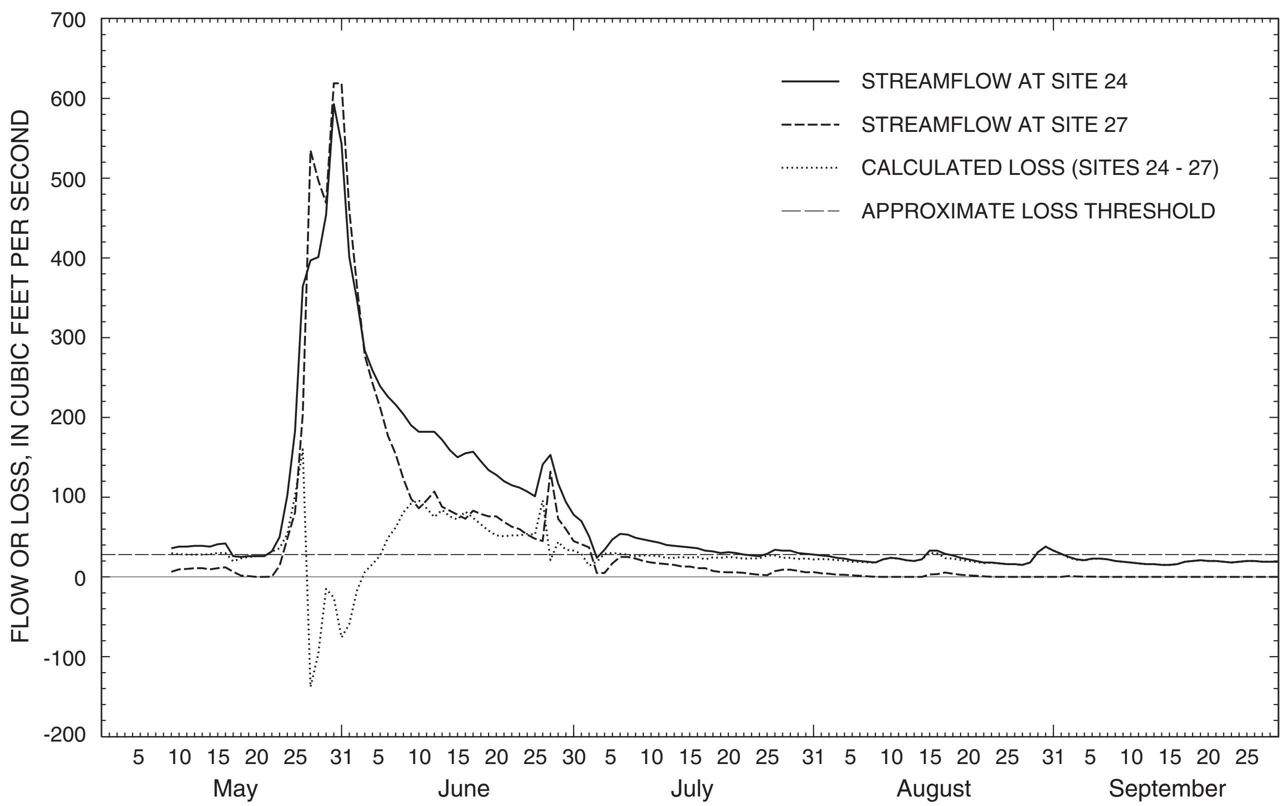


Figure 18. Daily hydrographs and calculated losses for site 24 (Spring Creek near Keystone) and site 27 (Spring Creek near Rapid City), water year 1996.

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.

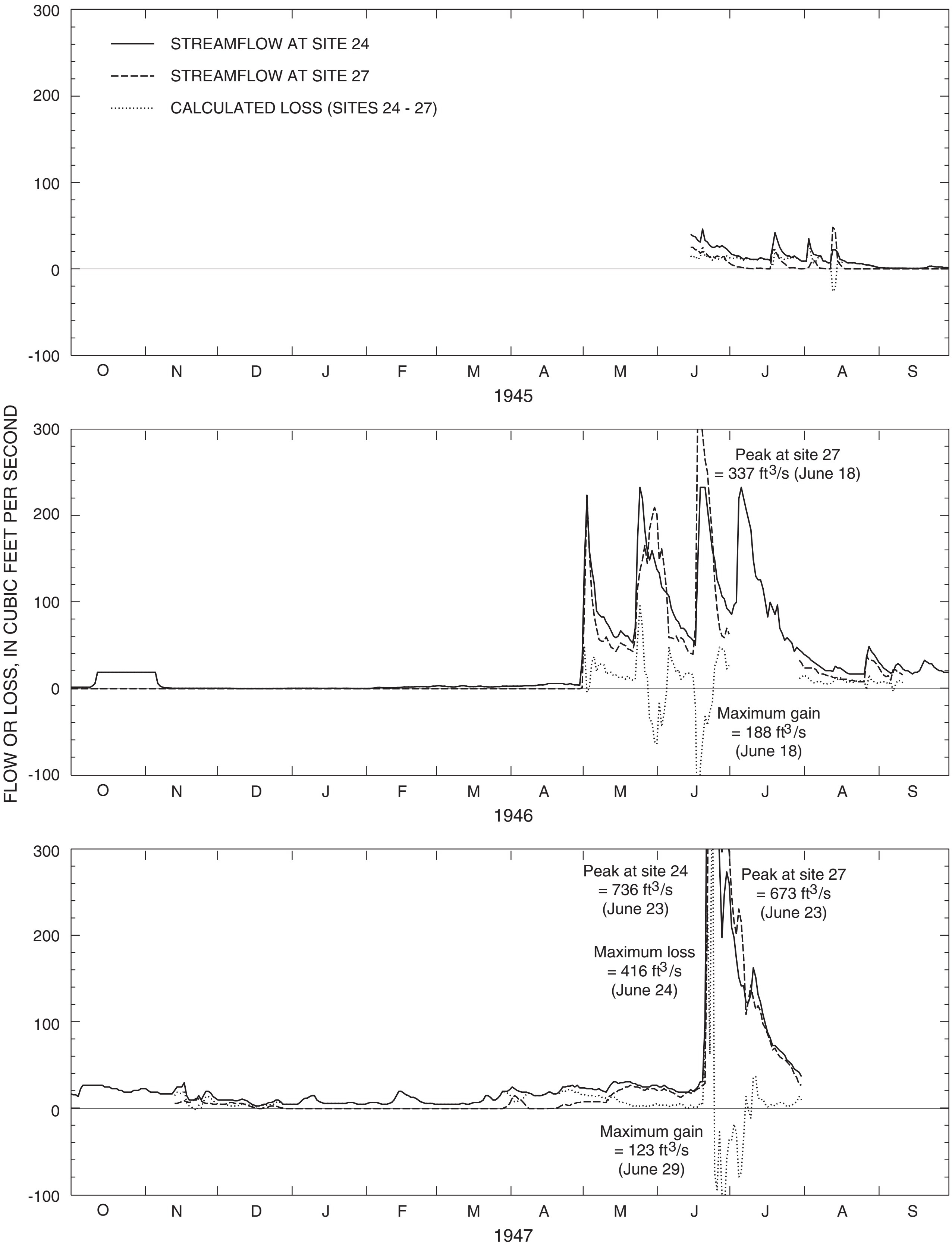


Figure 19. Daily hydrographs and calculated losses for site 24 (Spring Creek near Keystone) and site 27 (Spring Creek near Rapid City), water years 1945-47.

Rapid Creek and Victoria Creek

Calculations of losses for Rapid Creek and one major tributary, Victoria Creek, are presented in the following sections. Three continuous-record and two miscellaneous-record stations (fig. 16, table 3) are used in the analysis of Rapid and Victoria Creeks.

Rapid Creek

Examination of streamflow records for sites 29 and 33 for WY56-96 provides initial insights regarding long-term loss characteristics for Rapid Creek. Annual streamflow loss rates between sites 29 and 33 are plotted in figure 20 as a function of weighted annual precipitation, within the intervening 51-mi^2 drainage area. Annual precipitation is estimated by weighting precipitation data (U.S. Department of Commerce, 1996), using the Thiessen polygon method, for gages at Pactola Dam (78.3 percent) and Rapid City (21.7 percent) (Driscoll, 1987). Examination of figure 20 indicates that the maximum annual loss rates are about 8 to 9 ft^3/s and generally occur during years of lower precipitation, when minimal tributary inflows would be expected.

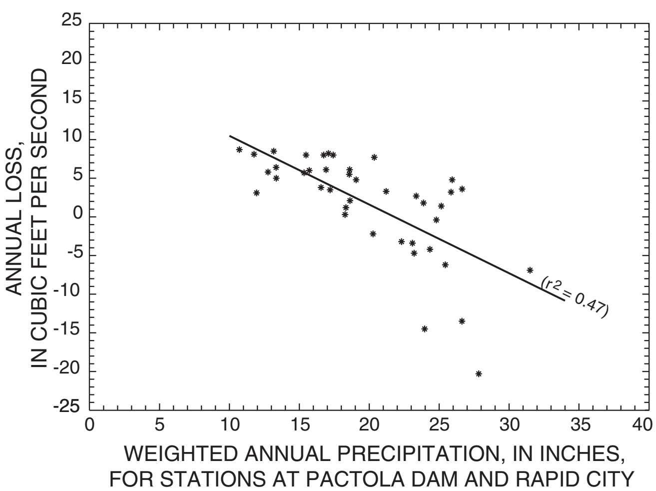


Figure 20. Annual loss rate for Rapid Creek (sites 29-33), as a function of weighted annual precipitation, water years 1956-96.

Daily streamflow records are available for WY89-96 for site 30, which is located downstream from site 29, but immediately upstream from the loss zone areas on Rapid Creek (fig. 16). The drainage area between sites 30 and 33 increases by only 16 mi^2 (table 3); thus, calculated losses are less susceptible to effects of tributary inflows than calculated losses between sites 29 and 33. Therefore, even though site 29 has a longer period of record, site 30 is used for subsequent comparisons with site 33.

Subsequent loss calculations between sites 30 and 33 exclude springflow from Tittle Springs, which is located within the intermediate reach (fig. 16). Numerous measurements for WY89-96 for station 06412300, Tittle Springs at Rapid City, (not included in this report) indicate that flow generally ranges from 1 to 3 ft^3/s. Hines (1991) concluded that water from Tittle Springs probably is derived from Rapid Creek. Hines also noted other areas of ground-water inflow, or streamflow gains, within the Rapid Creek loss zone. Because springflow is excluded, subsequent loss calculations represent net losses to the Madison Limestone, as well as possible losses to the Deadwood and Minnelusa Formations.

Annual losses between sites 30 and 33 are presented in table 18. A regression plot of monthly losses between sites 30 and 33, as a function of monthly flow at site 30, is shown in figure 21. These monthly losses exhibit considerably more variability than the annual losses (table 18). The median value of 8.2 ft^3/s for these monthly losses also is shown, which corresponds fairly closely with the Y-intercept of about 10.2 ft^3/s for the regression line. The Y-intercept may be more representative of the loss threshold than the median, because the regression line accounts for some of the variability in losses, while the median represents only the central tendencies. The mean monthly loss of 7.0 ft^3/s also is shown. The mean is smaller than the median because of effects of occasional tributary inflows, which result in smaller calculated losses, or occasional gains. Thus, the mean is a poorer representation of the loss threshold.

Table 18. Annual streamflow losses for Rapid Creek, between sites 30 and 33, water years 1989-96

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

Water year	Annual mean flow, in ft^3/s		Annual loss, in ft^3/s[1]
	Upstream station site 30	Downstream station site 33	
1989	34.3	26.5	7.8
1990	28.8	19.0	9.8
1991	26.4	17.5	8.9
1992	33.7	20.7	13.0
1993	54.5	48.3	6.2
1994	62.5	55.5	7.0
1995	94.7	89.8	4.9
1996	103	105	-2

[1]Annual loss calculated as annual mean flow at upstream station minus downstream station.

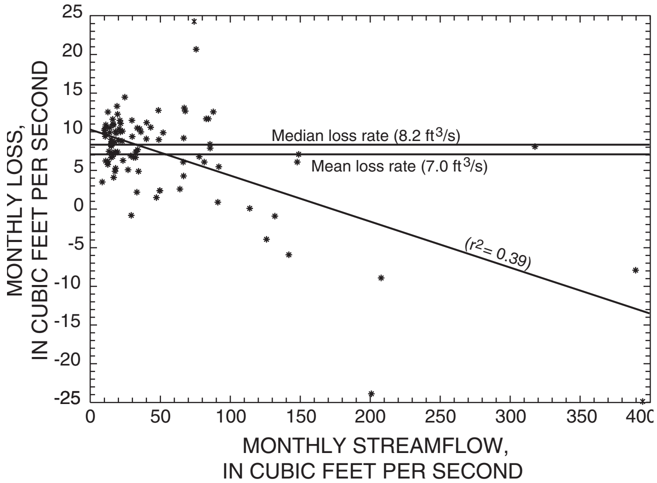


Figure 21. Monthly loss rate for Rapid Creek (sites 30-33), as a function of monthly streamflow at site 30, water years 1989-96.

Loss calculations using individual measurements for sites 30, 32, and 33 are presented in table 19. Histograms of loss rates calculated from both individual measurements and monthly streamflow records are presented in figure 22. Both histograms indicate that the loss rate most frequently is in the range of 7 to 11 ft^3/s.

Additional insights can be obtained by examination of figure 23, which shows plots of monthly weighted precipitation, monthly flow at site 30, and monthly losses between sites 30 and 33. The smallest monthly losses, including months of net gains, generally correspond with periods of high precipitation and associated tributary inflows. A line representing an approximate loss threshold of 10 ft^3/s also is shown in figure 23. Monthly losses during WY89-92 generally are about 10 ft^3/s; however, losses during WY93-96 generally are less than 10 ft^3/s. This decrease probably results primarily from increased springflow (groundwater discharge) within the loss zone, resulting from a general increase in precipitation during this period.

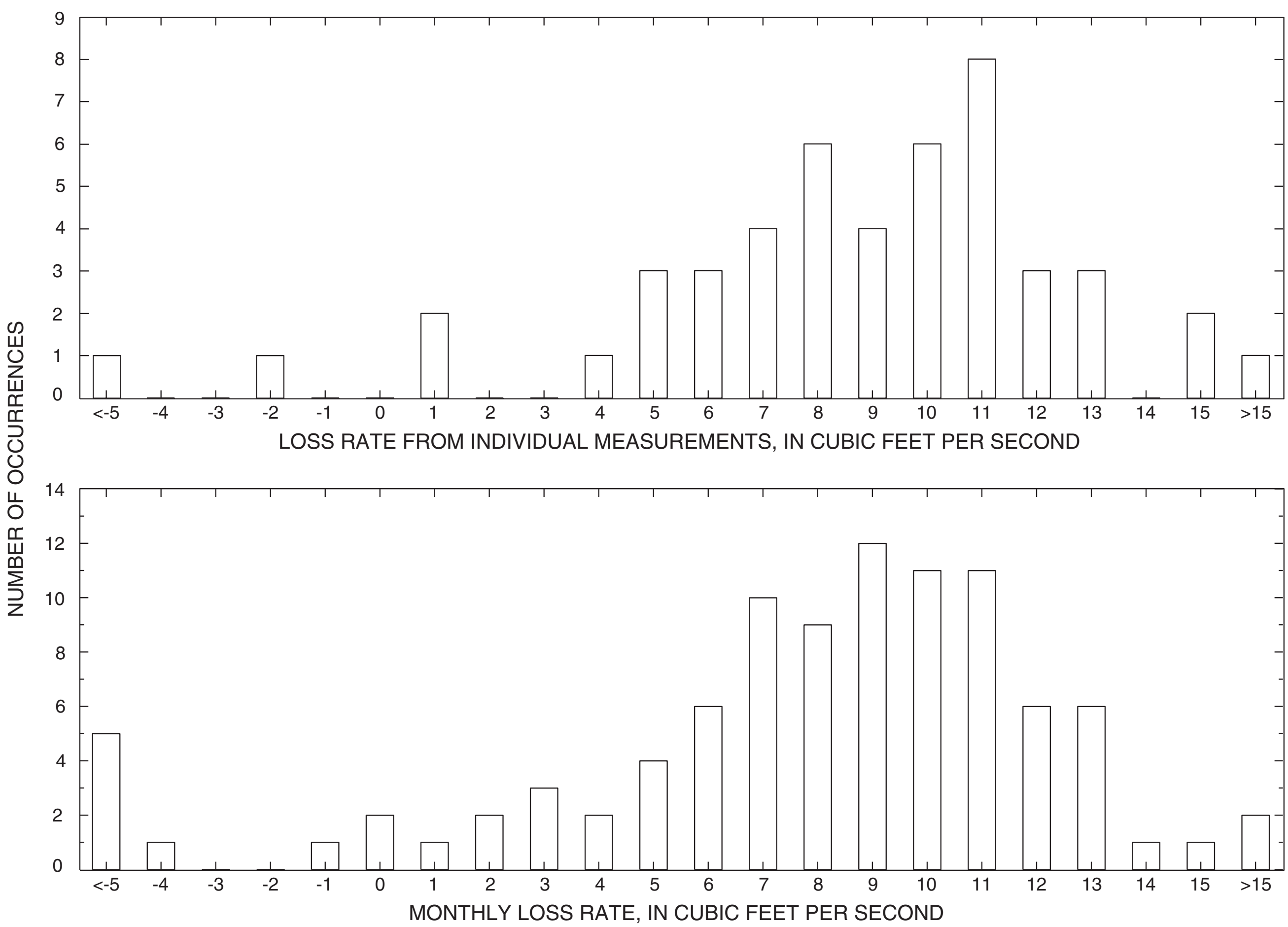


Figure 22. Histograms of calculated loss rate for Rapid Creek (between sites 30 and 33) from individual measurements and monthly flows, water years 1989-96.

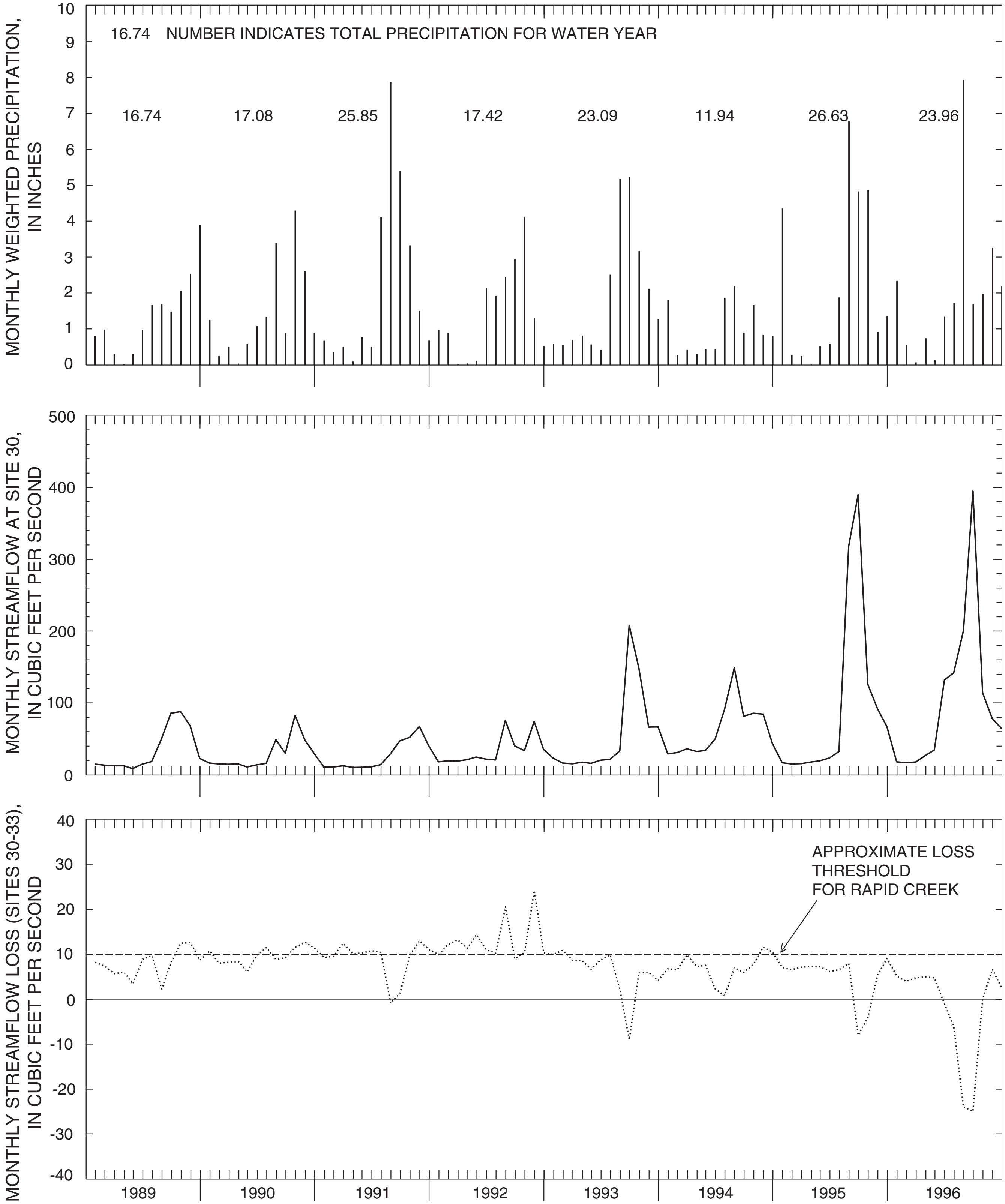


Figure 23. Monthly weighted precipitation, monthly streamflow at site 30, and monthly streamflow losses (sites 30-33), for Rapid Creek, water years 1989-96.

Table 19. Calculations of streamflow losses for Rapid Creek

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operations; --, no data available]

Date	Upstream station site 30		Upstream tributary site 32		Downstream station site 33		Total loss, in ft^3/s (30 + 32 - 33)	Hydrograph changes[1]
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s		
10-14-88	1040	14.3	--	--	1840	5.00	9.3	0%
11-21-88	0855	11.0	--	--	1050	3.89	7.1	0%
12-21-88	1200	12.9	--	--	1415	5.78	7.1	0%
6-06-89	0755	107	--	--	1005	95.6	11	+9%
7-06-89	1145	91.9	--	--	0920	77.4	14.5	-2%
10-02-89	1320	14.8	--	--	1520	3.88	10.9	0%
10-17-89	1130	16.9	--	--	1330	5.31	11.6	0%
11-06-89	1215	17.8	--	--	1635	7.59	10.2	+6%
2-01-90	0940	8.84	--	--	1210	2.80	6.04	-18%
4-19-90	1530	10.5	--	--	1320	2.10	8.4	-14%
5-16-90	1225	60.2	--	--	1410	48.8	11.4	-2%
6-12-90	0935	14.8	--	--	1315	5.24	9.6	0%
8-17-90	0945	43.9	--	--	1240	30.9	13.0	+5%
9-27-90	0915	22.2	--	--	1240	9.96	12.2	0%
3-27-91	1230	11.4	--	--	1435	.73	10.7	-9%
10-22-91	1358	16.7	--	--	1545	6.43	10.3	0%
7-09-92	1210	37.6	--	--	1025	26.8	10.8	-3%
8-28-92	1335	48.6	--	--	1105	35.9	12.7	0%
10-02-92	1315	48.6	--	--	1045	37.9	10.7	-19%
11-05-92	1355	16.3	--	--	1155	4.56	11.7	0%
1-05-93	1115	16.3	--	--	1345	9.07	7.2	0%
3-17-93	1150	23.7	--	--	0945	6.08	17.6	-5%
4-15-93	1140	22.5	--	--	1010	12.8	9.5	0%
5-27-93	1035	28.4	0800	3.05	1210	21.9	9.6	-3%
8-10-93	0915	50.0	0745	0.26	1045	46.0	4.3	-2%
9-03-93	1050	62.3	--	--	0930	61.5	.8	+2%
10-06-93	1200	22.5	--	--	1030	15.2	7.3	-11%
11-09-93	1155	30.4	--	--	1025	24.9	5.5	0%
1-12-94	1120	36.1	--	--	0905	28.9	7.2	+3%
3-29-94	1515	87.4	--	--	1355	96.3	-8.9	0%
5-02-94	0950	163	0850	0	0815	162	1	+1%
6-21-94	1510	64.7	1405	0	1345	59.3	5.4	-4%
10-07-94	1200	19.4	--	--	1045	10.8	8.6	+12%
11-29-94	1015	13.8	--	--	0825	7.49	6.3	0%
12-29-94	1110	17.5	1000	0	0845	8.71	8.8	0%
2-02-95	1035	23.2	0915	0	0840	14.1	9.1	+15%

Table 19. Calculations of streamflow losses for Rapid Creek —Continued

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operations; --, no data available]

Date	Upstream station site 30		Upstream tributary site 32		Downstream station site 33		Total loss, in ft^3/s (30 + 32 - 33)	Hydrograph changes[1]
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s		
3-09-95	1055	26.7	0900	0	0835	12.6	14.1	+42%
4-07-95	1055	33.2	0900	0	0735	26.8	6.4	0%
5-05-95	1015	33.0	0910	0	0830	26.6	6.4	0%
8-21-95	1550	93.3	1445	0	1430	85.0	8.3	0%
11-03-95	1400	12.8	--	--	1210	5.35	7.4	-7%
12-01-95	1125	16.8	--	--	1310	12.4	4.4	0%
1-03-96	1030	28.5	--	--	0835	17.5	11.0	-4%
2-06-96	1040	31.9	--	--	0810	27.8	4.1	+13%
3-05-96	0920	37.4	--	--	0800	28.0	9.4	-3%
5-07-96	0820	144	--	--	0950	146	-2	-17%
6-04-96	0755	561	--	--	0910	555	6	-2%
7-09-96	0840	129	--	--	1000	125	4	0%

[1]Hydrograph changes calculated using daily mean streamflow at site 30: [(current day - previous day) / previous day] x 100%.

The general decrease in monthly loss rates corresponds to general decreases in individual losses (table 19) and annual losses (table 18), with the exception of WY92. Large monthly losses for May and August of 20.6 and 24.2 ft^3/s, respectively (fig. 23), are reflected in the annual losses for WY92 (table 18). Small calculated losses and calculated gains can result from inflows within the measurement reach; however, no physical explanation is available for the anomalously large calculated losses. Using site 29 instead of site 30 as the upstream site, calculated losses for May and August are 9.8 and 12.4 ft^3/s, respectively (U.S. Geological Survey, 1993), which are more representative of typical loss rates. Using these values, the annual loss rate for WY92 would be about 11.2 ft^3/s, which corresponds better with generally decreasing losses over the period (table 18).

Considering all of the data collectively, the loss threshold for Rapid Creek is estimated to be 10 ft^3/s. The generally lower loss rates during WY93-96 probably result from a decrease in the net loss rate, which is caused by an increase in springflow within the loss zone. Thus, it is hypothesized that the net loss rate to the bedrock outcrops along Rapid Creek is approximately constant. The "gross" loss rate is not determined, however, because of springflow within the reach.

Victoria Creek

Loss calculations for Victoria Creek, a tributary to Rapid Creek, are presented in table 20, which includes measurements for sites 31 and 32 (fig. 16). Calculated losses include combined losses to the Deadwood Formation and Madison Limestone (table 3).

Calculated losses for May 27 and August 10, 1993, are both about 1.0 ft^3/s; however, measurements for May 19, 1995 and June 10, 1996 indicate a gain between the two stations. The small calculated loss rate for July 11, 1996, probably is affected by continuing tributary inflow or springflow, resulting from wet conditions during preceding months. Thus, the loss threshold for Victoria Creek, using measurements from 1993, is estimated to be 1.0 ft^3/s.

Boxelder Creek

Two continuous-record and three miscellaneous-record stations are used to calculate losses on Boxelder Creek (fig. 16, table 3). Daily streamflow records also are available for WY78-80 for station 06422600, Boxelder Creek at Camp Columbus, which was located approximately 2 mi downstream from current site 34; however, these records are not used in subsequent analyses because site 34 has a longer period of record with very similar streamflow.

Table 20. Calculations of streamflow losses for Victoria Creek

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

Date	Upstream station site 31		Downstream station site 32		Total loss, in ft^3/s (31 - 32)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	
5-27-93	0910	3.95	0800	3.05	0.90
8-10-93	0805	1.44	0745	.26	1.18
5-19-95	0930	11.7	1250	13.0	-1.3
6-10-96	0745	7.89	0730	11.5	-3.6
7-11-96	0950	1.46	0900	1.19	.27

Determination of losses for Boxelder Creek is especially difficult because all of the factors that can affect loss calculations have potential for maximum effects. The stream length between sites 34 and 38 is approximately 10 mi (fig. 16) and the drainage area increases by 32 mi^2 (table 3); thus, effects of channel storage and tributary inflow can be large. The largest alluvial deposits within a loss zone for any of the stream reaches considered in this report occur between sites 36 and 38. Three springs (Gravel Spring, Doty Spring, and Dome Spring) are located within the Madison Limestone between sites 35 and 36 (fig. 16). Rahn and Gries (1973) reported that individual flows from each of these springs ranged from zero to about 10 ft^3/s during 1966-69. They also documented through dye testing that these springs are directly connected to sinkholes located just upstream, with travel times ranging from 1 to 6 hours. Another spring, Lang Spring, is located between sites 36 and 37 (fig. 16). The effects of these springs on loss calculations are discussed later in this section.

Individual measurements made at sites 34 and 35 during WY93-96 are used to analyze potential losses to the Deadwood Formation along Boxelder Creek (table 21). High-flow measurements for two dates indicate relatively large losses; however, high-flow measurements for two other dates indicate relatively large gains. Measuring conditions generally are poor at site 35 because of an extremely rocky channel, which probably affects measurement accuracy, especially during high flows. Measurements for other dates indicate either gains, or very small losses that could result from evapotranspiration. Therefore, it is concluded that losses to the Deadwood Formation along Boxelder Creek are negligible, relative to losses to other units.

Losses calculated using individual measurements from sites 35, 36, 37, and 38 during WY93-96 are presented in table 22. Losses to individual outcrops are identified for several dates. It should be noted that an unmapped outcrop of Madison Limestone is located within the Minnelusa reach of Boxelder Creek between sites 36 and 37 (fig. 16). Thus, losses denoted as "Minnelusa" in table 22 also may include losses to the Madison Limestone, which may be as large or larger than losses to the Minnelusa. In addition, losses denoted as "Minnekahta" may include losses to alluvial deposits between sites 37 and 38. The calculated losses in table 22 are extremely variable and individual loss calculations generally are considered only when analyzing hydrographs that are presented later in this section.

Individual measurements for sites 34 and 38 during WY88-94 are presented in table 40 of the Supplemental Information section. Zero flow was recorded at site 38 on all but two of the measuring dates. Calculated losses for these dates are subject to many complicating factors; thus, little insight is gained from analysis of these measurements.

The most useful insights on loss characteristics are obtained by analyzing hydrographs of daily streamflow for sites 34 and 38 for WY83-84, 91, and 93-96 (fig. 24). Flow during these years was sufficient to make it entirely through the loss zone for extended periods of time. An approximate bedrock loss threshold of 50 ft^3/s, which is estimated during subsequent discussions, is included on all graphs in figure 24.

The effects of streamflow losses to extensive alluvial deposits are evident in the hydrograph for WY83 (fig. 24A). Flow at the upstream station (site 34) exceeded the approximate loss threshold on

Table 21. Calculations of streamflow losses to the Deadwood Formation along Boxelder Creek

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

Date	Upstream station site 34		Intermediate station site 35		Loss to Deadwood, in ft^3/s (34 - 35)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	
5-17-93	0910	58.7	1040	62.0	-3.3
5-03-94	0820	111	0930	102	9
6-22-94	0900	28.6	1005	28.6	.0
7-26-94	1300	10.1	1405	8.56	1.5
8-30-94	0830	5.14	0935	4.65	.49
5-23-95	1055	127	1229	122	5
7-07-95	1040	65.1	1027	65.5	-.4
8-17-95	1340	21.7	1135	22.1	-.4
3-15-96	0845	67.2	0950	79.5	-12.3
5-13-96	1230	59.7	1255	62.1	-2.4
6-12-96	0925	137	1030	145	-8
7-02-96	0745	51.0	0920	51.1	-.1
8-28-96	0730	17.2	1100	17.0	.2

April 18, 1983; however, flow did not occur at the downstream station (site 38) until April 24. With the exception of a 5-day period in May of 1982, flow had not occurred at site 38 since WY78 (Miller and Driscoll, 1998). Therefore, total loss values that continued to exceed the threshold through the end of April probably resulted from filling initial storage in extensive alluvial deposits to a level equal to that of the stream stage. Alluvial storage volume in the area between sites 36 and 38 is estimated to exceed 600 acre-ft.

The existence of springflow upstream from site 38 also is evident in the hydrograph for WY83. Small and steadily decreasing flow was maintained at site 38 during most of June and July, although flow at site 34 decreased below the approximate threshold in late May. The calculated loss rate during June and July converges with flow at site 34, as measured springflow at site 38 approaches zero. Because springflow upstream from site 38 is not accounted for, the loss rates shown in figure 24 represent net losses. Actual losses would be larger than net losses during periods when springflow is occurring upstream from site 38.

The effects of alluvial storage and springflow also are evident in figure 24B-24F. These effects are quite variable, however, because of the transient nature of the springflow that occurs in the reach (Rahn and Gries, 1973) and complexities associated with alluvial storage. The alluvial deposits within the loss zone may be subject to rapid drainage into the underlying bedrock units; however, if springflow within the loss zone becomes sufficiently large, much of the alluvial area may remain saturated. As an example, large losses that occur in filling alluvial storage are evident for WY91 (fig. 24C) and WY93 (fig. 24D), indicating that alluvial storage was largely diminished during WY92 (not shown). Losses in filling alluvial storage are small during WY94 (fig. 24E), which indicates that alluvial storage was nearly satisfied when upstream flow first exceeded the loss threshold. Initial alluvial losses were again large during WY95 (fig. 24F) but almost nonexistent during WY96 (fig. 24G).

Considering all of the factors involved, 50 ft^3/s is selected as an approximate total loss threshold, based primarily on hydrographs for water years shown in figure 24. During these water years, total (net) losses that are consistently smaller than the approximate threshold of 50 ft^3/s generally are associated with springflow upstream from site 38. During many water years, the total (net) loss rate varies considerably, because of a wide variety of factors, as previously discussed.

Table 22. Calculations of streamflow losses for Boxelder Creek, water years 1993-96

[ft^3/s, cubic feet per second; Mdsn, Madison; Mnls, Minnelusa; Mnkt, Minnekahta; ( ), 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 35		Intermediate station site 36		Intermediate station site 37		Downstream station site 38		Loss to Mdsn, in ft^3/s (35 - 36)	Loss to Mnls, in ft^3/s (36 - 37)	Loss to Mnkt, in ft^3/s (37 - 38)	Total loss, in ft^3/s (35 - 38)	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					
5-17-93	1040	62.0	0910	35.0	--	--	--	[2]0	27.0	--	--	>62.0	-8%
5-03-94	0930	102	1030	84.5	--	--	1215	47.6	18	--	--	54	+13%/day 3 of flow through
6-22-94	1005	28.6	1020	0	--	--	1215	0.16	>28.6	--	--	28.4	+39%
7-26-94	1405	8.56	1425	0	--	--	--	[2]0	>8.56	--	--	--	0%
8-30-94	0935	4.65	0700	0	--	--	--	[2]0	>4.65	--	--	--	+2%
5-23-95	1229	122	1342	117	--	--	--	[2]102	5	--	--	20	-8%
7-07-95	1027	65.5	1135	40.4	--	--	--	[2]22	25.1	--	--	44	+14%
8-17-95	1135	22.1	1015	3.29	--	--	1150	1.82	18.8	--	--	20.3	0%
3-15-96	0950	79.5	1100	67.1	--	--	1230	52.0	12.4	--	--	27.5	-14%
5-13-96	1255	62.1	1510	37.7	1240	19.5	1520	20.0	24.4	18.2	-0.5	42.1	+2%
6-12-96	1030	145	1200	138	1150	118	1340	114	7	20	4	31	-1%
7-02-96	0920	51.1	1025	31.2	1400	20.0	1215	20.8	19.9	11.2	-.8	30.3	-4%
8-28-96	1100	17.0	1220	0	1210	4.70	1250	1.71	>17.0	-4.7	2.99	15.3	-6%

[1]Hydrograph changes calculated using daily mean streamflow at site 34: [(current day - previous day) / previous day] x 100%.
[2]Indicated value for this date is the daily mean.

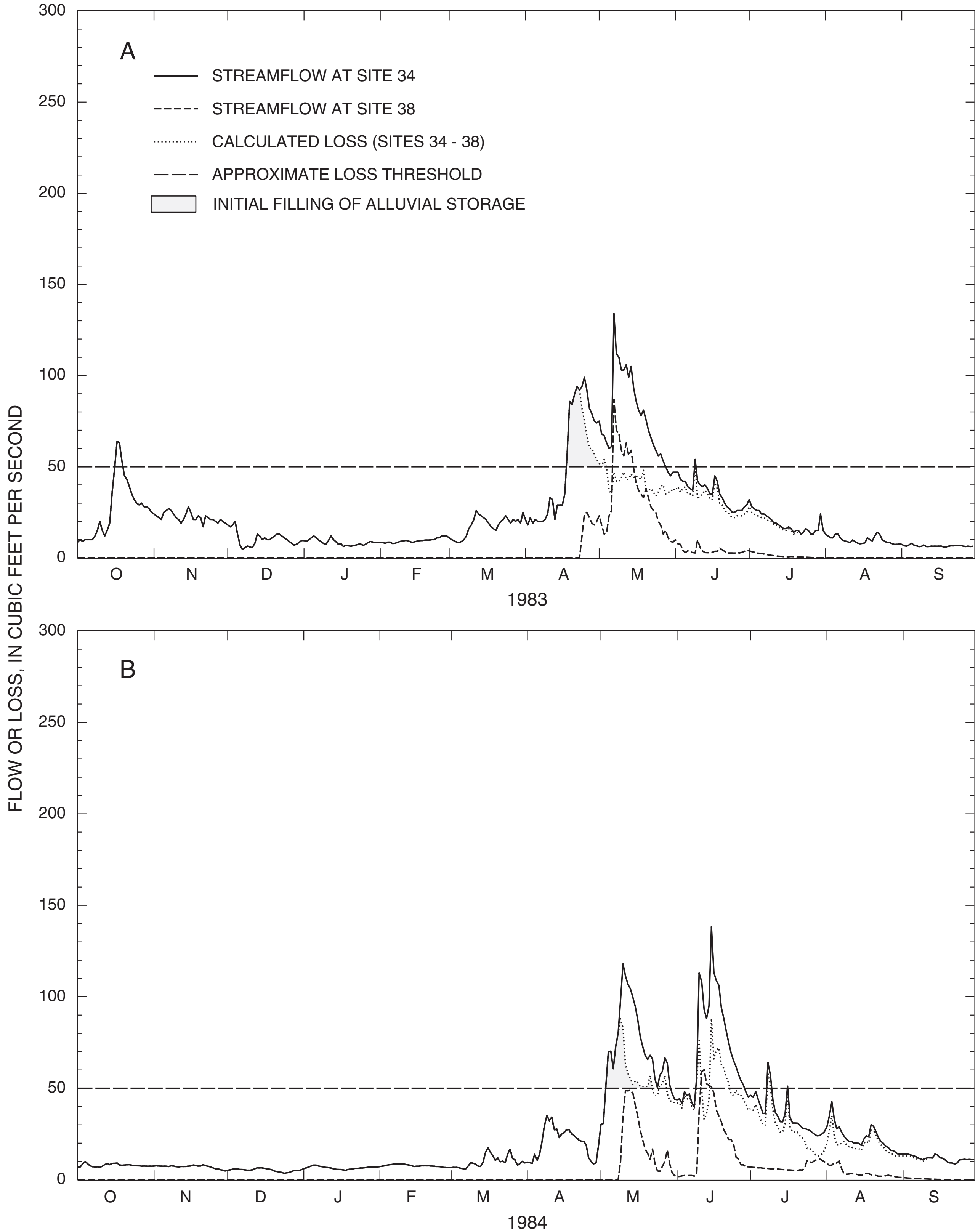


Figure 24. Daily hydrographs and calculated losses for site 34 (Boxelder Creek near Nemo) and site 38 (Boxelder Creek near Rapid City) for selected water years.

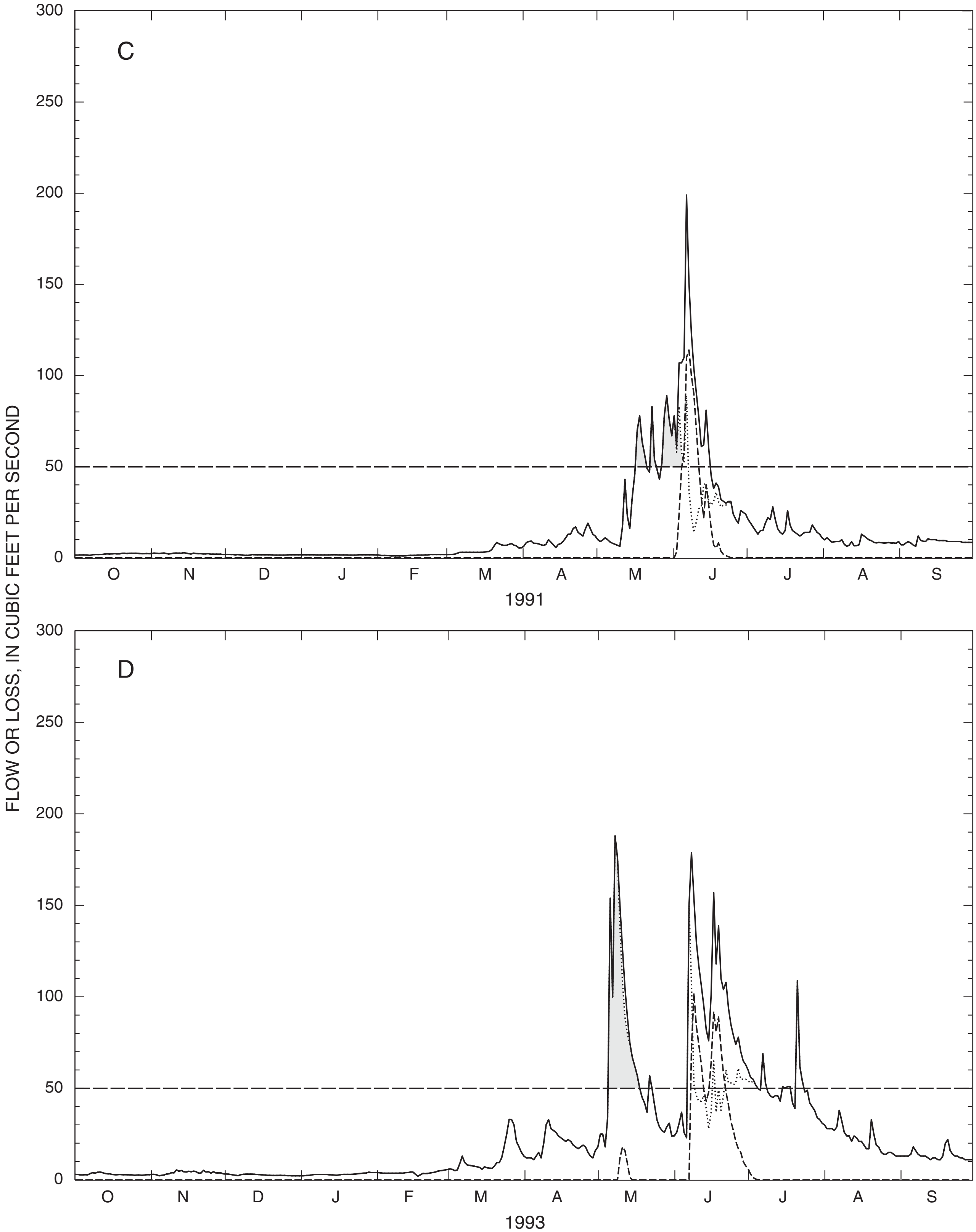


Figure 24. Daily hydrographs and calculated losses for site 34 (Boxelder Creek near Nemo) and site 38 (Boxelder Creek near Rapid City) for selected water years.--Continued

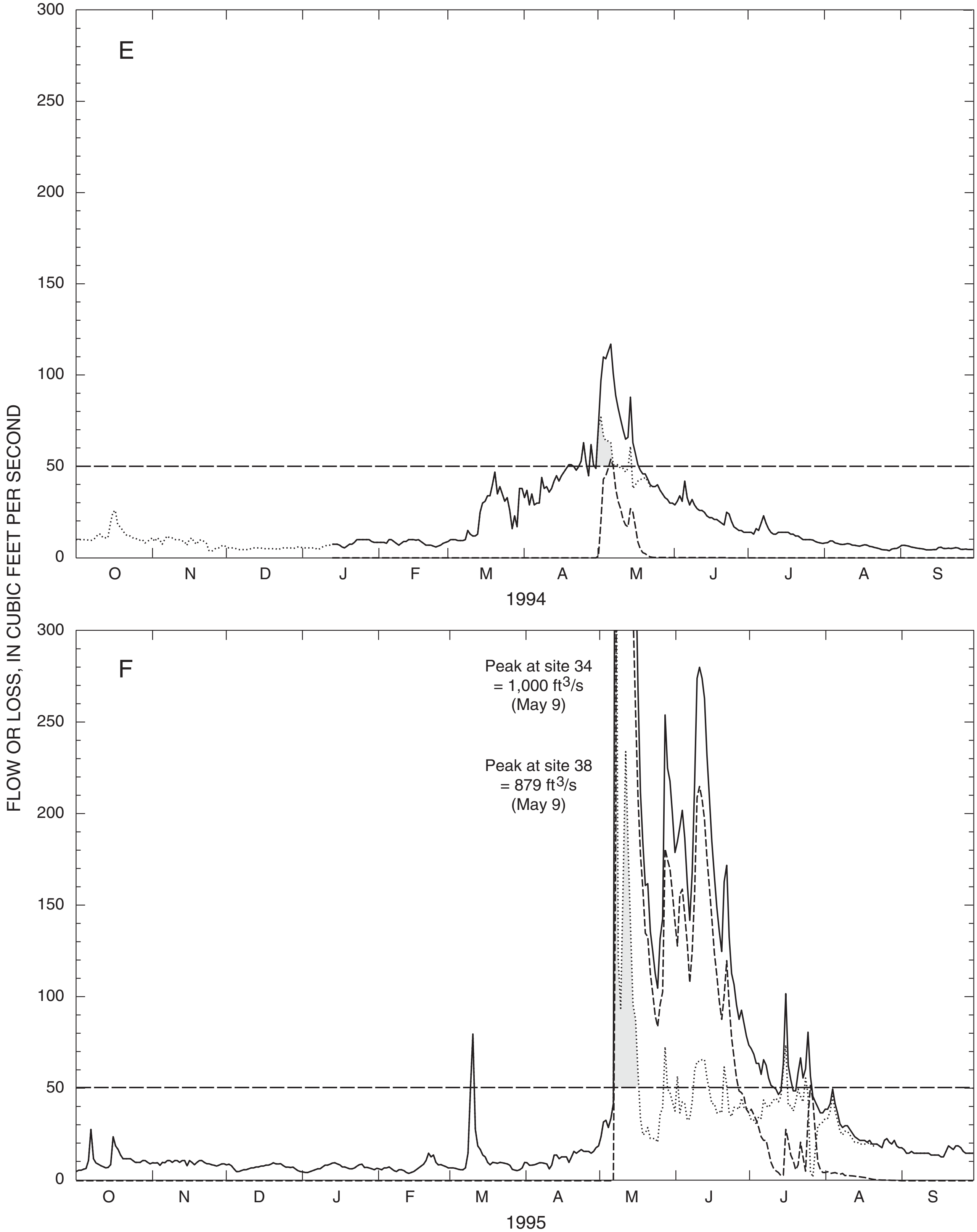


Figure 24. Daily hydrographs and calculated losses for site 34 (Boxelder Creek near Nemo) and site 38 (Boxelder Creek near Rapid City) for selected water years.--Continued

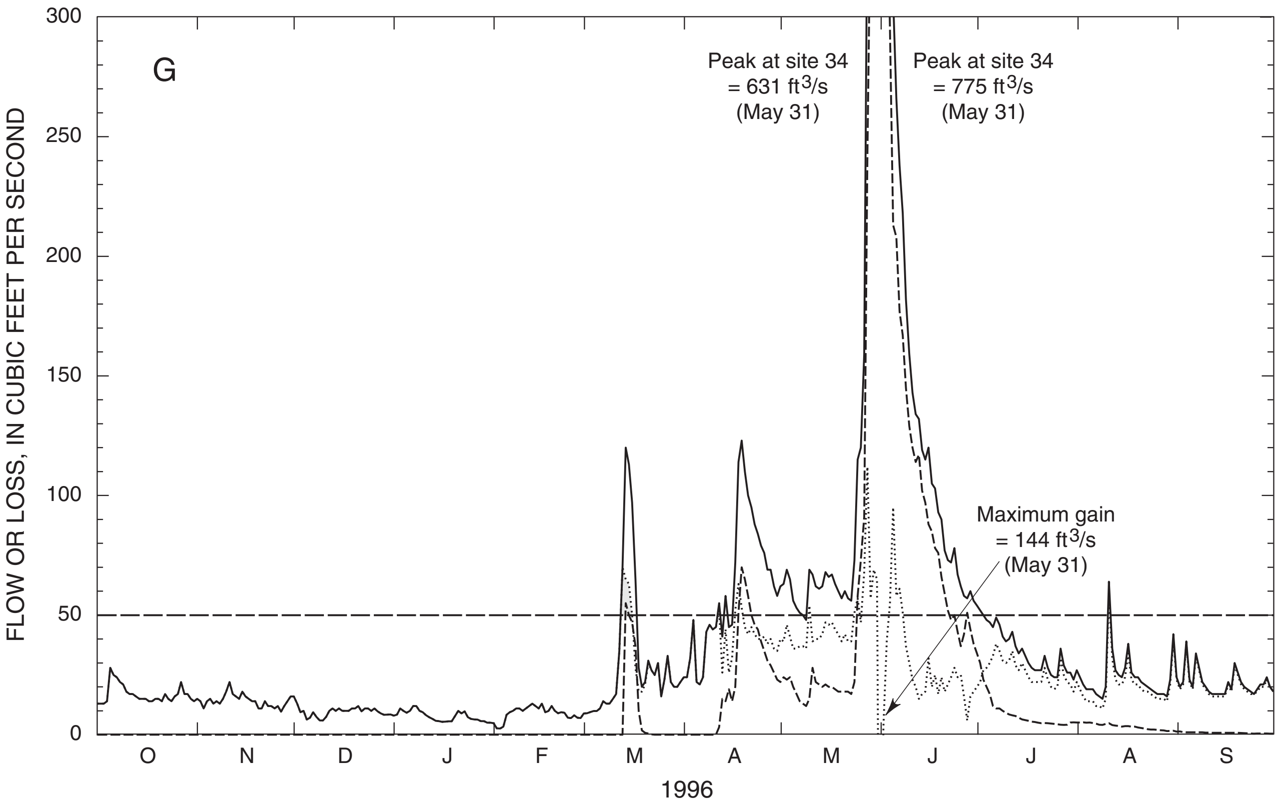


Figure 24. Daily hydrographs and calculated losses for site 34 (Boxelder Creek near Nemo) and site 38 (Boxelder Creek near Rapid City) for selected water years.--Continued

Hydrographs of daily streamflow for sites 34, 36, and 38 for WY78 (fig. 25) and WY96 (fig. 26) provide additional insights on the complicated interactions that occur within the loss zone of Boxelder Creek. The hydrograph for site 36 for WY96 is derived from daily staff gage readings by an observer (table 3).

Figures 25 and 26 both show total (net) losses between sites 34 and 38, as well as losses to an upstream reach (between sites 34 and 36) and a downstream reach (between sites 36 and 38). Losses in the upstream reach occur primarily to the Madison Limestone (assuming losses to the Deadwood Formation are negligible). Losses in the downstream reach may occur to several outcrops. The predominant outcrop within the downstream reach is the Minnelusa Formation; however, losses also occur to the previously mentioned outcrop of Madison Limestone located within this reach. In addition, an outcrop of the Minnekahta Limestone and extensive alluvial deposits are located within the downstream reach.

Losses appear to be divided about evenly between the upstream and downstream reaches. During late May and early June of WY78 (fig. 25), losses to both the upstream and downstream reaches were relatively steady and averaged about 20 ft^3/s, with total (net) losses averaging about 40 ft^3/s. During late June and early July of WY96 (fig. 26), losses to the upstream reach also were about 20 ft^3/s; however, losses in the downstream reach during this period were inconsistent, primarily because of a small peak in the flow at site 38 during late June.

Gradually declining springflow upstream from site 38 is evident during the latter months of both WY78 and WY96 (figs. 25A and 26A), which indicates that zero-flow must occur somewhere between sites 34 and 38. Furthermore, it can be deduced that the zero-flow zone can encompass site 36 and extends into the downstream reach, because flow was maintained at site 38, after flow ceased at site 36, during both years (figs. 25C and 26C). The location of the zero-flow zone can also be confirmed by measurements made on August 28, 1996 (table 22), when zero flow was recorded at site 36 and 4.70 ft^3/s was measured at site 37.

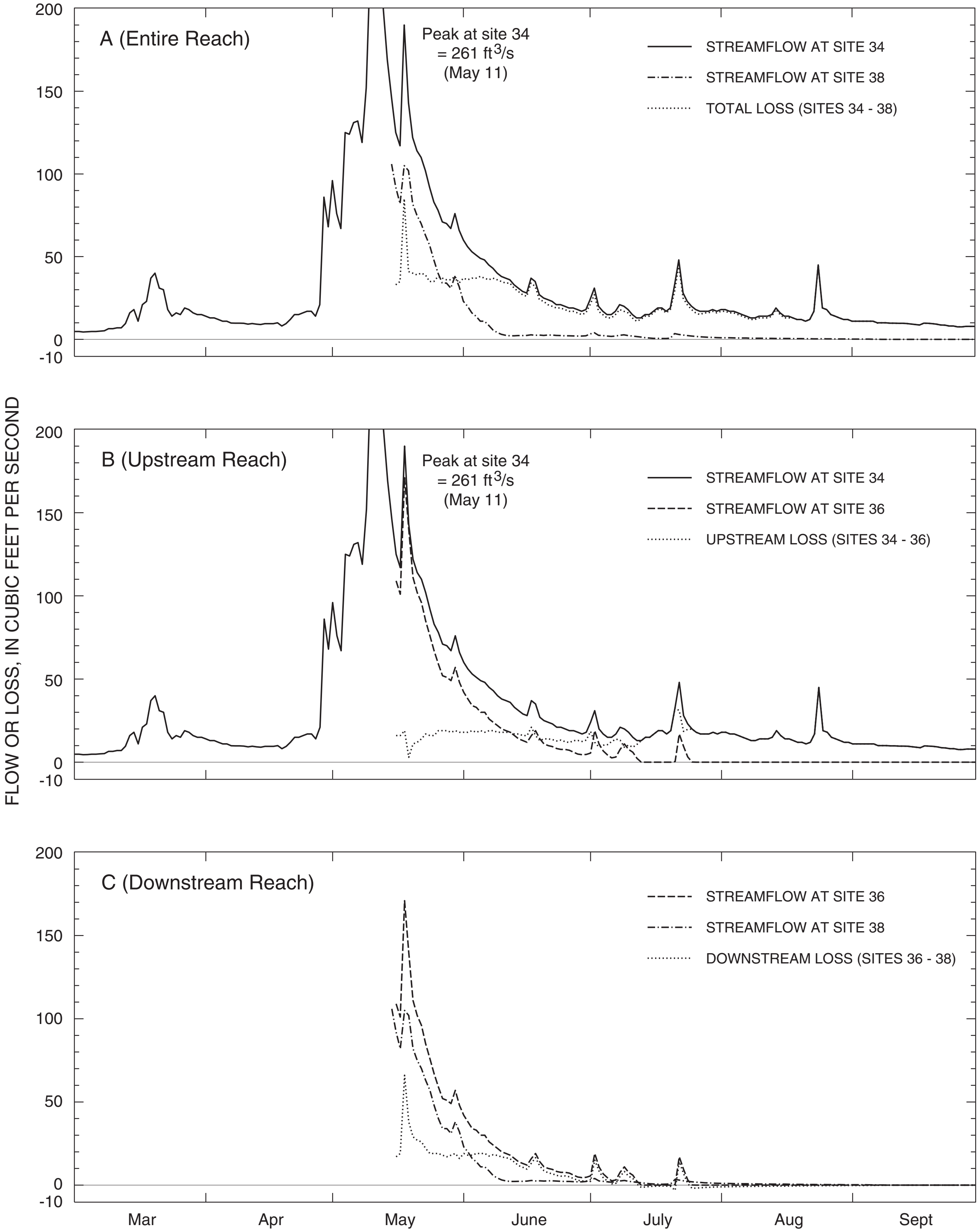


Figure 25. Daily hydrographs and calculated losses for site 34 (Boxelder Creek near Nemo), site 36 (Boxelder Creek at Doty School), and site 38 (Boxelder Creek near Rapid City), water year 1978.

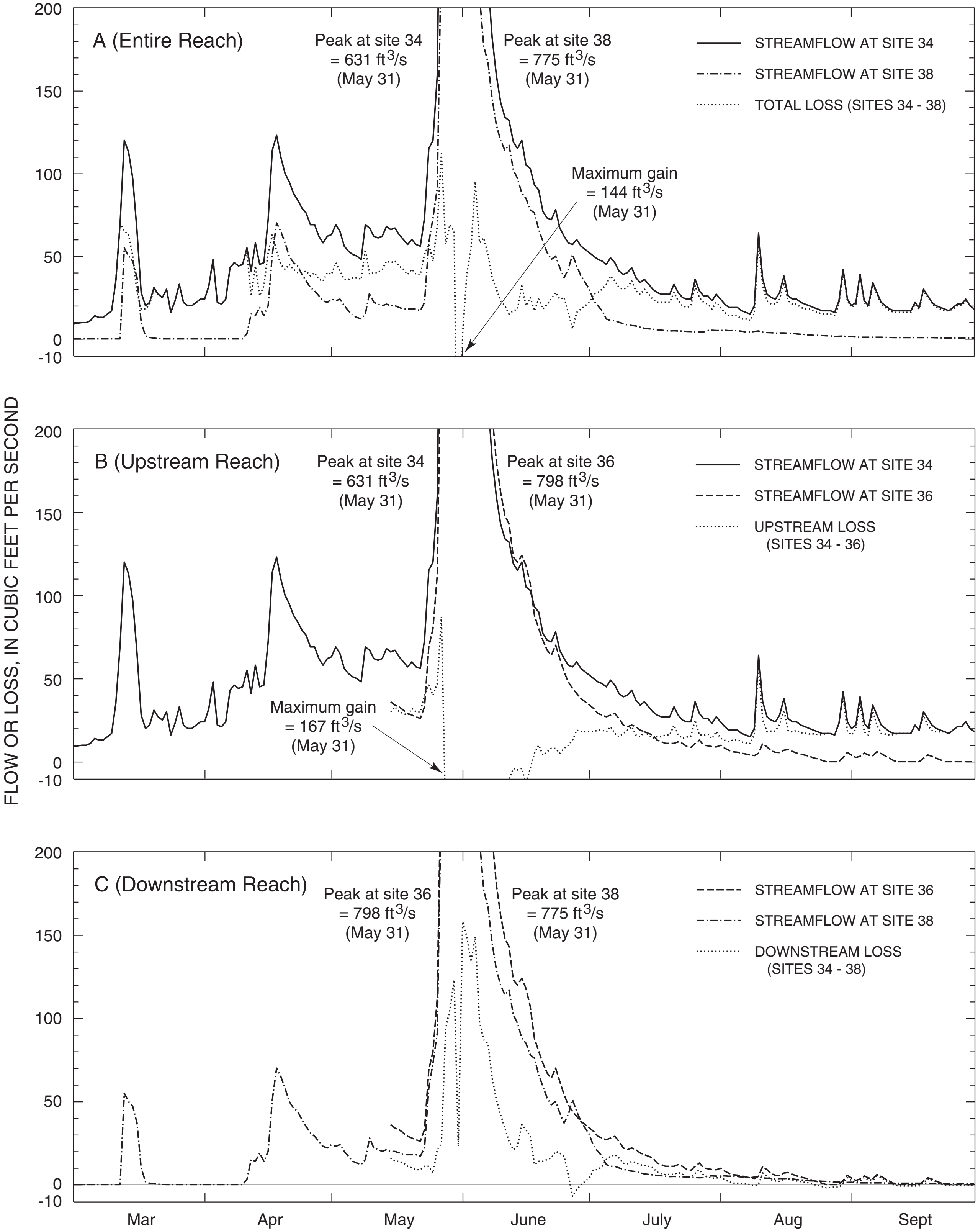


Figure 26. Daily hydrographs and calculated losses for site 34 (Boxelder Creek near Nemo), site 36 (Boxelder Creek at Doty School), and site 38 (Boxelder Creek near Rapid City), water year 1996.

Rahn and Gries (1973) documented large, transient springflow from Gravel, Doty, and Dome Springs upstream from site 36, as previously discussed. It can be deduced that large flows from these springs are intermixed within the loss zones upstream from site 36 because the hydrograph for site 36 is dampened, relative to site 34, similar to the dampening seen between sites 36 and 38 (figs. 25 and 26). In addition, the calculated net loss rate in the upstream reach consistently decreased to less than 20 ft^3/s as flow at site 34 decreased.

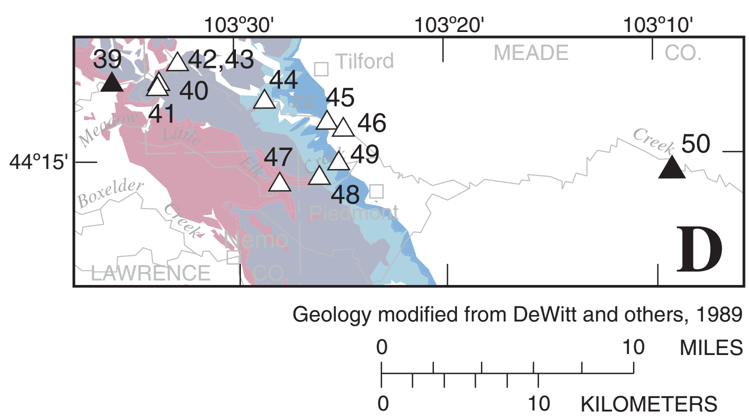
After analyzing calculated losses in figures 24, 25, and 26 and considering the effects of variable springflow within both the upstream and downstream reaches, it is estimated that the loss rate is about 25 ft^3/s in each reach during years of relatively small recharge and coinciding small springflow. The net loss rate probably decreases to about 20 ft^3/s or less in each reach, when recharge is sufficient to increase springflow within the loss zone. Losses to the Madison Limestone probably are larger than to the Minnelusa Formation, because subsequent field observations have confirmed large losses to the Madison outcrop located within the Minnelusa reach, between sites 36 and 37. Losses to the Minnekahta Limestone between sites 37 and 38 probably are relatively small (less than 5 ft^3/s) and may include alluvial losses. Losses within this reach apparently are affected by transient springflow, which probably varies considerably with recharge conditions, based on individual measurements presented in table 22. Thus, the total loss threshold for Boxelder Creek is estimated as 50 ft^3/s, with losses to the various individual outcrops estimated as follows: Madison, >25 ft^3/s; Minnelusa, <20 ft^3/s; and Minnekahta, <5 ft^3/s.

Elk Creek and Little Elk Creek

Losses are calculated for the main stem of Elk Creek and one major tributary, Little Elk Creek. Two continuous-record and ten miscellaneous-record stations are located along Elk Creek and Little Elk Creek (fig. 27, table 3).

Elk Creek

Loss calculations for Elk Creek for WY96 are presented in table 23, which includes measurements for sites 39-45. Site 39 is the only continuous-record station of this group; the other sites are miscellaneous-record stations that were established during WY96 to determine losses in various reaches of Elk Creek.



Site Number	Station Name
39	Elk Creek near Roubaix
40	Elk Creek above Meadow Creek
41	Meadow Creek above Elk Creek
42	Elk Creek trib (from North)
43	Elk Creek below trib from North
44	Elk Creek below Madison outcrop
45	Elk Creek at Minnekahta outcrop
46	Elk Creek at I-90
47	Little Elk Creek below Dalton Lake
48	Little Elk Creek below Madison outcrop
49	Little Elk Creek at Minnekahta outcrop
50	Elk Creek near Rapid City

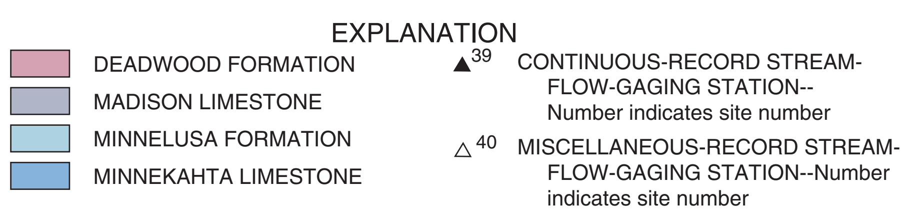


Figure 27. Insert D from figure 6, showing location of measurement sites and generalized outcrops for Elk Creek and Little Elk Creek. Outcrops shown may include other formations.

Table 23. Calculations of streamflow losses for Elk Creek, water year 1996

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

Date	Upstream station site 39		Intermediate station site 40		Upstream tributary site 41		Upstream tributary site 42		Intermediate station site 43	
	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	Time, in hours	Flow, in ft^3/s
4-24-96	0715	31.9	0900	31.0	1000	1.56	1320	2.81	1228	29.5
5-07-96	1050	26.6	0720	22.8	0805	1.66	0920	1.81	0950	23.6
7-01-96	0910	12.1	1040	11.2	1115	3.13	1210	1.20	1245	8.80
7-12-96	0930	9.85	0750	6.91	0830	2.84	0915	.91	0940	5.50
7-22-96	0930	7.35	1105	6.11	1140	2.56	1250	.65	1320	2.36
8-20-96	0830	4.65	1010	2.96	1045	1.80	1200	.55	1220	0

Date	Intermediate station site 44		Downstream station site 45		Loss to Madison, in ft^3/s				Loss to Minnelusa, in ft^3/s (44 - 45)	Total loss, in ft^3/s (39 + 41 + 42 - 45)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Upstream (39 - 40)	Intermediate (40 + 41 + 42 - 43)	Downstream (43 - 44)	Total (39 + 41 + 42 - 44)		
4-24-96	1435	26.2	1538	18.3	0.9	5.9	3.3	10.1	7.9	18.0
5-07-96	1125	18.8	1210	10.7	3.8	2.7	4.8	11.3	8.1	19.4
7-01-96	1350	16.3	1440	9.90	.9	6.7	-7.5	.1	6.4	6.5
7-12-96	1040	10.9	1130	5.56	2.94	5.16	-5.4	2.7	5.3	8.0
7-22-96	1240	7.49	1340	2.72	1.24	6.96	-5.13	3.07	4.77	7.84
8-20-96	1310	5.17	1405	.68	1.69	>5.31	-5.17	1.83	4.49	6.32
				Mean loss[1]	1.9	5.5	[2]4.0	[2]10.7	[2]8.0	[2]18.7
				Median loss[1]	1.5	5.9	[2]4.0	[2]10.7	[2]8.0	[2]18.7

[1]Calculated using finite values only.
[2]Calculated using only measurements for April 24 and May 7, 1996.

Individual measurements for April 24 and May 7, 1996, produced similar results (table 23). Total bedrock losses through the entire reach, which include losses to the Madison Limestone and Minnelusa Formation, as well as possible losses to the Deadwood Formation, were very similar. Losses in individual reaches also were quite similar. On July 1, however, a streamflow gain of 7.5 ft^3/s was measured in the downstream portion of the Madison loss zone, between sites 43 and 44. Streamflow gains within this same reach were slightly larger than 5.0 ft^3/s for subsequent measurements during the remainder of WY96 (table 23).

Streamflow gains across a specific stream reach generally result from tributary inflows or springflow. Increased tributary inflows were not observed within the reach after May 7, 1996; however, extremely wet climatic conditions during the spring and early summer of 1996 provided an opportunity for significant recharge to the large outcrops of the Madison Limestone along Elk Creek. Thus, it is likely that springflow (ground-water discharge) from the Madison is the cause of streamflow gains within the reach. Rahn and Gries (1973) noted springflow within this same reach that averaged about 5 ft^3/s during WY67-70, which also was a very wet period. They also stated that, except for periods of high flow, the channel generally was dry upstream from the spring area. The calculated loss rates to the Minnelusa Formation also decreased slightly subsequent to the measurements made on May 7, 1996 (table 23). Springflow within this reach also is a likely explanation for decreased calculated losses to the Minnelusa.

Because springflow probably had an effect on loss calculations subsequent to May 7, 1996, the individual measurements for April 24 and May 7, 1996, are used to estimate the loss threshold for Elk Creek. Total bedrock losses are estimated to be at least 19 ft^3/s, with individual losses of 11 ft^3/s to the Madison and 8 ft^3/s to the Minnelusa. In each case, the loss threshold may be even larger because of possible springflow within the loss zones.

Additional insights regarding streamflow losses and springflow along Elk Creek can be obtained from examination of streamflow data for sites 46 and 50. Individual measurements during WY94-96 for site 46 are presented in table 24, along with individual measurements or daily mean values for site 39 and daily mean values for site 50, which is a continuous-record station located downstream from the confluence with Little Elk Creek and other smaller tributaries (fig. 27). Direct calculation of streamflow losses using data from the two continuous-record stations (sites 39 and 50) fails to produce meaningful results because of unmeasured tributary inflows within the large intervening drainage area and because of complicated interactions with extensive alluvial deposits, between sites 46 and 50 (table 3). Intermittent springflow upstream from site 50 (Miller and Driscoll, 1998) further complicates loss calculations. Following is a discussion of how streamflow between sites 39 and 50 is affected by tributary inflows, springflow, and alluvial interactions.

Table 24. Calculations of streamflow losses for Elk Creek, water years 1994-96

[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 39		Intermediate station site 46		Upstream loss[1], in ft^3/s (39 - 46)	Downstream station site 50		Downstream loss[1], in ft^3/s (46 - 50)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s		Time, in hours	Flow, in ft^3/s	
5-11-94	1155	37.6	1315	8.37	29.2	--	[2]5.9	2.5
5-18-95	1225	70.2	1103	77.8	-7.6	--	[2]141	-63
7-10-95	--	[2]10	1700	5.21	5	--	[2]32	-27
7-14-95	--	[2]9.8	1200	2.00	7.0	--	[2]34	-32
7-28-95	--	[2]5.8	1200	0	>5.8	--	[2]31	-31
7-22-96	0930	7.35	1400	0	>7.35	--	[2]27	-27

[1]Calculated loss does not account for tributary inflows within reach.
[2]Indicated value for this date is the daily mean.

Streamflow hydrographs for WY93-96 are presented in figure 28 for sites 39 and 50. Individual measurements obtained during WY94-96 for site 46 also are shown in figure 28. Springflow at site 50 was nonexistent during the beginning and ending months of WY93-94 (figs. 28A and 28B). Zero-flow conditions at this site are common during dry years (Miller and Driscoll, 1998).

Flow at the upstream station (site 39) exceeded the approximate bedrock loss threshold of about 20 ft^3/s for several extended periods during May and June of WY93 (fig. 28A); however, most of the flow that may have passed through the Madison and Minnelusa loss zones probably was subsequently lost to alluvial deposits upstream from site 50. Periods when downstream peak flows exceeded upstream peak flows probably resulted primarily from tributary inflow between sites 39 and 50.

Flow at the upstream station (site 39) also exceeded the approximate bedrock loss threshold for an extended period during March through May of WY94 (fig. 28B). Again, most of the flow that may have passed through the bedrock loss zone probably was lost to alluvial storage, considering that various peaks in excess of 20 ft^3/s at the upstream site were not transmitted to the downstream site. An upstream loss of 29.2 ft^3/s is calculated for May 11, 1994 (table 24); however, the validity of this calculation is questionable because of unmeasured tributary inflows, rapidly changing streamflow, and the possibility of losses to the alluvium.

Springflow upstream from site 50 apparently started during November or December of WY95 (fig. 28C). Flow at site 39 generally was less than the approximate bedrock loss threshold through most of April; however, the threshold was exceeded for most of May and June. Alluvial storage probably was satisfied during early May of 1995, concurrent with large peaks at sites 39 and 50. Flow at site 50 generally exceeded flow at site 39 for the remainder of the year. Calculated upstream losses for July 10 and July 14, 1995, were 5 and 7 ft^3/s (table 24), respectively, which is considerably less than the approximate bedrock loss threshold. The occurrence of flow at site 46 for these dates, even when flow at site 39 was well below the estimated threshold, indicates a strong likelihood that springflow probably was occurring in the downstream portion of the Madison loss zone. In addition, zero flow was recorded at site 46 on July 28, 1995, which indicates that all flow at site 50 resulted from springflow or tributary inflow between sites 46 and 50.

Flow at site 50 approached or exceeded 10 ft^3/s for all of WY96 (fig. 28D). Much of this flow occurred during baseflow conditions, when flow at site 39 was less than the approximate bedrock loss threshold of 20 ft^3/s. Peaks in excess of this threshold generally were transmitted to the downstream station, indicating that the alluvial storage capacity remained satisfied during this period. Zero flow was again recorded at site 46 on July 22, 1996. Therefore, flow occurring at site 50 after July 22 probably resulted from springflow between sites 46 and 50.

As previously mentioned, streamflow data for sites 46 and 50 are not useful for improving the estimated threshold for Elk Creek; however, several conclusions can be derived from these data sets. First, the available storage in the alluvial deposits upstream from site 50 is apparently quite large, consistent with alluvial deposits downstream from loss zones in other area streams. Second, springflow, or ground-water discharge, within the Madison loss zone along Elk Creek apparently occurred during WY95, prior to the extensive measurements collected during WY96 (table 24). This springflow seems to decline relatively quickly when dryer conditions occur. Springflow within the loss zone apparently began prior to July 10, 1995 (table 24), and declined between July 10 and July 14, 1995. It cannot be determined if springflow ceased after July 14, because losses to the Minnelusa can approach or exceed 5 ft^3/s (table 23). Thus, there may have been measurable springflow between sites 43 and 44 on July 28, 1995, when zero flow was observed at site 46 (table 24). Furthermore, it is possible that springflow also was occurring within the Madison loss zone on April 24 and May 7, 1996, when losses to the downstream portion of the Madison loss zone were measured (table 23). Thus, total losses to the Madison may be larger than the estimated threshold of 11 ft^3/s (table 23). Finally, springflow between sites 46 and 50 is quite variable (ranging from less than 1.0 to in excess of 10 ft^3/s) and most likely is related to recent recharge conditions. It cannot be determined from this analysis, however, whether springflow between sites 46 and 50 is derived from alluvial sources, bedrock sources, or a combination of both.

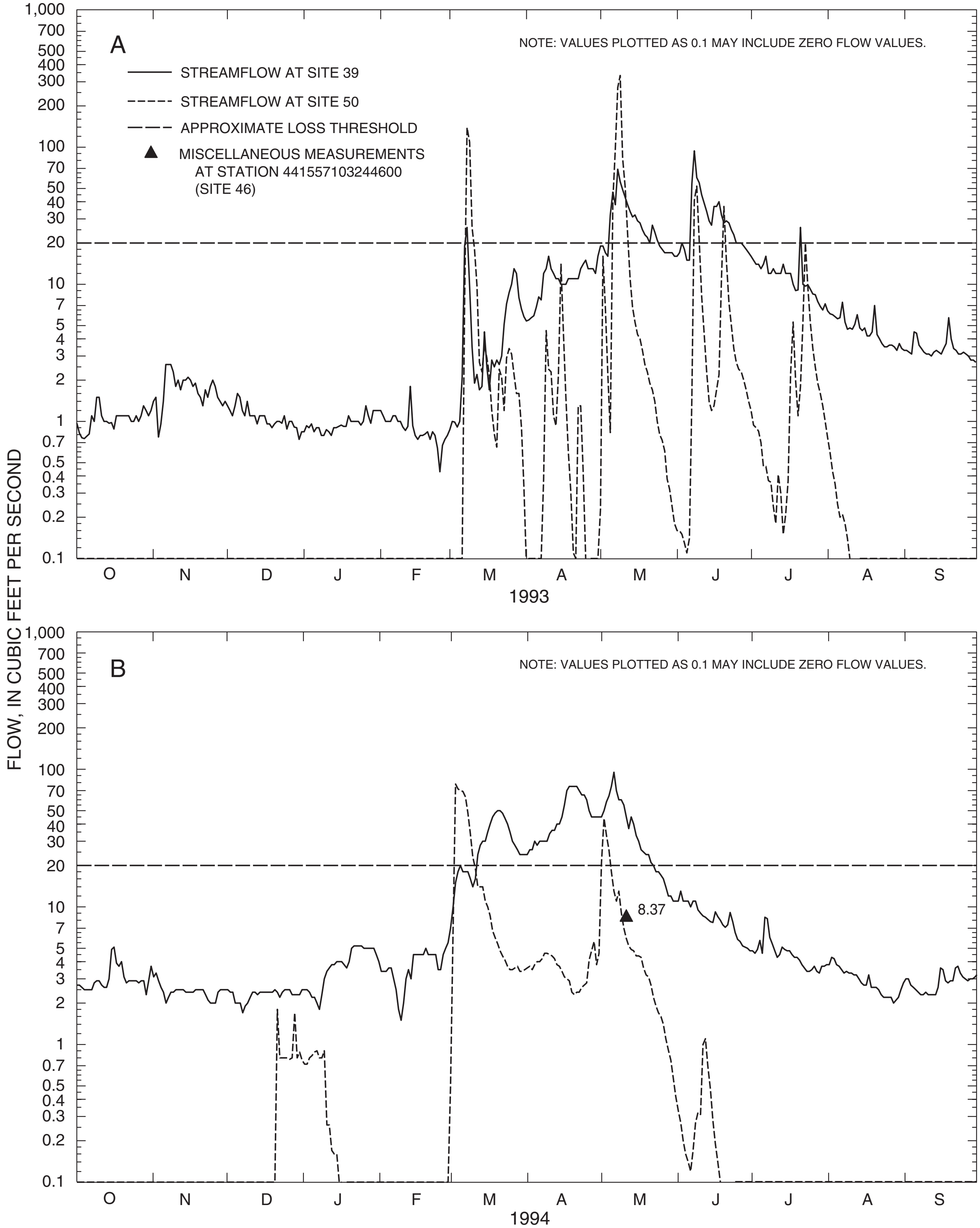


Figure 28. Daily hydrographs and miscellaneous measurements for site 39 (Elk Creek near Roubaix) and site 50 (Elk Creek near Rapid City), water years 1993-96.

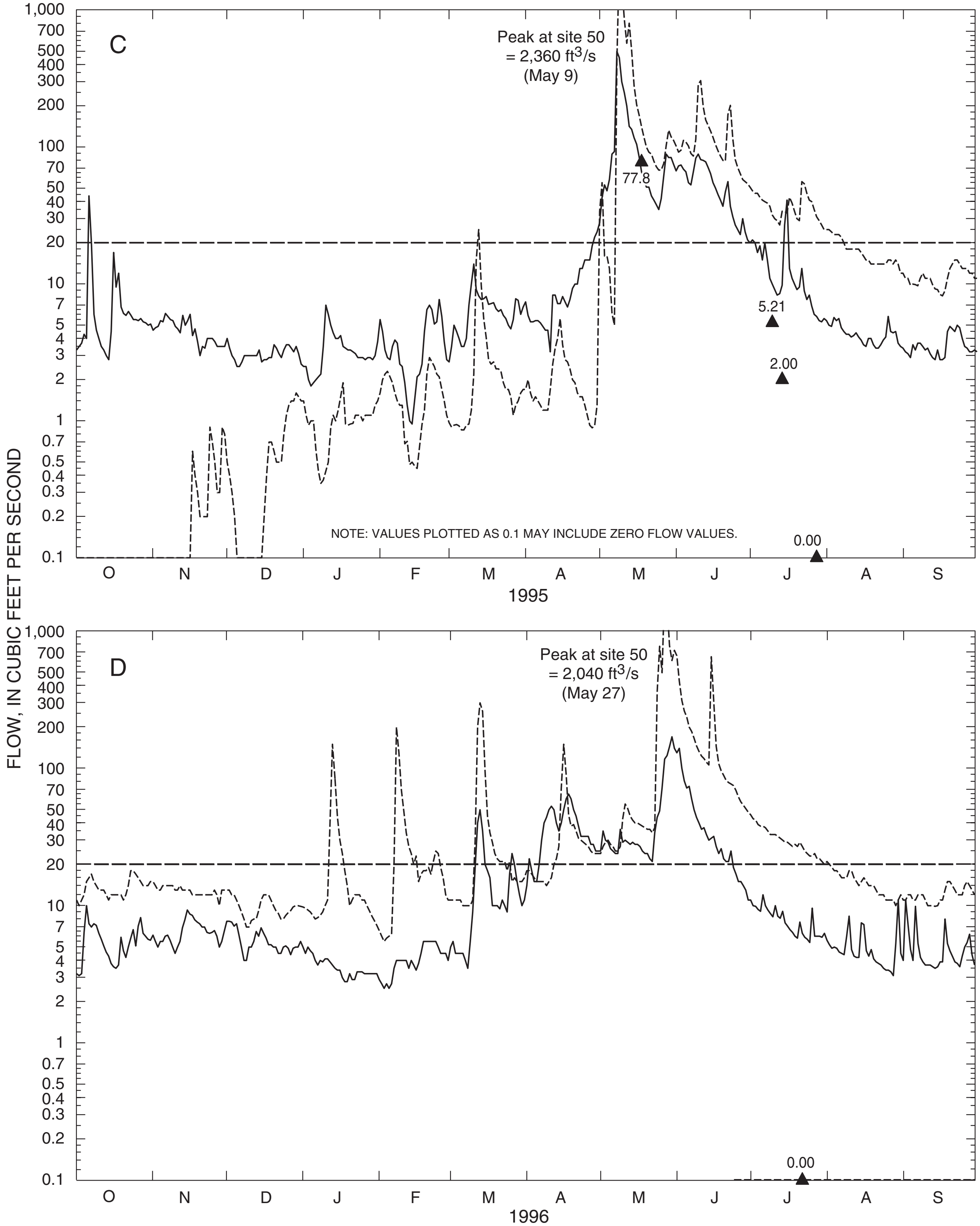


Figure 28. Daily hydrographs and miscellaneous measurements for site 39 (Elk Creek near Roubaix) and site 50 (Elk Creek near Rapid City), water years 1993-96.--Continued

Little Elk Creek

Loss calculations for Little Elk Creek are presented in table 25, which includes measurements for sites 47, 48, and 49 (fig. 27). Losses to the Madison Limestone can be differentiated from losses to the Minnelusa Formation. Calculated losses to the Madison in the upstream reach also may include minor losses to the Deadwood Formation (table 3).

Calculated losses to the Madison for July 8, 1996, probably are not representative of actual losses because of apparent tributary inflows between sites 47 and 48. The calculated loss to the Minnelusa for this date is somewhat larger than losses for other dates, which indicates that tributary inflow probably was not significant within this reach. Using the median values, the following bedrock loss thresholds for Little Elk Creek are estimated: Madison Limestone, 0.7 ft^3/s; Minnelusa Formation, 2.6 ft^3/s; and combined losses to the Madison and Minnelusa, 3.3 ft^3/s.

Redwater River Tributaries

Losses are calculated for four tributaries to the Redwater River (Bear Gulch, Beaver Creek, Spearfish Creek, and False Bottom Creek), as well as two tributaries to Spearfish Creek (Iron Creek and Higgins Gulch). Two continuous-record stations, twenty-two miscellaneous-record stations, and one zero-flow station are located along these streams (fig. 29, table 3)

Bear Gulch

Loss calculations for Bear Gulch are presented in table 26, which includes measurements for sites 51 and 52. Calculated losses in table 26 are combined losses to the Madison Limestone, Minnelusa Formation, and Minnekahta Limestone. Zero flow was recorded at the downstream station (site 52) on three dates during WY95-96 (table 26). Mean and median loss rates of 4.4 ft^3/s and 4.0 ft^3/s are calculated using the remaining measurements. Thus, the bedrock loss threshold for Bear Gulch is estimated to be 4 ft^3/s.

Beaver Creek

Loss calculations for Beaver Creek are presented in table 27, which includes measurements for sites 53 and 55. Also included in table 27 is a single measurement for site 54, which is located approximately 1.0 mi downstream from site 53 and just upstream from the outcrop of Madison Limestone (fig. 29). The single measurement was made to account for tributary inflows that were occurring downstream from site 53 during high-flow conditions on June 2, 1995. Calculated losses in table 27 are combined losses to the Madison Limestone, Minnelusa Formation, and Minnekahta Limestone (table 3).

Zero flow was recorded at the downstream station (site 55) on three of the dates shown in table 27. Mean and median loss rates of 9.4 and 9.1 ft^3/s are calculated using the remaining measurements. Thus, the bedrock loss threshold for Beaver Creek is estimated to be 9 ft^3/s.

Spearfish Creek and Tributaries

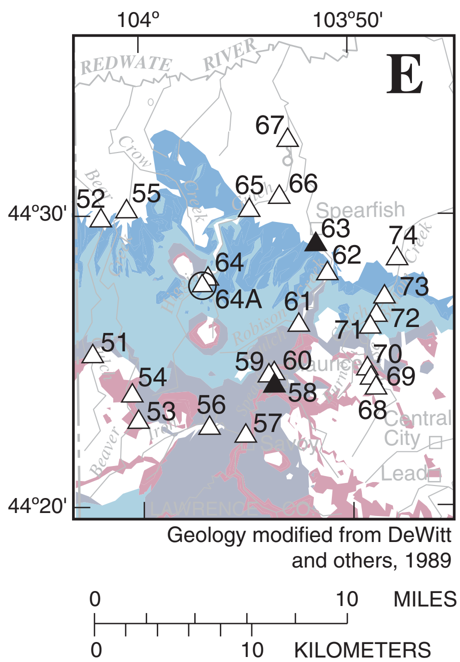
Losses are calculated for Spearfish Creek and two of its tributaries, Iron Creek and Higgins Gulch (fig. 29, table 3). The confluence with Iron Creek is upstream from the loss zone on Spearfish Creek and the confluence with Higgins Gulch is downstream from the loss zone.

Table 25. Calculations of streamflow losses for Little Elk Creek

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

Date	Upstream station site 47		Intermediate station site 48		Downstream station site 49		Loss to Madison, in ft^3/s (47 - 48)	Loss to Minnelusa, in ft^3/s (48 - 49)	Total loss, in ft^3/s (47 - 49)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s			
4-26-96	1351	5.13	1523	4.61	1636	2.13	0.52	2.48	3.00
7-08-96	1110	7.64	1515	9.14	1620	4.68	[1]-1.50	4.46	[1]2.96
7-22-96	0810	6.19	0905	5.22	1015	2.60	.97	2.62	3.59
						Mean loss	.74	3.19	3.30
						Median loss	.74	2.62	3.30

[1]Excluded from calculations of mean and median values because of apparent tributary inflow.



Site Number	Station Name
51	Bear Gulch near Maurice
52	Bear Gulch below Minnekahta outcrop
53	Beaver Creek near Maurice
54	Beaver Creek below Beaver Crossing
55	Beaver Creek below Minnekahta outcrop
56	Iron Creek below Sawmill Gulch
57	Iron Creek near Lead
58	Spearfish Creek above Spearfish
59	Aqueduct Inlet below Maurice
60	Spearfish Creek below Homestake Diversion
61	Spearfish Creek below Robison Gulch
62	Spearfish Creek below Madison outcrop
63	Spearfish Creek at Spearfish
64A	Higgins Gulch above East Fork
64	Higgins Gulch below East Fork
65	Higgins Gulch above Spearfish
66	Higgins Gulch at Spearfish
67	Higgins Gulch below I-90
68	False Bottom Creek above Madison outcrop
69	False Bottom Creek trib (1st West trib)
70	False Bottom Creek trib (2nd West trib)
71	False Bottom Creek below Madison outcrop
72	Burno Gulch above False Bottom Creek
73	False Bottom Creek (below Minnelusa outcrop)
74	False Bottom Creek at I-90

EXPLANATION

DEADWOOD FORMATION

MADISON LIMESTONE

MINNELUSA FORMATION

MINNEKAHTA LIMESTONE

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

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

64A ZERO-FLOW STATION--Number indicates site number

Figure 29. Insert E from figure 6, showing location of measurement sites and generalized outcrops for Redwater River tributaries. Outcrops shown may include other formations.

Table 26. Calculations of streamflow losses for Bear 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 51		Downstream station site 52		Total loss, in ft^3/s (51 - 52)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	
6-02-95	1510	24.8	1704	20.6	4.2
6-21-95	1340	7.43	1510	1.85	5.58
7-17-95	1315	2.28	1100	0	>2.28
5-01-96	1200	10.7	1330	6.78	3.9
6-12-96	1520	6.84	1650	3.12	3.72
7-10-96	1530	1.44	1415	0	>1.44
8-27-96	1545	.37	1720	0	>.37
				Mean loss[1]	4.4
				Median loss[1]	4.0

[1]Calculated using finite values only.

Table 27. Calculations of streamflow losses for Beaver 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 53		Intermediate station site 54		Downstream station site 55		Total loss, in ft^3/s (53 - 55)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s	
6-02-95	0915	18.7	1005	22.4	1251	13.4	[1]9.0
6-21-95	1030	8.32	--	--	1200	.07	8.25
7-17-95	1020	.37	--	--	1400	0	>.37
5-01-96	1520	17.5	--	--	1415	8.32	9.2
6-11-96	1330	11.2	--	--	1415	.15	11.0
7-11-96	1000	2.30	--	--	1410	0	>2.30
8-29-96	1200	1.18	--	--	1300	0	>1.18
						Mean loss[2]	9.4
						Median loss[2]	9.1

[1]Loss calculated as flow at site 54 minus site 55, because of tributary inflows upstream.
[2]Calculated using finite values only.

Iron Creek (tributary)

Loss calculations for Iron Creek (table 28) show a gain of about 1 to 2 ft^3/s between sites 56 and 57. A distinct decrease in streamflow was noted downstream from site 56 on both measurement dates, with zero flow observed on July 19, 1996; however, flow increased farther downstream on both dates. No tributary inflow was observed on either date; thus, it is hypothesized that streamflow gains were a result of springflow (ground-water discharge) within the downstream portion of the reach. It is concluded that Iron Creek is a net discharge zone for the Madison Limestone, rather than a recharge zone.

Spearfish Creek (main stem)

Most of the flow of Spearfish Creek is diverted around the bedrock loss zone, from a diversion dam located about 5 mi south of Spearfish to a power plant located in Spearfish, just upstream from site 63 (fig. 29). Flow in the stream channel upstream from the power plant occurs only when flow at site 58 exceeds both the capacity of the diversion aqueduct and the loss threshold of the creek. Measurements made at sites 58, 59, and 60 provide insights regarding the approximate maximum diversion rate from Spearfish Creek (table 29). On May 10, 1994, measurements were made at sites 58 and 60 (located upstream and downstream from the diversion dam, respectively) indicating a diversion rate of about 116 ft^3/s. On May 18, 1995, a flow of 136 ft^3/s was measured in the aqueduct inlet (site 59), with additional flow bypassing the diversion dam. Thus, the maximum diversion rate is estimated to be in the range of 115 to 135 ft^3/s.

Table 28. Calculations of streamflow losses for Iron Creek

[ft^3/s, cubic feet per second; mi, miles; ( ), losses between specified sites calculated by performing indicated arithmetic operation; u/s, upstream; d/s, downstream]

Date	Upstream station site 56		Downstream station site 57		Total loss, in ft^3/s (56 - 57)	Remarks
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s		
6-28-96	1415	1.33	1550	2.71	-1.38	Flow estimated as 0.2 to 0.3 ft^3/s about 0.75 mi d/s from site 56
7-19-96	1303	.40	1410	2.20	-1.80	Zero flow observed 0.3 mi d/s from site 56

Table 29. Measurements of streamflow diverted from Spearfish Creek for power plant

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

Date	Above diversion site 58		Diversion inlet site 59		Below diversion site 60		Estimated diversion, 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	
5-10-94	1105	139	--	--	1145	23.1	116
5-18-95	--	--	0815	136	--	--	136

Loss calculations for the main stem of Spearfish Creek are presented in table 30, which includes measurements for sites 61 and 62. Calculated losses are combined losses to the Madison Limestone and Minnelusa Formation (fig. 29, table 3). The calculated loss for April 17, 1996, probably is affected by alluvial losses because flow was just beginning to pass completely through the loss zone. The other three finite loss values are quite consistent and are used to estimate the loss threshold for Spearfish Creek as 21 ft^3/s.

The entire flow of Spearfish Creek, up to the maximum diversion rate, generally is diverted through the aforementioned aqueduct to the power plant. During periods when the entire flow upstream from the diversion dam is diverted, flow at site 61 (located about 2 mi downstream from the diversion dam) results from possible seepage through the diversion dam, tributary inflow, and ground-water discharge within the reach. Numerous discharge measurements for WY89-91, when the upstream diversion threshold was not exceeded, are available for site 61. For these measurements, flow generally ranged from about 2 to 5 ft^3/s, and averaged about 3 ft^3/s (Driscoll and Hayes, 1995).

Bedrock losses also occur within the diversion aqueduct, as shown by an analysis of monthly flow data for sites 58 and 63 for WY89-96 (table 31). Mean and median values are not calculated for April through September because the flow of Spearfish Creek frequently exceeded the maximum diversion rate during these months. The mean and median loss values calculated for October through March are 2.1 and 1.8 ft^3/s, respectively. Thus, the loss threshold within the diversion aqueduct is estimated to be about 2 ft^3/s.

Table 30. Calculations of streamflow losses for the main stem of Spearfish 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 61		Downstream station site 62		Total loss, in ft^3/s (61 - 62)	Remarks
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s		
5-10-94	1300	34.8	1425	15.4	19.4	
5-18-95	1150	107	1245	84.1	23	
4-17-96	1555	42.9	1650	3.39	39.5	Just starting to flow through loss zone
6-04-96	1000	53.8	1100	32.5	21.3	
6-13-96	1435	15.9	1530	0	>15.9	
				Mean loss[1]	21	
				Median loss[1]	21.3	

[1]Calculated using finite values only, excluding the value from April 17, 1996, because of probable alluvial losses.

Table 31. Monthly streamflow and loss values for Spearfish Creek, water years 1989-96

[--, not calculated]

Station	Monthly mean values, in cubic feet per second											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
WY89												
06430900 (site 58)	43.3	41.7	41.4	41.2	39.2	43.8	51.1	71.5	46.5	39.8	41.6	39.1
06431500 (site 63)	40.0	39.9	38.4	33.5	32.6	37.4	43.0	72.5	44.6	38.4	39.2	39.3
Calculated loss	3.3	1.8	3.0	7.7	6.6	6.4	8.1	-1.0	1.9	1.4	2.4	-0.2
WY90												
06430900 (site 58)	38.8	39.2	36.9	37.6	37.4	40.8	58.7	74.7	48.3	37.7	36.7	36.4
06431500 (site 63)	37.2	37.7	35.8	35.9	36.5	39.1	56.8	69.3	45.9	35.2	35.2	36.5
Calculated loss	1.6	1.5	1.1	1.7	0.9	1.7	1.9	5.4	2.4	2.5	1.5	-0.1
WY91												
06430900 (site 58)	36.4	37.2	36.0	38.0	37.9	39.8	47.0	81.7	63.9	43.6	37.8	34.9
06431500 (site 63)	34.6	36.5	30.0	30.8	34.3	35.8	43.6	70.8	63.3	41.0	33.0	34.3
Calculated loss	1.8	0.7	6.0	7.2	3.6	4.0	3.4	10.9	0.6	2.6	4.8	0.6
WY92												
06430900 (site 58)	36.7	41.7	41.4	41.2	37.9	40.8	44.8	45.3	41.4	39.4	35.9	36.0
06431500 (site 63)	39.1	40.8	39.6	38.5	39.2	39.0	45.5	48.7	37.8	35.2	32.9	31.2
Calculated loss	-2.4	0.9	1.8	2.7	-1.3	1.8	-0.7	-3.4	3.6	4.2	3.0	4.8
WY93												
06430900 (site 58)	35.5	37.3	38.3	37.2	37.0	39.5	60.4	81.8	103	53.5	43.9	42.7
06431500 (site 63)	32.1	31.2	32.7	31.4	31.4	36.5	52.1	71.0	74.7	50.1	42.9	43.8
Calculated loss	3.4	6.1	5.6	5.8	5.6	3.0	8.3	10.8	28	3.4	1.0	-1.1
WY94												
06430900 (site 58)	42.5	41.1	44.2	40.5	39.1	51.6	112	114	63.2	64.8	50.4	57.2
06431500 (site 63)	46.8	39.7	40.4	38.1	37.7	49.4	91.9	95.9	54.5	55.5	52.3	55.3
Calculated loss	-4.3	1.4	3.8	2.4	1.4	2.2	20	18	8.7	9.3	-1.9	1.9
WY95												
06430900 (site 58)	67.2	54.1	49.9	47.7	47.8	55.6	65.4	307	123	86.7	72.0	67.0
06431500 (site 63)	75.3	57.1	46.7	45.2	49.7	56.4	60.7	269	110	81.9	63.9	65.0
Calculated loss	-8.1	-3.0	3.2	2.5	-1.9	-0.8	4.7	38	13	4.8	8.1	2.0
WY96												
06430900 (site 58)	72.0	73.7	70.2	63.6	64.1	70.4	125	150	129	84.5	92.1	78.5
06431500 (site 63)	71.3	71.8	68.8	62.8	63.6	68.5	93.2	118	114	74.4	74.1	78.8
Calculated loss	0.7	1.9	1.4	0.8	0.5	1.9	32	32	15	10.1	18.0	-0.3
Mean loss	-0.5	1.4	3.2	3.9	1.9	2.5	--	--	--	--	--	--
Median loss	1.2	1.5	3.1	2.6	1.2	2.1	--	--	--	--	--	--
Mean loss (October through March)			2.1									
Median loss (October through March)			1.8									

In summary, bedrock losses along Spearfish Creek consist of two components. Losses within the diversion aqueduct average about 2 ft^3/s and the total loss threshold for the main stem of Spearfish Creek is estimated to be 21 ft^3/s. Bedrock losses within the main stem typically are much less than this, because most of the flow generally is diverted through the aqueduct. Bedrock losses along the main stem generally are less than 5 ft^3/s, except when upstream flow exceeds the maximum diversion rate (115 to 135 ft^3/s).

Higgins Gulch (tributary)

Streamflow information for Higgins Gulch is presented in table 32, which includes measurements on three dates for sites 64, 65, 66, and 67 (fig. 29). Also included in the table are notations of zero flow at site 64A, Higgins Gulch above East Fork, which is located just upstream from site 64. Individual measurement notes for all three dates also indicate that zero flow occurred at several locations within the reach between sites 64 and 65. Flow generally increased in a downstream direction between sites 64 and 67, with the exception of small decreases between sites 65 and 66 on July 19 and August 6, 1996. Much of the reach between sites 65 and 67 generally is dry; however, the reach immediately upstream from site 67 was previously identified as a perennial spring reach, with measured flows of 3.4 and 7.1 ft^3/s on July 12, 1991, and September 26, 1994, respectively (Driscoll and others, 1996).

It is concluded that no significant streamflow losses occur within Higgins Gulch. It is further concluded that Higgins Gulch is a discharge point for the Minnelusa Formation between sites 64A and 65. Klemp (1995) concluded from geochemical analysis, that springflow just upstream from site 67 probably originates primarily from the Madison Limestone.

Higgins Gulch heads within an outcrop of the Madison Limestone with no drainage area upstream from the Madison. Thus, there is no opportunity for the loss of streamflow that originates upstream from the Madison. Streamflow seldom occurs in the portion of Higgins Gulch located within the Madison outcrop due to lack of runoff, presumably because precipitation rates seldom exceed infiltration rates for the Madison. As an example, no flow was observed in the channel of Higgins Gulch, within the Madison outcrop area, on June 2, 1995, following an extended period of heavy rainfall. In comparison, large flows upstream from the Madison Limestone were measured on the same date in two nearby streams (Bear Gulch, table 26; and Beaver Creek, table 27).

False Bottom Creek

Seven miscellaneous-record stations (sites 68, 69, 70, 71, 72, 73, and 74) are used in the calculation of losses for False Bottom Creek (fig. 29, table 3). Losses to the Madison Limestone, Minnelusa Formation, and Minnekahta Limestone are presented in table 33. Calculated losses to the Madison may include minor losses to the Deadwood Formation and calculated losses to the Minnekahta may include losses to alluvial deposits.

Measurements for May 18, 1995, indicate a gain of about 1 ft^3/s across the Madison Limestone and a loss of about 5 ft^3/s across the Minnelusa Formation. The gain across the Madison on this date probably is a result of unmeasured tributary inflows, in addition to the estimated tributary inflows, resulting from large precipitation amounts during the preceding week. Similarly, it is likely that minor, unmeasured tributary inflows also were occurring within the Minnelusa reach. Thus, measurements for this date are excluded from subsequent calculations of means and medians. Measured flows on two subsequent dates were considerably smaller, with less likelihood of tributary inflows. Thus, combined losses to the Madison and Minnelusa are estimated to be 8.7 ft^3/s, with individual losses of 1.4 and 7.3 ft^3/s, respectively.

Table 32. Streamflow information for Higgins Gulch

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

Date	Zero-flow station[1] site 64A	Upstream station site 64		Intermediate station site 65		Intermediate station site 66		Downstream station site 67	
	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	Time, in hours	Flow, in ft^3/s
6-28-96	0	1245	1.16	0825	3.04	0945	3.11	1030	6.26
7-19-96	0	1200	.64	0840	2.32	0928	2.13	1007	6.88
8-06-96	0	1215	.54	0905	2.04	1245	1.50	1330	6.66

[1]On each measurement date, zero flow was observed at site 64A, which is located at a road crossing about 0.25 mi upstream from site 64.

Table 33. Calculations of streamflow losses for False Bottom Creek

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

Date	Upstream station site 68		Upstream tributary site 69		Upstream tributary site 70		Intermediate station site 71		Upstream tributary site 72	
	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	Time, in hours	Flow, in ft^3/s
5-18-95	1410	26.7	est	1	est	1	1525	29.3	est	2
4-26-96	0845	14.5	1000	0.70	0932	0.21	1025	13.5	1115	2.96
5-14-96	1005	10.8	est	0.3	est	0.1	1200	10.3	est	0.2

Date	Intermediate station site 73		Downstream station site 74		Loss to Madison, in ft^3/s (68 + 69 + 70 -71)	Loss to Minnelusa, in ft^3/s (71 + 72 - 73)	Combined loss to Madison and Minnelusa, in ft^3/s (68 + 69 + 70 + 72 - 73)	Loss to Minnekahta, in ft^3/s (73 - 74)	Total loss, in ft^3/s (68 + 69 + 70 + 72 - 74)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s					
5-18-95	1625	26.6	--	--	[1]-1	[1]5	[1]4	--	>4
4-26-96	1200	9.80	est	3	1.9	6.7	8.6	7	15
5-14-96	1315	2.6	1400	0	0.9	7.9	8.8	>2.6	>11.4
				Mean loss[2]	1.4	7.3	8.7	--	--
				Median loss[2]	1.4	7.3	8.7	--	--

[1]Excluded from mean and median loss calculation because of unmeasured tributary inflows.
[2]Calculated excluding values from May 18, 1995.

One measurement is available for calculation of losses to the Minnekahta Limestone; however, the measurement reach between sites 73 and 74 includes extensive alluvial deposits. Thus, the calculated loss of 7 ft^3/s on April 26, 1996, also may include alluvial losses that may be large relative to losses to the Minnekahta. The total bedrock loss threshold for False Bottom Creek is estimated to be about 15 ft^3/s.

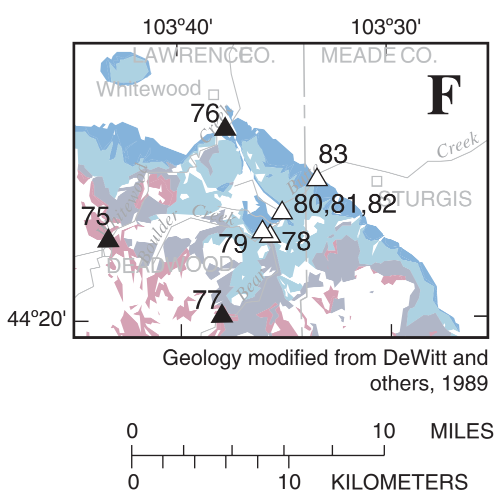
Whitewood Creek

Two continuous-record stations are used to calculate losses for Whitewood Creek (fig. 30, table 3). Monthly flows and calculated losses for both stations (sites 75 and 76) for WY83-95 are presented in table 41 of the Supplemental Information section. Calculated losses in table 41 indicate that Whitewood Creek generally is a gaining stream. The mean and median loss rates for the period of record are both -2 ft^3/s, which indicates a small net gain across the stratigraphic section from the Deadwood Formation through the Minnekahta Limestone. A histogram of calculated monthly loss rates for Whitewood Creek is presented in figure 31. Values used to generate this histogram (table 34) indicate that monthly gains occur about 78 percent of the time and losses occur only about 22 percent of the time.

Table 34. Distribution of monthly losses for Whitewood Creek, water years 1983-95

[ft^3/s, cubic feet per second; Š≥, greater than or equal to; >, greater than]

Calculated monthly loss rate (ft^3/s)	Number of occurrences	Cumulative frequency (percent)
Š≥-5.00	16	10.32
-4.99 to -4.00	5	13.55
-3.99 to -3.00	14	22.58
-2.99 to -2.00	31	42.58
-1.99 to -1.00	33	63.87
-0.99 to 0.00	22	78.06
0.01 to 1.00	11	85.16
1.01 to 2.00	10	91.61
2.01 to 3.00	6	95.48
3.01 to 4.00	1	96.13
4.01 to 5.00	3	98.06
>5.00	3	100.00



Site Number	Station Name
75	Whitewood Creek at Deadwood
76	Whitewood Creek above Whitewood
77	Bear Butte Creek near Deadwood
78	Bear Butte Creek above Boulder Creek
79	Boulder Creek above Bear Butte Creek
80	Bear Butte Creek at Boulder Park
81	Bear Butte Trib No. 1 at Boulder Park
82	Bear Butte Trib No. 2 at Boulder Park
83	Bear Butte Creek above Sturgis

EXPLANATION

DEADWOOD FORMATION

MADISON LIMESTONE

MINNELUSA FORMATION

MINNEKAHTA LIMESTONE

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

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

Figure 30. Insert E from figure 6, showing location of measurement sites and generalized outcrops for Whitewood Creek and Bear Butte Creek. Outcrops shown may include other formations.

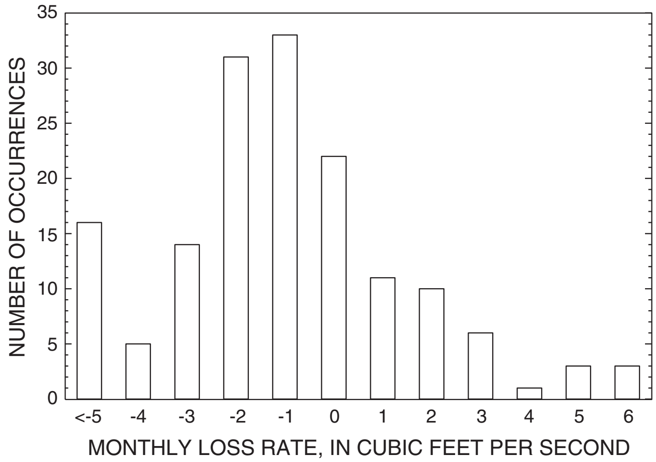


Figure 31. Histogram of monthly loss rates for Whitewood Creek (sites 75-76), water years 1983-95.

Monthly loss rates in table 41 indicate that most losses occur during January to February and July to August. The calculated losses for these months are minor and probably result from ice formation in the winter and evapotranspiration in the summer. Thus, it is concluded that significant losses do not occur to the bedrock units along Whitewood Creek.

There is evidence that Whitewood Creek was a "losing stream" in the late 1800's. Newton and Jenney (1880) observed flow in Whitewood Creek of about 300 miner's inches (approximately 7.5 ft^3/s), that was completely lost near the east edge of present-day Deadwood (fig. 30). Thus, Whitewood Creek apparently changed from a "losing" to a "non-losing" stream sometime between the 1880's and 1980's.

The apparent change in the loss characteristics of Whitewood Creek may have resulted from the extensive gold-mining activity in the area. Goddard (1989) reported that as much as 100 million tons of mill tailings were discharged into Whitewood Creek and its tributaries between 1876 and 1977. These fine-ground mill tailings may have effectively sealed the loss zones along Whitewood Creek.

Bear Butte Creek

One continuous-record and six miscellaneous-record stations are used in the calculation of losses for Bear Butte Creek (fig. 30, table 3). Loss calculations for Bear Butte Creek (table 35) include measurements for sites 77, 78, 79, 80, 81, 82, and 83. Sites 80-82 are located within an outcrop of Minnekahta Limestone that is perched within the Minnelusa section (DeWitt and others, 1989). This small Minnekahta outcrop probably is isolated from the main outcrop of the Minnekahta, which occurs several miles downgradient; thus, these stations are treated as being within the Minnelusa Formation.

Losses are not calculated for May 4, 1994, because tributary inflows were not measured. Calculated losses within each reach are similar for the two remaining dates. Thus, the estimated loss thresholds for Bear Butte Creek are as follows: Madison Limestone, 4 ft^3/s; upstream Minnelusa Formation, 4 ft^3/s; downstream Minnelusa Formation (including possible losses to Minnekahta Limestone), 4 ft^3/s; and total bedrock losses, 12 ft^3/s.

Summary of Losses

A summary of approximate loss thresholds is presented in table 36 for the 24 streams previously discussed. The first and second columns of table 36 list the stream names and bedrock aquifers that are exposed within the entire measurement reach for each stream. The third column lists the approximate threshold for total bedrock losses within the entire measurement reach. The last three columns list individual loss thresholds to the Madison Limestone, Minnelusa Formation, and Minnekahta Limestone.

Previous investigators have identified the Madison Limestone and Minnelusa Formation as the primary bedrock outcrops to which streamflow losses occur. The "total loss" thresholds listed in table 36, with several exceptions, occur primarily to the Madison or Minnelusa. Loss thresholds to the Minnekahta Limestone are estimated for Spring Creek, Boxelder Creek, and False Bottom Creek; however, these losses may include large losses to extensive alluvial deposits. Losses to the Minnekahta Limestone are difficult to isolate from losses to extensive alluvial deposits that commonly occur near outcrops of the Minnekahta. Because the total thickness of the Minnekahta is only about 20-40 ft (fig. 2), outcrops generally occur over relatively short stream reaches and are difficult to bracket with measurement sites. Loss thresholds for the other 21 streams listed in table 36 also may include alluvial losses, which are assumed to be small relative to bedrock losses, based on field observations by the authors.

Table 35. Calculations of streamflow losses for Bear Butte Creek

[ft^3/s, cubic feet per second; ( ), losses between specified sites calculated by performing indicated arithmetic operations; u/s, upstream; d/s, downstream; --, no data available]

Date	Upstream station site 77		Intermediate station site 78		Upstream tributary site 79		Intermediate station site 80		Upstream tributary site 81	
	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	Time, in hours	Flow, in ft^3/s
5-04-94	--	63	--	--	--	--	--	--	--	--
4-25-96	0725	29.0	1155	25.1	1105	5.68	1410	25.4	1320	1.40
5-07-96	1235	19.2	1020	15.4	1115	1.40	1245	14.0	1150	0.84

Date	Upstream tributary site 82		Downstream station site 83		Loss to Madison, in ft^3/s (77 - 78)	Loss to u/s Minnelusa, in ft^3/s (78 + 79 - 80)	Loss to d/s Minnelusa[1], in ft^3/s (80 + 81 + 82 - 83)	Total loss to Minnelusa[1], in ft^3/s (78 + 79 + 81 + 82 - 83)	Total loss, in ft^3/s (77 + 79 + 81 + 82 - 83)
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s					
5-04-94	--	--	1345	80.4	--	--	--	--	--
4-25-96	1340	1.32	1505	24.6	3.9	5.4	3.5	8.9	12.8
5-07-96	1215	0.99	1340	11.0	3.8	2.8	4.8	7.6	11.4
				Mean loss	3.8	4.1	4.2	8.2	12.1
				Median loss	3.8	4.1	4.2	8.2	12.1

[1]May include losses to the Minnekahta Limestone.

Table 36. Summary of approximate loss thresholds from Black Hills streams to bedrock aquifers

[ft3/s, cubic feet per second; --, data not available; e, estimated; >, greater than; <, less than; Ddwd, Deadwood Formation; Mdsn, Madison Limestone; Mnls, Minnelusa Formation; Mnkt, Minnekahta Limestone]

Stream name	Bedrock aquifers within measurement reach	Approximate loss thresholds to bedrock aquifers (ft^3/s)			
		Total loss	Mdsn loss	Mnls loss	Mnkt loss
Beaver Creek[1]	Ddwd[2], Mdsn, Mnls, Mnkt	5	--	--	--
Reaves Gulch	Ddwd[2], Mdsn	>.2	>0.2	--	--
Highland Creek	Ddwd[2], Mdsn, Mnls, Mnkt	e10	--	--	--
South Fork Lame Johnny Creek[3]	Ddwd, Mdsn, Mnls, Mnkt[2]	1.4	--	--	--
North Fork Lame Johnny Creek	Ddwd, Mdsn	2.3	--	--	--
French Creek	Ddwd[2], Mdsn, Mnls, Mnkt[2]	15	11	4	--
Battle Creek	Ddwd[2], Mdsn	12	12	--	--
Grace Coolidge Creek	Ddwd[2], Mdsn, Mnls	21	18	3	--
Bear Gulch[1]	Ddwd[2], Mdsn	.4	--	--	--
Spokane Creek	Ddwd, Mdsn, Mnls, Mnkt	2.2	--	--	--
Spring Creek	Mdsn, Mnls, Mnkt	28	21	3	4
Rapid Creek	Ddwd[2], Mdsn, Mnls	10	--	--	--
Victoria Creek	Ddwd, Mdsn	1.0	--	--	--
Boxelder Creek	Mdsn, Mnls, Mnkt	50	>25	<20	<5
Elk Creek	Ddwd, Mdsn, Mnls, Mnkt[2]	19	11	8	--
Little Elk Creek	Ddwd[2], Mdsn, Mnls, Mnkt[2]	3.3	.7	2.6	--
Bear Gulch[4]	Ddwd[2], Mdsn, Mnls, Mnkt	4	--	--	--
Beaver Creek[4]	Ddwd[2], Mdsn, Mnls, Mnkt	9	--	--	--
Iron Creek	Ddwd[2], Mdsn	0	--	--	--
Spearfish Creek	Ddwd[2], Mdsn, Mnls	[5]23	--	--	--
Higgins Gulch	Mnls, Mnkt[2]	0	--	0	0
False Bottom Creek	Ddwd[2], Mdsn, Mnls, Mnkt	e15	1.4	7.2	e7
Whitewood Creek	Ddwd[2], Mdsn, Mnls, Mnkt[2]	0	--	--	--
Bear Butte Creek	Ddwd[2], Mdsn, Mnls, Mnkt[2]	12	4	8	--

[1]Located in southern Black Hills.
[2]Only part of outcrop is located within measurement reach.
[3]Includes Flynn Creek.
[4]Located in northern Black Hills.
[5]Includes thresholds of 21 ft^3/s in the main-stem channel and 2 ft^3/s in the diversion aqueduct.

Most of the stream reaches considered include outcrops of the Deadwood Formation (table 36). Many of the upstream measurement sites are located immediately upstream from the outcrop of the Madison Limestone; however, in some cases the entire Deadwood section is included within the measurement reach. Streamflow measurements indicate that losses to the Deadwood Formation are minimal along Boxelder Creek (table 21). Qualitative information for several other streams also indicates that losses to the Deadwood probably are minimal. Meadow Creek (tributary to Elk Creek) and Little Elk Creek both have relatively long stream reaches within outcrops of the Deadwood (fig. 27). Both streams have perennial, or nearly perennial flow within the Deadwood reaches and field observations have indicated no apparent loss zones. Similarly, the channel of Spearfish Creek is incised into the Deadwood Formation for many miles upstream from the outcrop of the Madison Limestone (fig. 29). Streamflow records for several gaging stations along upper Spearfish Creek and its tributaries (not considered within this report) indicate that streamflow gains consistently occur. Thus, it is concluded that streamflow losses to the Deadwood Formation generally are minimal.

FACTORS AFFECTING LOSS RATES

Previous investigators have offered various hypotheses regarding factors that may affect streamflow losses to bedrock outcrops. Gries (1969) hypothesized that loss rates may be proportional to the rate of streamflow. Crooks (1968) and Gries (1969) also hypothesized that loss rates may decrease after extended periods of flow across a loss zone. Potential effects of flow rate and duration of flow are discussed in the following sections for selected streams for which relevant data are available.

South Fork Lame Johnny Creek (including Flynn Creek)

Although few flow measurements are available for the South Fork of Lame Johnny Creek and Flynn Creek (table 8), the limited evidence indicates that loss rates are not affected by the flow rate or duration of flow. Measured flows downstream from the loss zone (site 8) ranged from 1.20 to 30.9 ft^3/s, while calculated losses ranged from only 0.63 to 3.44 ft^3/s. Because the smallest and largest losses both were associated with the higher flow rates, there is little indication that loss rates are affected by the flow rate. In addition, various reports from several observers and hydrographers indicate that the South Fork of Lame Johnny Creek flowed nearly continuously through the loss zone from June 1995, through May 1996; however, available measurement data (table 8) provides no indication that the loss rate decreased during this time. Thus, it is concluded that losses on South Fork Lame Johnny Creek and Flynn Creek are not measurably affected by flow rate or duration of flow through the loss zone.

French Creek

Hydrographs of daily streamflow for site 11 are presented in figure 32. Hydrographs are presented for selected water years with sustained periods of high flow, for which multiple individual measurements of losses are available. Measured losses for specific dates (table 10), as well as the approximate loss threshold of 15 ft^3/s for French Creek, also are shown in figure 32. Measured loss rates during WY91 decrease with time; however, measured losses for WY84, 93, 95, and 96 are nearly constant during extended periods of flow through the loss zone. It also is evident that, with the possible exception of WY91, measured losses are independent of upstream flow. Thus, considering all of the available data collectively, it is concluded that loss rates for French Creek generally are unaffected by flow rate or duration of flow.

Battle Creek

A hydrograph of daily streamflow for WY96 for site 14 is presented in figure 33. Measured losses to the Madison Limestone for specific dates and the estimated loss threshold to the Madison (table 11) also are shown. WY96 is the only period for which multiple measurements of losses to the Madison Limestone along Battle Creek are available. The first three measured losses are very near the approximate threshold of 12 ft^3/s; however, the fourth measured loss for WY96 is slightly lower, at about 10 ft^3/s. Thus, with the exception of the fourth measurement, loss rates probably are not affected by flow rate or duration of flow. Because flow at the upstream station was less than the approximate threshold for the fourth measurement, it is possible that there may be a narrow flow range for which the loss threshold is smaller.

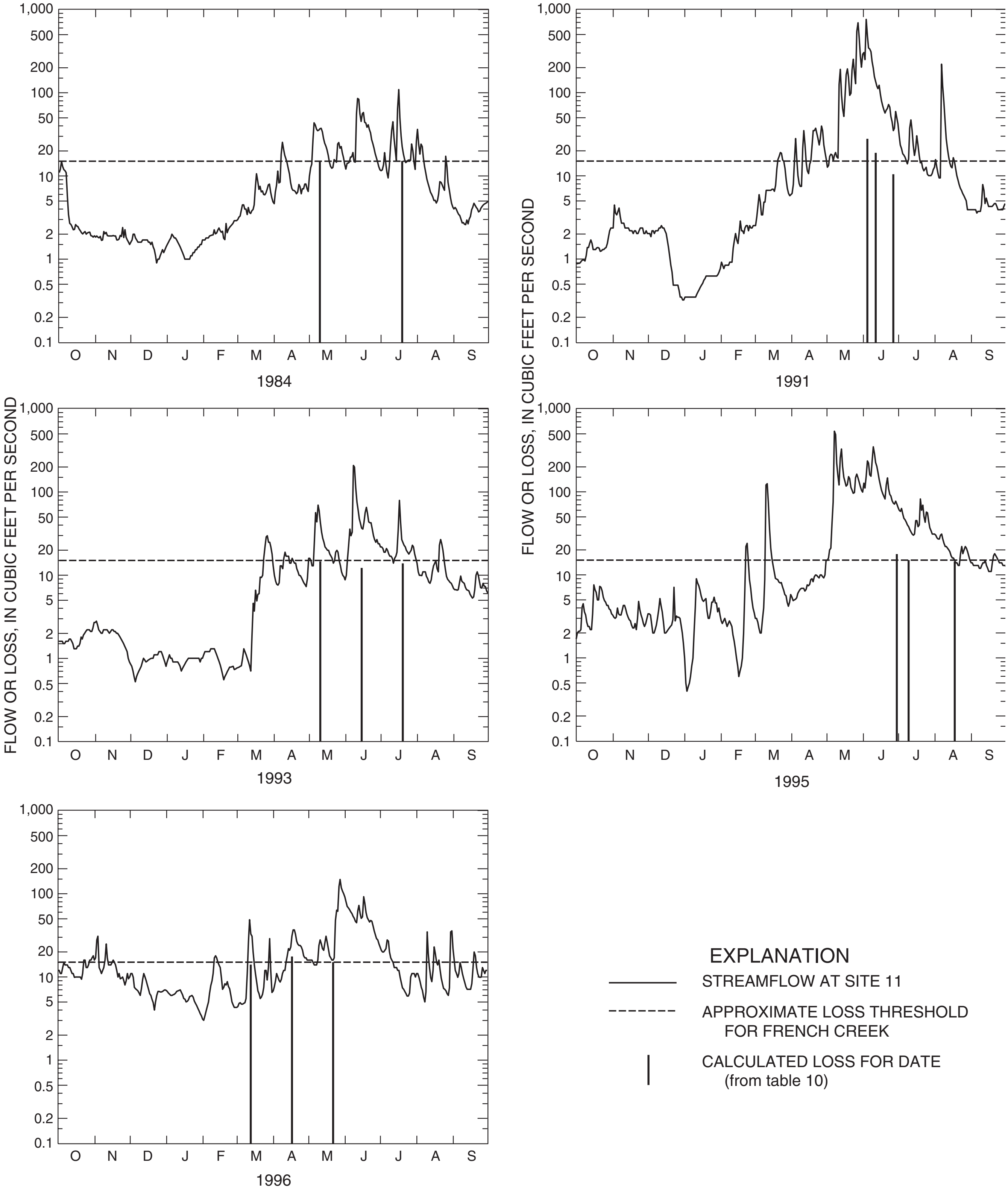


Figure 32. Daily hydrographs for site 11 (French Creek near Fairburn), relative to calculated losses (sites 11-13) for selected water years.

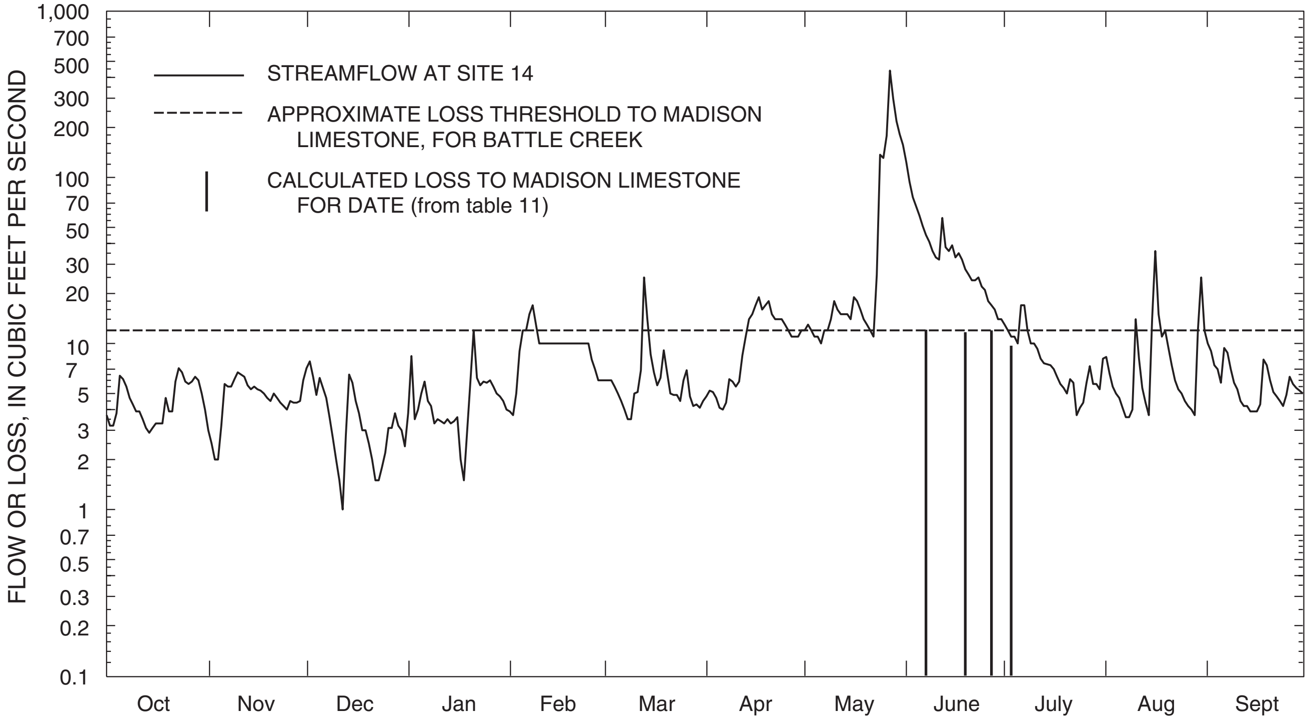


Figure 33. Daily hydrographs for site 14 (Battle Creek near Keystone), relative to calculated losses to the Madison Limestone (sites 14-15), water year 1996.

Grace Coolidge Creek

A hydrograph of daily streamflow for WY96 for site 17 is presented in figure 34. Measured losses to the Madison Limestone for specific dates and the approximate loss threshold to the Madison (table 12) also are shown. WY96 is the only water year for which more than two finite loss calculations to the Madison Limestone along Grace Coolidge Creek are available. Although measured losses during WY96 are somewhat variable, there is insufficient evidence to conclude that loss rates to the Madison Limestone along Grace Coolidge Creek are affected by flow rate or duration of flow.

As discussed in a previous section on Grace Coolidge Creek, measured losses during WY90-95 are significantly smaller than during WY78 (table 13) and WY96 (table 12). The apparent change in loss rates during WY90-95 probably resulted from deposition of large quantities of fine-grained sediment mobilized after the Galena Fire, as previously discussed.

Measured losses to the Madison Limestone for WY90-95 (table 12) are plotted in figure 35 as a function of flow at site 17. The losses are quite variable, ranging from 4.6 to 10.3 ft^3/s, and cannot be related to flow rate with a regression line. Thus, there is no evidence that loss rates to the Madison along Grace Coolidge Creek during WY90-95 were affected by upstream flow rates.

Spring Creek

A hydrograph of daily streamflow for site 24 for WY96, measured losses used in calculation of the mean and median values (table 16), and the approximate bedrock loss threshold of 28 ft^3/s are presented in figure 36. The first three measured losses for WY96 are very similar to the approximate loss threshold; the fourth measured loss of 23.7 ft^3/s on August 19 is slightly smaller. The smaller loss rate on August 19 probably can be attributed to effects of changes in channel or alluvial storage associated with attenuation of a small peak at site 24 during August 16-20 (fig. 18). Thus, it is concluded that loss rates are unaffected by duration of flow through the loss zone area.

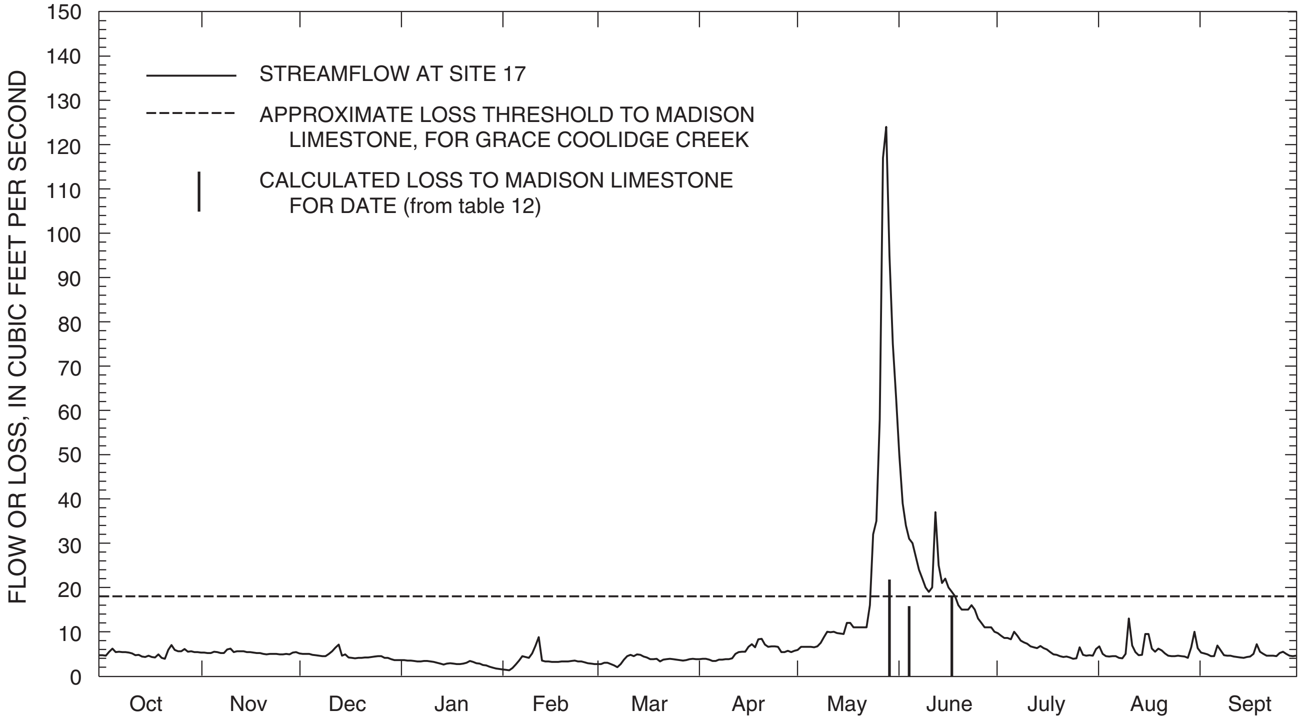


Figure 34. Daily hydrographs for site 17 (Grace Coolidge Creek near Game Lodge), relative to calculated losses to the Madison Limestone (sites 17-18), water year 1996.

Total bedrock loss values for Spring Creek are plotted in figure 37, as a function of streamflow at site 24. Figure 37 includes all losses used in the calculation of mean and median loss values (table 16). The linear regression line has a small, positive slope, which results primarily from an anomalously large loss value of 46 ft^3/s measured on May 14, 1993. Thus, it is concluded that bedrock losses for Spring Creek generally are not affected by upstream flow rates.

Rapid Creek

Monthly streamflow losses for Rapid Creek between sites 30 and 33 for WY89-96 were presented previously in figure 23. Monthly losses during WY89-92 generally were about 10 ft^3/s; however, losses during WY93-96 generally were about 8 ft^3/s, except during periods affected by tributary inflows. As discussed in the previous section on Rapid Creek, precipitation within the Rapid Creek drainage was larger during WY93-96 than during WY89-92, which probably resulted in increased springflow and increased tributary inflow. Thus, the apparent decrease in loss rate for Rapid Creek, which flows nearly continuously through its loss zone, probably is unrelated to duration of flow.

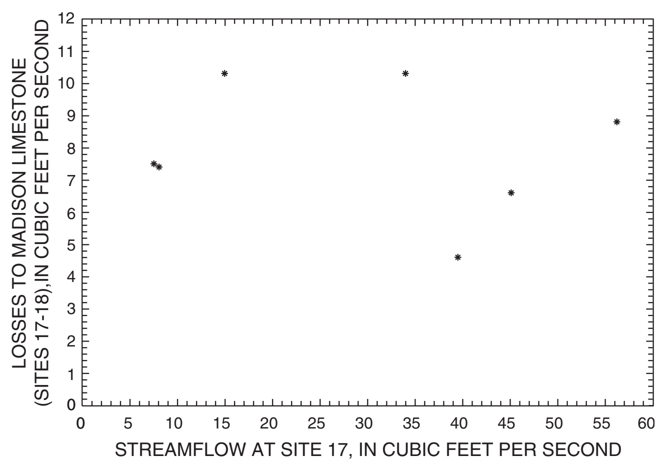


Figure 35. Calculated losses to the Madison Limestone for Grace Coolidge Creek (sites 17-18), as a function of streamflow at site 17, water years 1990-95.

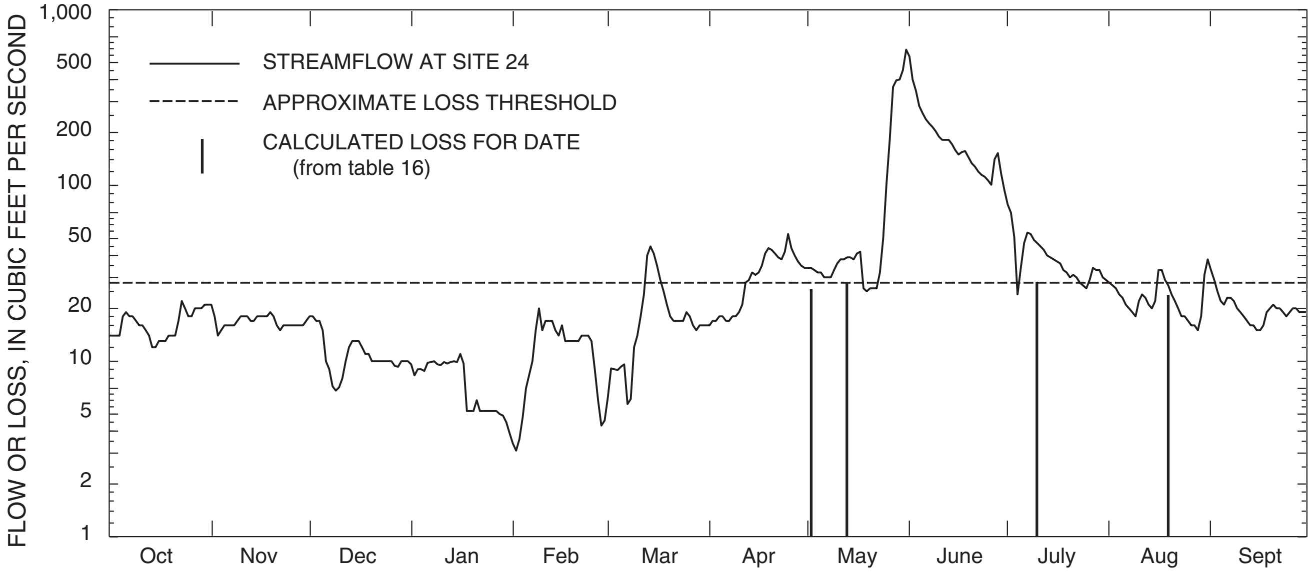


Figure 36. Daily hydrographs for site 24 (Spring Creek near Keystone), relative to calculated losses (sites 17-18), water year 1996.

Monthly losses for Rapid Creek were previously shown to be inversely related to streamflow (fig. 21). Annual loss rates generally decrease during periods of increased precipitation (fig. 20) because of increased tributary inflow and ground-water discharge. Calculated monthly losses and streamflow (fig. 21) are poorly related ($r^2 = 0.39$) because streamflow is controlled by releases from Pactola Reservoir. Although calculated losses are somewhat related to flow rate, the actual bedrock loss rate does not appear to be affected by streamflow of Rapid Creek.

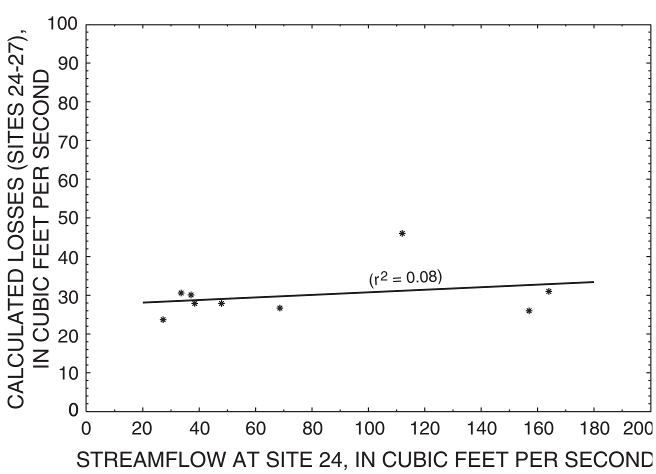


Figure 37. Calculated losses for Spring Creek (sites 24-27), as a function of streamflow at site 24 (Spring Creek near Keystone).

Boxelder Creek and Elk Creek

As discussed in previous sections, springflow is known to occur within the outcrops of the Madison Limestone and Minnelusa Formation along both Boxelder Creek and Elk Creek. In the case of both streams, streamflow gains have been observed across various subreaches, which shows that ground-water discharge (springflow) within a loss zone can have a significant effect on calculated loss rates. Although calculated (net) loss rates are shown to decrease as a result of springflow during prolonged, wet climatic conditions, it has not been determined whether actual loss rates decrease as well. Stream reaches with large adjacent outcrops of the Madison Limestone and Minnelusa Formation, such as Boxelder Creek and Elk Creek, have potential for large springflow within the loss zones, because of large potential for localized recharge from precipitation.

Summary of Factors

Considering information for all stream reaches collectively, it is concluded that bedrock losses generally are not measurably affected by flow rates or duration of flow through loss zones. Calculated losses for measurements made during high-flow conditions generally have larger variability than calculated losses during low-flow conditions; however, consistent relations between loss rates and flow rates have not been identified. Some of this variability probably results from decreased measurement accuracy during high flows. Additional variability also can be caused by tributary inflows and changes in channel and alluvial storage that may occur during high-flow conditions.

Calculated loss rates are shown to decrease, in some cases, during periods of extended flow through loss zones. Decreased (net) loss rates, however, generally can be attributed to springflow within a loss zone, which occurs during prolonged periods of wet climatic conditions. Stream reaches with large adjacent outcrops of the Madison Limestone and Minnelusa Formation, which have large potential for localized recharge, have the greatest potential for large springflow within loss zones. Rapid Creek provides additional evidence that effects of localized recharge on adjacent outcrop areas may be a larger factor than duration of flow through a loss zone. Rapid Creek flows nearly continuously through its loss zone; however, the loss rate in Rapid Creek is relatively constant. Although outcrop areas of the Madison and Minnelusa adjacent to Rapid Creek are small, relative to Boxelder Creek and Elk Creek, slight decreases in the net loss rate for Rapid Creek are discernible during prolonged periods of wet climatic conditions.

SUMMARY AND CONCLUSIONS

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. When streamflow exceeds this threshold, flow is maintained through loss zones located within bedrock outcrops. 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 ft^3/s. Loss thresholds generally are shown to be relatively constant, without measurable effects from flow rate or duration of flow through loss zones.

Although most losses occur within outcrops of the Madison Limestone and Minnelusa Formation, small losses may occur to other bedrock outcrops. It is concluded that losses to the Deadwood Formation probably are minimal. Losses to the Minnekahta Limestone generally are small, relative to losses to the Madison and Minnelusa; however, they are difficult to quantify because of potential losses to extensive alluvial deposits that commonly are located near Minnekahta outcrops. Potential losses to aquifers in the Inyan Kara Group were not investigated.

Streamflow losses are calculated by subtracting downstream flow from upstream flow (plus inflows, when applicable), which yields a positive residual for net losses. Several variables can affect loss calculations; however, the effects of many of these variables generally are small relative to streamflow losses that may occur to bedrock outcrops. Differences between alluvial inflows and outflows are assumed to be negligible. This assumption generally is valid, except for streams in which the extent of alluvial deposits varies significantly from upstream to downstream. A larger potential source of error is the inability to distinguish bedrock losses from losses to alluvial deposits. Losses that occur when initially filling unsaturated alluvial deposits downstream from loss zones can be especially large, with documented losses to alluvial deposits in the range of tens of cubic feet per second and storage capacities in the range of hundreds of acre-feet. The inability to account for tributary inflow, springflow, and changes in channel and alluvial storage also can cause large errors in calculations of bedrock losses.

Although bedrock loss thresholds are concluded to be relatively constant, losses calculated using individual measurements or flow records for any given stream can exhibit considerable variability. Most of this variability probably results from an inability to accurately account for all of the variables involved. Calculated losses for long stream reaches, especially those with extensive alluvial deposits, generally have the largest variability. It also is evident that calculated losses for measurements made during high-flow conditions have larger variability than calculated losses for low-flow conditions; however, consistent relations between losses and streamflow have not been identified. Calculated losses are shown to decrease, in some cases, during periods of extended flow through loss zones; however, this decrease generally can be attributed to springflow (ground-water discharge) within a loss zone, which may occur during prolonged periods of wet climatic conditions. In several cases, streamflow gains are documented that can be attributed to springflow within loss zones. Stream reaches with large adjacent outcrops of the Madison Limestone and Minnelusa Formation, which have large potential for localized recharge, are shown to have the greatest potential for large springflow within loss zones.

Changes in loss thresholds that have resulted from changes in channel conditions are documented for three streams. The loss threshold for Grace Coolidge Creek probably was reduced by deposition of large quantities of fine-grained sediment mobilized after the Galena Fire, which occurred during July 1988. Streamflow losses along Spring Creek apparently were temporarily reduced as a result of efforts to seal the channel with bentonite and rocks during 1937-40. Historic accounts by Newton and Jenney (1880) document losses on Whitewood Creek that no longer occur, possibly as a result of deposition of mine tailings into Whitewood Creek.

SELECTED REFERENCES

Brown, C.B., 1944, Report on an investigation of water losses in streams flowing east out of the Black Hills, South Dakota: U.S. Soil Conservation Service, Special Report 8, 45 p.

Buchanan, T.J., and Somers, W.P., 1969, Discharge measurements at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A8, 65 p.

Crooks, T.J., 1968, Water losses and gains across the Pahasapa Limestone, Box Elder Creek, Black Hills, South Dakota: Rapid City, South Dakota School of Mines and Technology, unpublished M.S. thesis, 22 p.

DeWitt, Ed., Redden, J.A., Buscher, David., and Wilson, A.B., 1989, Geologic map of the Black Hills area, South Dakota and Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-1910.

Dodge, Lt. Col. R. Irving, 1876, The Black Hills: New York, J. Miller, 151 p.

Downey, J.S., and Dinwiddie, G.A., 1988, The regional aquifer system underlying the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming-Summary: U.S. Geological Survey Professional Paper 1402-A, 64 p.

Driscoll, D.G., 1987, Water yield and streamflow characteristics of Rapid Creek above Rapid City, South Dakota: Rapid City, South Dakota School of Mines and Technology, unpublished M.S. thesis, 116 p.

———1992, Plan of study for the Black Hills Hydrology Study, South Dakota: U.S. Geological Survey Open-File Report 92-84, 10 p.

Driscoll, D.G., Bradford, W.L., and Neitzert, K.M., 1996, Selected hydrologic data, through water year 1994, Black Hills Hydrology Study, South Dakota: U.S. Geological Survey Open-File Report 96-399, 162 p.

Driscoll, D.G., and Hayes, T.S., 1995, Arsenic loads in Spearfish Creek, western South Dakota, water years 1989-91: U.S. Geological Survey Water-Resources Investigations Report 95-4080, 28 p.

Feldman, R.M., and Heimlich, R.A., 1980, The Black Hills: K/H Geology Field Guide Series, Kendall/Hunt Publishing Company, Kent State University, Kent, Ohio, 190 p.

Goddard, K.E., 1989, Composition, distribution, and hydrologic effects of contaminated sediments resulting from the discharge of gold milling wastes to Whitewood Creek at Lead and Deadwood, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 87-4051, 76 p.

Greene, E.A., 1993, Hydraulic properties of the Madison aquifer system in the western Rapid City area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 93-4008, 56 p.

Gries, J.P., 1969, Investigations of water losses to sinkholes in the Pahasapa Limestone and their relation to resurgent springs, Black Hills, South Dakota: Project Completion Report A-0100-South Dakota FY 1969, 15 p.

Hines, G.K., 1991, Ground-water and surface-water interaction in a reach of Rapid Creek near Rapid City, South Dakota: Rapid City, South Dakota School of Mines and Technology, unpublished M.S. thesis, 86 p.

Johnson, B.N., 1933, A climatological review of the Black Hills: The Black Hills Engineer, Rapid City, South Dakota School of Mines and Technology, 71 p.

Kennedy, E.J., 1984, Discharge ratings at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A10, 59 p.

Klemp, J.A., 1995, Source aquifers for large springs in northwestern Lawrence County, South Dakota: Rapid City, South Dakota School of Mines and Technology, unpublished M.S. thesis, 175 p.

Kyllonen, D.P., and Peter, K.D., 1987, Geohydrology and water quality of the Inyan Kara, Minnelusa, and Madison aquifers of the northern Black Hills, South Dakota and Wyoming, and Bear Lodge Mountains, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 86-4158, 61 p.

Miller, L.D., and Driscoll, D.G., 1998, Streamflow characteristics for the Black Hills of South Dakota, through water year 1993: U.S. Geological Survey Water-Resources Investigations Report 97-4288, 322 p.

Newton, Henry, and Jenney, W.P., 1880, Report of the geology and resources of the Black Hills of Dakota: Washington, D.C., Government Printing Office, 566 p.

Novak, C.E., 1985, WRD Data Reports Preparation Guide: U.S. Geological Survey Water Resources Division, 199 p.

Peter, K.D., 1985, Availability and quality of water from the bedrock aquifers in the Rapid City area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 85-4022, 34 p.

Powell, B.F., 1940, Construction history and technical details of the Sheridan Dam: The Black Hills Engineer, Rapid City, South Dakota School of Mines and Technology, 261 p.

Rahn, P.H., and Gries, J.P., 1973, Large springs in the Black Hills, South Dakota and Wyoming: South Dakota Geological Survey Report of Investigations 107, 46 p.

Shortridge, C.G., 1953, The geological relationship of water loss and gain problems on Battle Creek near Hermosa, South Dakota: Rapid City, South Dakota School of Mines and Technology, unpublished M.S. thesis, 48 p.

Streeter, V.L., and Wylie, B.E., 1985, Fluid Mechanics: New York, McGraw-Hill, Inc., 586 p.

U.S. Department of Commerce, 1996, Climatological data for South Dakota, annual summary: Asheville, North Carolina (issued annually).

U.S. Geological Survey, 1967-75, Water resources data for South Dakota, 1966-74—part 1. Surface-water records (published annually).

———1976-97, Water resources data for South Dakota, water years 1975-96: U.S. Geological Survey Water Data Reports SD-75-1 to SD-96-1 (published annually).

Whitesides, D.H., 1989, Geomorphologic effects of the Galena forest fire in Custer State Park, South Dakota: Rapid City, South Dakota School of Mines and Technology, unpublished M.S. thesis, 96 p.

SUPPLEMENTAL INFORMATION

Table 37. Daily flow data, in cubic feet per second, used in estimation of losses for Highland Creek

[ft^3/s, cubic feet per second; ( ), values calculated by performing indicated arithmetic operation]

Date	(1) Flow at site 5	(2) Estimated bedrock springflow	(3) Calculated flow above spring (col. 1 - col. 2)	(4) Flow at site 1	(5) Beaver Creek flow below loss zone (col. 4 - 5 ft^3/s)	(6) Estimated tributary inflow (col. 3 - col. 5)	(7) Estimated flow at site 4
5-1-95	11	11	0	3.1	0	0	2
5-2-95	11	11	0	3.4	0	0	3
5-3-95	10	10	0	3.9	0	0	3
5-4-95	10	10	0	4.9	0	0	3
5-5-95	11	11	0	4.9	0	0	3
5-6-95	11	11	0	5.4	0	-0	3
5-7-95	11	11	0	6.4	1	-1	4
5-8-95	12	12	0	6.6	2	-2	4
5-9-95	11	11	0	6.3	1	-1	4
5-10-95	11	11	0	8.1	3	-3	4
5-11-95	11	11	0	9.9	5	-5	5
5-12-95	11	11	0	11	6	-6	6
5-13-95	12	12	0	8.2	3	-3	4
5-14-95	11	11	0	8.8	4	-4	5
5-15-95	11	11	0	13	8	-8	6
5-16-95	11	11	0	12	7	-7	6
5-17-95	11	11	0	10	5	-5	5
5-18-95	11	11	0	12	7	-7	6
5-19-95	11	11	0	12	7	-7	6
5-20-95	11	11	0	13	8	-8	6
5-21-95	11	11	0	18	13	-13	8
5-22-95	11	11	0	14	9	-9	7
5-23-95	11	11	0	13	8	-8	6
5-24-95	11	11	0	15	10	-10	7
5-25-95	11	11	0	15	10	-10	7
5-26-95	12	12	0	18	13	-13	8
5-27-95	11	11	0	17	12	-12	8
5-28-95	11	11	0	19	14	-14	8
5-29-95	11	11	0	21	16	-16	9
5-30-95	11	11	0	25	20	-20	11
5-31-95	11	11	0	26	21	-21	11
6-1-95	11	11	0	29	24	-24	12
6-2-95	11	11	0	33	28	-28	14
6-3-95	12	12	0	30	25	-25	12
6-4-95	13	13	0	28	23	-23	12
6-5-95	12	12	0	31	26	-26	13
6-6-95	12	12	0	36	31	-31	15

Table 37. Daily flow data, in cubic feet per second, used in estimation of losses for Highland Creek —Continued

[ft^3/s, cubic feet per second; ( ), values calculated by performing indicated arithmetic operation]

Date	(1) Flow at site 5	(2) Estimated bedrock springflow	(3) Calculated flow above spring (col. 1 - col. 2)	(4) Flow at site 1	(5) Beaver Creek flow below loss zone (col. 4 - 5 ft^3/s)	(6) Estimated tributary inflow (col. 3 - col. 5)	(7) Estimated flow at site 4
6-7-95	12	12	0	33	28	-28	14
6-8-95	12	12	0	34	29	-29	14
6-9-95	14	14	0	61	56	-56	24
6-10-95	47	16	31	85	80	-49	33
6-11-95	45	16	29	71	66	-37	28
6-12-95	42	16	26	59	54	-28	23
6-13-95	42	16	26	52	47	-21	21
6-14-95	41	16	25	45	40	-15	18
6-15-95	39	16	23	37	32	-9	15
6-16-95	36	16	20	33	28	-8	14
6-17-95	35	16	19	30	25	-6	12
6-18-95	33	16	17	27	22	-5	11
6-19-95	32	16	16	25	20	-4	11
6-20-95	30	16	14	23	18	-4	10
6-21-95	33	16	17	24	19	-2	10
6-22-95	41	16	25	36	31	-6	15
6-23-95	41	16	25	31	26	-1	13
6-24-95	38	16	22	27	22	0	11
6-25-95	40	16	24	30	25	-1	12
6-26-95	36	16	20	23	18	2	10
6-27-95	33	16	17	21	16	1	9
6-28-95	35	16	19	26	21	-2	11
6-29-95	40	16	24	31	26	-2	13
6-30-95	37	16	21	24	19	2	10
7-1-95	33	16	17	21	16	1	9
7-2-95	31	16	15	20	15	0	9
7-3-95	32	16	16	20	15	1	9
7-4-95	29	16	13	19	14	-1	8
7-5-95	28	16	12	17	12	0	8
7-6-95	26	16	10	16	11	-1	7
7-7-95	25	16	9	15	10	-1	7
7-8-95	24	16	8	15	10	-2	7
7-9-95	23	16	7	14	9	-2	7
7-10-95	23	16	7	14	9	-2	7
7-11-95	22	16	6	13	8	-2	6
7-12-95	22	16	6	13	8	-2	6
7-13-95	22	16	6	13	8	-2	6

Table 37. Daily flow data, in cubic feet per second, used in estimation of losses for Highland Creek —Continued

[ft^3/s, cubic feet per second; ( ), values calculated by performing indicated arithmetic operation]

Date	(1) Flow at site 5	(2) Estimated bedrock springflow	(3) Calculated flow above spring (col. 1 - col. 2)	(4) Flow at site 1	(5) Beaver Creek flow below loss zone (col. 4 - 5 ft^3/s)	(6) Estimated tributary inflow (col. 3 - col. 5)	(7) Estimated flow at site 4
7-14-95	22	16	6	13	8	-2	6
7-15-95	22	16	6	13	8	-2	6
7-16-95	28	16	12	19	14	-2	8
7-17-95	28	16	12	21	16	-4	9
7-18-95	27	16	11	18	13	-2	8
7-19-95	27	16	11	20	15	-4	9
7-20-95	30	16	14	25	20	-6	11
7-21-95	30	16	14	20	15	-1	9
7-22-95	28	16	12	19	14	-2	8
7-23-95	29	16	13	19	14	-1	8
7-24-95	27	16	11	16	11	0	7
7-25-95	26	16	10	17	12	-2	8
7-26-95	28	16	12	20	15	-3	9
7-27-95	26	16	10	15	10	0	7
7-28-95	24	16	8	13	8	0	6
7-29-95	22	16	6	12	7	-1	6
7-30-95	21	16	5	12	7	-2	6
7-31-95	21	16	5	11	6	-1	6
8-1-95	21	16	5	12	7	-2	6
8-2-95	20	16	4	11	6	-2	6
8-3-95	19	16	3	10	5	-2	5
8-4-95	19	16	3	9.8	5	-2	5
8-5-95	18	16	2	9.8	5	-3	5
8-6-95	18	16	2	10	5	-3	5
8-7-95	18	16	2	9.8	5	-3	5
8-8-95	18	16	2	9.0	4	-2	5
8-9-95	17	16	1	8.3	3	-2	5
8-10-95	16	16	0	8.2	3	-3	4
8-11-95	16	16	0	7.7	3	-3	4
8-12-95	16	16	0	7.7	3	-3	4
8-13-95	15	15	0	7.7	3	-3	4
8-14-95	15	15	0	6.8	2	-2	4
8-15-95	15	15	0	6.5	2	-2	4
8-16-95	15	15	0	6.5	2	-2	4
8-17-95	15	15	0	6.2	1	-1	4
8-18-95	15	15	0	5.7	1	-1	4
8-19-95	15	15	0	5.7	1	-1	4

Table 37. Daily flow data, in cubic feet per second, used in estimation of losses for Highland Creek —Continued

[ft^3/s, cubic feet per second; ( ), values calculated by performing indicated arithmetic operation]

Date	(1) Flow at site 5	(2) Estimated bedrock springflow	(3) Calculated flow above spring (col. 1 - col. 2)	(4) Flow at site 1	(5) Beaver Creek flow below loss zone (col. 4 - 5 ft^3/s)	(6) Estimated tributary inflow (col. 3 - col. 5)	(7) Estimated flow at site 4
8-20-95	14	14	0	5.4	0	0	3
8-21-95	14	14	0	5.4	0	0	3
8-22-95	14	14	0	5.4	0	0	3
8-23-95	14	14	0	6.1	1	-1	4
8-24-95	14	14	0	7.4	2	-2	4
8-25-95	13	13	0	6.5	2	-2	4
8-26-95	23	14	9	14	9	0	7
8-27-95	16	14	2	12	7	-5	6
8-28-95	15	14	1	9.4	4	-3	5
8-29-95	14	14	0	8.5	4	-4	4
8-30-95	13	13	0	7.4	2	-2	4
8-31-95	14	14	0	6.8	2	-2	4
9-1-95	14	14	0	6.5	2	-2	4
9-2-95	14	14	0	6.2	1	-1	4
9-3-95	13	13	0	5.7	1	-1	4
9-4-95	14	14	0	5.7	1	-1	4
9-5-95	14	14	0	5.9	1	-1	4
9-6-95	13	13	0	5.6	1	-1	4
9-7-95	13	13	0	5.2	0	0	3
9-8-95	13	13	0	5.2	0	0	3
9-9-95	13	13	0	5.2	0	0	3
9-10-95	13	13	0	5.2	0	0	3
9-11-95	13	13	0	7.5	2	-2	4
9-12-95	13	13	0	6.1	1	-1	4
9-13-95	13	13	0	5.2	0	0	3
9-14-95	13	13	0	5.0	0	0	3
9-15-95	13	13	0	4.9	0	0	3
9-16-95	13	13	0	4.5	0	0	3
9-17-95	13	13	0	4.5	0	0	3
9-18-95	13	13	0	5.0	0	0	3

Table 38. Daily streamflow and calculated losses, in cubic feet per second, for selected sites on Grace Coolidge Creek, water year 1978

[( ), values calculated by performing indicated arithmetic operation; --, no data available]

Date	Flow at site 17	Flow at site 18	Loss to Madison (17 - 18)	Flow at site 19	Loss to Minnelusa (18 - 19)	Total loss (17 - 19)
5-1-78	40	--	--	0	--	--
5-2-78	31	--	--	0	--	--
5-3-78	25	--	--	0	--	--
5-4-78	54	--	--	0	--	--
5-5-78	61	--	--	5.7	--	55
5-6-78	64	--	--	19	--	45
5-7-78	59	--	--	22	--	37
5-8-78	55	--	--	17	--	38
5-9-78	65	--	--	26	--	39
5-10-78	76	--	--	42	--	34
5-11-78	62	--	--	32	--	30
5-12-78	47	--	--	20	--	27
5-13-78	36	15	21	13	2	23
5-14-78	30	10	20	8	2	22
5-15-78	24	6.4	18	4.1	2.3	20
5-16-78	19	3.5	16	1.1	2.4	18
5-17-78	19	2.6	16	.06	2.5	19
[1]5-18-78	75	69	6	44	25	31
[1]5-19-78	68	65	3	43	22	25
[1]5-20-78	50	36	14	26	10	24
5-21-78	41	24	17	18	6	23
5-22-78	34	15	19	11	4	23
5-23-78	29	11	18	8.3	3	21
5-24-78	32	14	18	10	4	22
5-25-78	25	7.6	17	5.2	2.4	20
5-26-78	20	4.8	15	2.9	1.9	17
5-27-78	18	3.5	14	1.5	2.0	16
5-28-78	21	5.4	16	3.5	1.9	18
5-29-78	17	3.3	14	1.4	1.9	16
5-30-78	28	8.2	20	5.5	2.7	23
5-31-78	27	8.3	19	5.5	2.8	22
6-1-78	22	5.5	16	3.4	2.1	19
6-2-78	22	4.2	18	2.1	2.1	20
6-3-78	17	3.0	14	.97	2.0	16
6-4-78	17	2.2	15	.22	2.0	17
6-5-78	17	1.5	16	.04	1.5	17
6-6-78	16	.89	15	.01	.88	16
6-7-78	14	.1	14	0	--	--
6-8-78	13	0	--	0	--	--
6-9-78	11	0	--	0	--	--
6-10-78	10	0	--	0	--	--
		Mean loss	17		2	19
		Median loss	17		2	19

[1]Measurements excluded from mean and median calculations.

Table 39. Daily streamflow and calculated losses, in cubic feet per second, for selected sites on Grace Coolidge Creek, water year 1979

[( ), values calculated by performing indicated arithmetic operation; --, no data available]

Date	Flow at site 17	Flow at site 18	Loss to Madison (17 - 18)	Flow at site 19	Loss to Minnelusa (18 - 19)	Total loss (17 - 19)
7-1-79	2.1	0	--	0	--	--
7-2-79	1.8	0	--	0	--	--
7-3-79	2.7	0	--	0	--	--
7-4-79	104	61	43	36	25	68
7-5-79	58	17	41	8.2	9	50
7-6-79	29	2.8	26	.43	2.4	29
7-7-79	20	.10	20	0	--	--
7-8-79	19	0	--	0	--	--
7-9-79	14	0	--	0	--	--
7-10-79	11	0	--	0	--	--
7-11-79	8.2	0	--	0	--	--
7-12-79	7.2	0	--	0	--	--
7-13-79	17	0	--	0	--	--
7-14-79	10	0	--	0	--	--
7-15-79	7.5	0	--	0	--	--
7-16-79	25	0	--	0	--	--
7-17-79	29	0	--	0	--	--
7-18-79	18	0	--	0	--	--
7-19-79	15	0	--	0	--	--
7-20-79	12	0	--	0	--	--
7-21-79	11	0	--	0	--	--
7-22-79	11	0	--	0	--	--
7-23-79	14	0	--	0	--	--
7-24-79	23	0	--	0	--	--
7-25-79	21	0	--	0	--	--
7-26-79	19	0	--	0	--	--
7-27-79	28	0	--	0	--	--
7-28-79	35	0	--	0	--	--
7-29-79	36	1.4	35	.01	1.4	36
7-30-79	32	.32	32	0	--	--
7-31-79	52	15	37	7.8	7	44
8-1-79	39	8.4	31	5.6	2.8	33
8-2-79	39	2.8	36	.90	1.9	38
8-3-79	23	.20	23	0	--	--
8-4-79	20	0	--	0	--	--
8-5-79	18	0	--	0	--	--
8-6-79	15	0	--	0	--	--
8-7-79	15	0	--	0	--	--
8-8-79	16	0	--	0	--	--
8-9-79	2.0	0	--	0	--	--
8-10-79	9.6	0	--	0	--	--

Table 40. Calculations of total streamflow losses for Boxelder Creek, water years 1988-94

[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; --, no data available]

Date	Upstream station site 34		Downstream station site 38		Total loss, in ft^3/s (34 - 38)	Hydrograph changes[1]
	Time, in hours	Flow, in ft^3/s	Time, in hours	Flow, in ft^3/s		
1/04/88	1130	0.97	1340	0	>0.97	
3/24/88	1240	11.5	1400	0	>11.5	
4/19/88	1300	9.36	1425	0	>9.36	
6/21/88	1200	3.08	1300	0	>3.08	
8/30/88	0905	.72	1030	0	>.72	
11/28/88	1440	2.12	--	0	>2.12	
8/14/89	1300	.94	1100	0	>.94	
3/14/90	1345	10.9	1145	0	>10.9	
4/17/90	1215	9.69	1343	0	>9.69	
6/13/90	1130	7.34	1305	0	>7.34	
7/12/90	1025	2.56	1030	0	>2.56	
12/11/90	1200	1.60	0840	0	>1.60	
2/12/91	0835	1.09	1035	0	>1.09	
6/04/91	1255	106	1000	42.8	63	0%
6/07/91	1335	145	1050	115	30	-24%
3/05/92	0940	17.0	1312	0	>17.0	
5/11/92	1405	11.3	1140	0	>11.3	
6/09/92	0810	5.27	1500	0	>5.27	
12/02/92	1245	3.12	1155	0	>3.12	
2/09/94	0915	7.70	1415	0	>7.70	

[1]Hydrograph changes calculated using daily mean streamflow at site 34: [(current day - previous day) / previous day] x 100%.

Table 41. Monthly streamflow and calculated losses, in cubic feet per second, for Whitewood Creek, water years 1983-95

[( ), values calculated by performing indicated arithmetic operation]

Date	Flow at site 75	Flow at site 76	Total loss (75 - 76)
Nov-82	34.7	41.6	-6.9
Dec-82	20.2	20.3	-.1
Jan-83	17.1	12.5	4.6
Feb-83	16.0	18.0	-2.0
Mar-83	38.6	47.4	-8.8
Apr-83	101	108	-7
May-83	153	150	3
Jun-83	35.2	36.7	-1.5
Jul-83	21.5	23.1	-1.6
Aug-83	24.3	24.9	-.6
Sep-83	18.2	19.5	-1.3
Oct-83	16.6	19.5	-2.9
Nov-83	13.8	16.1	-2.3
Dec-83	8.90	10.3	-1.4
Jan-84	13.2	11.9	1.3
Feb-84	12.4	14.0	-1.6
Mar-84	18.4	20.5	-2.1
Apr-84	40.0	42.4	-2.4
May-84	213	129	84
Jun-84	102	101	1
Jul-84	29.4	31.2	-1.8
Aug-84	19.1	17.5	1.6
Sep-84	14.7	14.7	.0
Oct-84	13.6	16.5	-2.9
Nov-84	11.5	13.6	-2.1
Dec-84	11.4	12.8	-1.4
Jan-85	10.1	13.0	-2.9
Feb-85	9.40	12.0	-2.6
Mar-85	12.2	16.0	-3.8
Apr-85	20.6	22.2	-1.6
May-85	14.7	15.0	-.3
Jun-85	13.9	13.4	.5
Jul-85	10.4	10.6	-.2
Aug-85	11.8	9.45	2.4
Sep-85	10.7	11.4	-.7
Oct-85	12.5	13.0	-.5
Nov-85	10.3	9.85	.5
Dec-85	8.95	8.84	0.11
Jan-86	10.0	11.7	-1.8
Feb-86	12.0	14.6	-2.6
Mar-86	20.9	22.3	-1.4

Table 41. Monthly streamflow and calculated losses, in cubic feet per second, for Whitewood Creek, water years 1983-95 —Continued

[( ), values calculated by performing indicated arithmetic operation]

Date	Flow at site 75	Flow at site 76	Total loss (75 - 76)
Apr-86	66.6	69.2	-2.6
May-86	50.2	50.8	-.6
Jun-86	41.5	37.7	3.8
Jul-86	19.0	16.9	2.1
Aug-86	13.7	16.3	-2.6
Sep-86	16.4	16.5	-.1
Oct-86	15.1	16.2	-1.1
Nov-86	13.3	16.4	-3.1
Dec-86	10.7	14.6	-3.9
Jan-87	11.7	12.3	-.6
Feb-87	11.6	13.1	-1.5
Mar-87	15.9	18.5	-2.6
Apr-87	59.9	48.7	11.2
May-87	34.2	41.4	-7.2
Jun-87	18.9	30.0	-11.1
Jul-87	13.3	19.3	-6.0
Aug-87	13.5	17.2	-3.7
Sep-87	11.7	14.3	-2.6
Oct-87	11.3	14.8	-3.5
Nov-87	12.6	14.2	-1.6
Dec-87	12.0	13.9	-1.9
Jan-88	11.2	12.1	-.9
Feb-88	13.4	15.3	-1.9
Mar-88	16.5	22.8	-6.3
Apr-88	29.9	34.8	-4.9
May-88	62.1	60.5	1.6
Jun-88	20.2	24.1	-3.9
Jul-88	14.4	15.4	-1.0
Aug-88	11.5	12.3	-.8
Sep-88	13.2	15.0	-1.8
Oct-88	14.3	16.1	-1.8
Nov-88	14.2	15.8	-1.6
Dec-88	12.8	13.6	-.8
Jan-89	12.5	12.2	.3
Feb-89	14.5	13.6	.9
Mar-89	17.2	18.7	-1.5
Apr-89	23.6	26.3	-2.7
May-89	56.5	59.7	-3.2
Jun-89	21.1	22.0	-.9
Jul-89	17.7	16.0	1.7
Aug-89	14.2	12.7	1.5

Table 41. Monthly streamflow and calculated losses, in cubic feet per second, for Whitewood Creek, water years 1983-95 —Continued

[( ), values calculated by performing indicated arithmetic operation]

Date	Flow at site 75	Flow at site 76	Total loss (75 - 76)
Sep-89	14.5	13.2	1.3
Oct-89	11.5	13.0	-1.5
Nov-89	12.1	15.8	-3.7
Dec-89	9.57	10.4	-.8
Jan-90	11.8	13.5	-1.7
Feb-90	12.4	14.5	-2.1
Mar-90	19.0	21.9	-2.9
Apr-90	33.1	35.5	-2.4
May-90	47.5	52.7	-5.2
Jun-90	21.0	24.3	-3.3
Jul-90	14.6	18.3	-3.7
Aug-90	12.3	11.7	.6
Sep-90	10.4	10.9	-.5
Oct-90	11.3	14.2	-2.9
Nov-90	10.7	13.5	-2.8
Dec-90	9.91	7.63	2.28
Jan-91	10.1	10.6	-.5
Feb-91	11.4	14.3	-2.9
Mar-91	13.9	18.6	-4.7
Apr-91	23.0	27.4	-4.4
May-91	54.4	73.6	-19.2
Jun-91	60.3	55.6	4.7
Jul-91	14.4	15.6	-1.2
Aug-91	12.5	12.1	.4
Sep-91	10.6	11.1	-.5
Oct-91	10.7	11.4	-.7
Nov-91	11.5	14.2	-2.7
Dec-91	10.9	15.6	-4.7
Jan-92	9.31	14.5	-5.2
Feb-92	10.5	14.3	-3.8
Mar-92	14.7	15.5	-.8
Apr-92	20.2	23.7	-3.5
May-92	22.1	28.4	-6.3
Jun-92	17.4	19.1	-1.7
Jul-92	12.9	16.1	-3.2
Aug-92	10.3	12.4	-2.1
Sep-92	9.64	11.5	-1.9
Oct-92	8.90	11.3	-2.4
Nov-92	9.87	11.4	-1.5
Dec-92	9.10	8.58	.52
Jan-93	9.55	7.77	1.78

Table 41. Monthly streamflow and calculated losses, in cubic feet per second, for Whitewood Creek, water years 1983-95 —Continued

[( ), values calculated by performing indicated arithmetic operation]

Date	Flow at site 75	Flow at site 76	Total loss (75 - 76)
Feb-93	9.87	8.57	1.30
Mar-93	13.7	17.2	-3.5
Apr-93	33.6	44.4	-10.8
May-93	76.2	78.0	-1.8
Jun-93	104	79.3	25
Jul-93	30.5	31.4	-.9
Aug-93	17.7	19.8	-2.1
Sep-93	13.8	15.4	-1.6
Oct-93	14.1	15.5	-1.4
Nov-93	12.5	13.2	-.7
Dec-93	11.7	9.94	1.8
Jan-94	11.8	9.74	2.1
Feb-94	13.0	12.2	.8
Mar-94	38.8	49.5	-10.7
Apr-94	107	111	-4
May-94	83.3	81.0	2.3
Jun-94	24.7	22.8	1.9
Jul-94	13.7	18.8	-5.1
Aug-94	10.5	11.9	-1.4
Sep-94	9.41	11.3	-1.9
Oct-94	38.7	41.4	-2.7
Nov-94	16.0	18.3	-2.3
Dec-94	13.4	15.0	-1.6
Jan-95	11.7	14.5	-2.8
Feb-95	13.0	15.4	-2.4
Mar-95	18.5	21.2	-2.7
Apr-95	29.0	31.8	-2.8
May-95	291	384	-93
Jun-95	86.1	95.4	-9.3
Jul-95	37.0	38.9	-1.9
Aug-95	21.0	16.4	4.6
Sep-95	14.7	14.6	.1
		Mean loss	-2
		Median loss	-2