Prepared in cooperation with the State of South Dakota,
West Dakota Water Development District, and the
U.S. Department of Agriculture (Forest Service)

Hydrologic Effects of the 1988 Galena Fire, Black Hills Area, South Dakota

Water-Resources Investigations Report 03-4323




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By Daniel G. Driscoll and Janet M. Carter, U.S. Geological Survey, and Donald O. Ohlen, SAIC, EROS Data Center, Sioux Falls, South Dakota

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre	4,047	square meter
acre	0.4047	hectare
cubic foot per acre (ft^3/acre)	0.0700	cubic meters per hectare
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer
cubic yard (yd^3)	0.7646	cubic meter
foot (ft)	0.3048	meter
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer
tons per acre (tons/acre)	2.242	metric tons per hectare

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:

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29); horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

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

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ABSTRACT

The Galena Fire burned about 16,788 acres of primarily ponderosa pine forest during July 5-8, 1988, in the Black Hills area of South Dakota. The fire burned primarily within the Grace Coolidge Creek drainage basin and almost entirely within the boundaries of Custer State Park. A U.S. Geological Survey gaging station with streamflow records dating back to 1977 was located along Grace Coolidge Creek within the burned area. About one-half of the gaging station's 26.8-square-mile drainage area was burned. The drainage basin for Bear Gulch, which is tributary to Grace Coolidge Creek, was burned particularly severely, with complete deforestation occurring in nearly the entirety of the area upstream from a gaging station that was installed in 1989.

A study to evaluate effects of the Galena Fire on streamflow, geomorphology, and water quality was initiated in 1988. The geomorphologic and water-quality components of the study were completed by 1990 and are summarized in this report. A data-collection network consisting of streamflow- and precipitation-gaging stations was operated through water year 1998 for evaluation of effects on streamflow characteristics, including both annual-yield and peak-flow characteristics, which are the main focus of this report.

Moderately burned areas did not experience a substantial increase in the rate of surface erosion; however, severely burned areas underwent surficial erosion nearly twice that of the unburned areas. The sediment production rate of Bear Gulch estimated 8 to 14 months after the fire was 870 ft^3/acre (44 tons/acre). Substantial degradation of stream channels within the severely burned headwater areas of Bear Gulch was documented. Farther downstream, channel aggradation resulted from deposition of sediments transported from the headwater areas.

The most notable water-quality effect was on concentrations of suspended sediment, which were orders of magnitude higher for Bear Gulch than for the unburned control area. Effects on several other water-quality constituents, such as organic carbon and nitrogen and phosphorus nutrient constituents, probably were influenced by the large concentrations of suspended matter that were documented in initial post-fire, storm-flow events. The first post-fire stormflow produced the highest measured concentrations of specific conductance, nitrogen, phosphorus, organic carbon, calcium, magnesium, potassium, manganese, and sulfate in the burned areas. For most constituents sampled, differences in concentrations between burned and unburned areas were no longer discernible within about 1 year following the Galena Fire.

The effects of the Galena Fire on annual-yield characteristics of Grace Coolidge Creek were evaluated primarily from comparisons with long-term streamflow records for Battle Creek, which is hydrogeologically similar and is located immediately to the north. Annual yield for Grace Coolidge Creek increased by about 20 percent as a result of the fire. This estimate was based on relations between annual yield for Grace Coolidge Creek and Battle Creek for pre- and post-burn periods. Many of the post-burn data points are well

beyond the range of the pre-burn data, which is a source of uncertainty for this estimate.

Substantial increases in peak-flow characteristics for severely burned drainages were visually apparent from numerous post-fire field observations. Various analyses of streamflow data indicated substantial increases in peak-flow response for burned drainage areas; however, quantification of effects was particularly difficult because peak-flow response diminished quickly and returned to a generally pre-burn condition by about 1991. Field observations of vegetation and analysis of remotely sensed data indicated that establishment of grasses and forbs occurred within a similar timeframe. Comparison of pre-fire peak flows to post-1991 peak flows indicates that these grasses and forbs were equally effective in suppressing peak flows as the predominantly ponderosa pine forest was prior to the Galena Fire.

Numerous peak-flow events with small recurrence intervals occurred within burned areas through 1990. Peak-flow events for Bear Gulch during this period were about one to two orders of magnitude larger than corresponding peaks for a small control drainage located along Grace Coolidge Creek upstream from the burn area. The small peaks do not provide quantitative information applicable to estimation of peak-flow magnitudes for larger events, however. Peak-flow events for Bear Gulch that occurred during 1991-98 were generally similar to those for the control drainage. A short-term increase in peak-flow potential also was documented for the longer-term gaging station located along Grace Coolidge Creek; however, peak-flow response was less pronounced than for Bear Gulch, which had nearly complete deforestation within a much smaller drainage area.

INTRODUCTION

On July 5, 1988, a forest fire was ignited by lightning along Galena Creek, which is a tributary to Grace Coolidge Creek, in the southern Black Hills of southwestern South Dakota. Firefighting efforts initially were largely unsuccessful because of the particularly dry conditions of the predominantly ponderosa pine forest; however, the Galena Fire was controlled the night of July 8 following approximately 0.75 in. of rain. The fire eventually burned about 16,788 acres, primarily within the Grace Coolidge Creek drainage basin and almost entirely within the boundaries of Custer State Park.

A U.S. Geological Survey (USGS) gaging station with streamflow records dating back to 1977 was located along Grace Coolidge Creek within the burned area. About one-half of the gaging station's 26.8-mi^2 drainage area was burned.

The existence of long-term, pre-burn streamflow data provided a unique opportunity to evaluate the hydrologic effects of forest fire, with potential to obtain additional insights regarding effects of timber harvest on streamflow in the Black Hills area. Numerous studies around the world have addressed the topic of hydrologic influences from silvicultural activities; however, information for the Black Hills area is sparse. In 1988, a study to evaluate effects of the Galena Fire on streamflow, geomorphology, and water quality was initiated by the USGS in cooperation with the South Dakota Department of Environment and Natural Resources and the South Dakota Department of Game, Fish and Parks. The geomorphologic (Whitesides, 1989) and water-quality (Gundarlahalli, 1990) components of the study were completed by 1990. A data-collection network consisting of streamflow- and precipitation-gaging stations was operated through water year 1998 for evaluation of effects on streamflow characteristics. Additional cooperators that have supported this continuing component of the study included the South Dakota Department of Agriculture (Forestry Division), West Dakota Water Development District, and U.S. Department of Agriculture (Forest Service).

Purpose and Scope

The purpose of this report is to describe the hydrologic effects of the 1988 Galena Fire. The main focus is to evaluate effects on streamflow characteristics, including both annual-yield and peak-flow characteristics. Results from the studies of geomorphology (Whitesides, 1989) and water quality (Gundarlahalli, 1990) also are summarized.

Acknowledgments

The authors acknowledge the various cooperators that have provided support throughout the extended duration of this study. Thanks are extended to staff from the Custer State Park Division of the South Dakota Department of Game, Fish and Parks for assisting with data collection and providing various data sets included in this report. Special thanks are due to Custer State Park Resource Program Manager Ron Walker for continued assistance throughout the duration of this study, including assistance with preparation of this report. The authors also thank Paul Horsted (Dakota Photographic LLC), Rollie Larson (retired Rapid City Central High School ecology teacher), and the Rapid City Journal for providing photographs.

DESCRIPTION OF STUDY AREA

The study area (fig. 1) encompasses the area burned by the Galena Fire. The fire burned about one-half of the drainage area for gaging station 06404998, which is located along Grace Coolidge Creek and has pre-fire records dating back to 1977. The study area also includes French Creek, which is generally south of the burn area, and Battle Creek, which is north of the burn area. Available streamflow records for both of these drainages pre-date the Galena Fire and are used for comparisons with records for station 06404998. Following the Galena Fire, station 06404800 was installed along Grace Coolidge Creek just upstream from the burn area. This station is used for comparisons with station 06405800, which also was installed after the Galena Fire and provides streamflow records for the extensively burned Bear Gulch drainage. Drainages considered for comparisons have general similarities in climate, hydrogeology, and land use, as described in the following sections.

Climate

The climate of southwestern South Dakota is continental, with generally low precipitation amounts, hot summers, cold winters, and extreme variations in both precipitation and temperatures (Johnson, 1933). Climatic conditions in the Black Hills area are influenced by orographic effects, with generally lower temperatures and higher precipitation at the higher altitudes.

Precipitation patterns are generally similar in all of the drainage basins considered. Mean annual precipitation for 1961-90 (fig. 2) ranges from about 17 in. in the southeastern part of the study area to more than 20 in. in the higher altitudes. The mean annual temperature is about 44°F at Custer and 45°F at Mt. Rushmore (National Oceanic and Atmospheric Administration, 1991). Annual evaporation potential generally exceeds annual precipitation throughout the study area. Mean pan evaporation for April through October for two stations located near the study area is about 30 in. at Pactola Reservoir (located north of the study area) and about 50 in. at Oral (located southeast of the study area) (National Oceanic and Atmospheric Administration, 1991).

Conditions in the study area prior to the Galena Fire on July 5, 1988, were hot and dry. Precipitation during May was 0.76 in. below normal at Custer and 0.37 in. below normal at Mt. Rushmore; June precipitation at these sites was 1.38 and 1.73 in. below normal, respectively (National Oceanic and Atmospheric Administration, 1988). Daily maximum air temperatures during late May and June prior to the Galena Fire generally were 10 to 20°F higher than normal for the Custer and Mt. Rushmore stations (fig. 3), and mean temperatures for June 1988 for these stations were the highest on record (South Dakota State University, 2003). These high temperatures coupled with scant precipitation created extreme fire potential.

Hydrogeology

Hydrology within the Black Hills area is greatly influenced by geology (Driscoll and Carter, 2001), which is highly complex. The Black Hills uplift is a northwest-trending, asymmetric, elongate dome, or doubly plunging anticline. Uplift began about 62 million years ago during the Laramide orogeny and probably continued in the Eocene period (Redden and Lisenbee, 1996). The oldest rocks in the study area are the igneous and metamorphic rocks of Precambrian age (fig. 4), which are exposed in the "crystalline core" of the central Black Hills (fig. 5). A sequence of younger sedimentary rocks is exposed around the periphery of the Black Hills area and includes outcrops of the Cambrian- and Ordovician-age Deadwood Formation, the Mississippian-age Madison Limestone (also locally known as the Pahasapa Limestone), and the Pennsylvanian- and Permian-age Minnelusa Formation. This layered sequence has been erosionally removed from the crystalline core area. The bedrock sedimentary formations typically dip away from the uplifted Black Hills at angles that can approach or exceed 15 to 20 degrees near the outcrops (Carter and others, 2002).

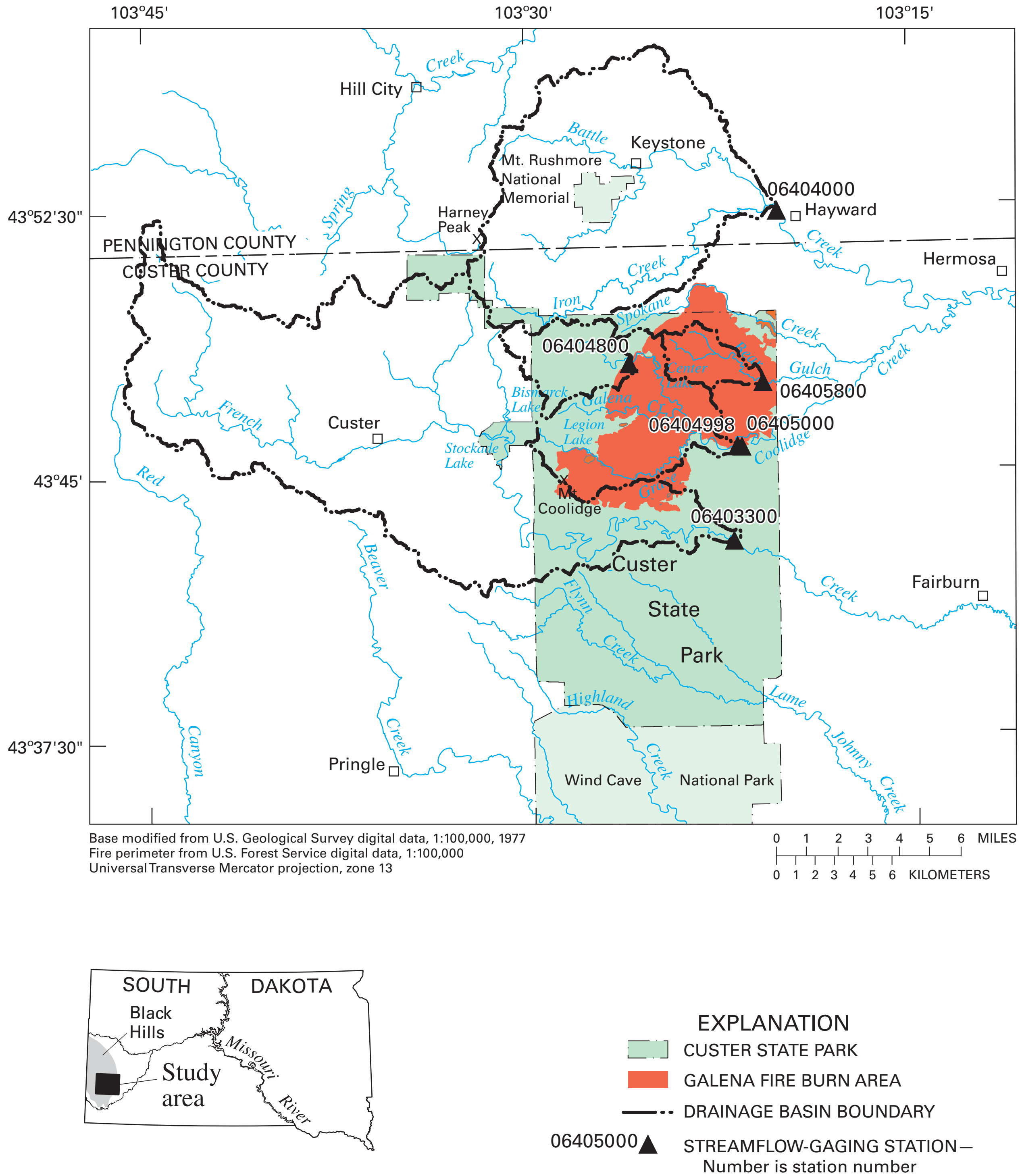


Figure 1. Location of study area. Locations of streamflow-gaging stations within the study area also are shown.

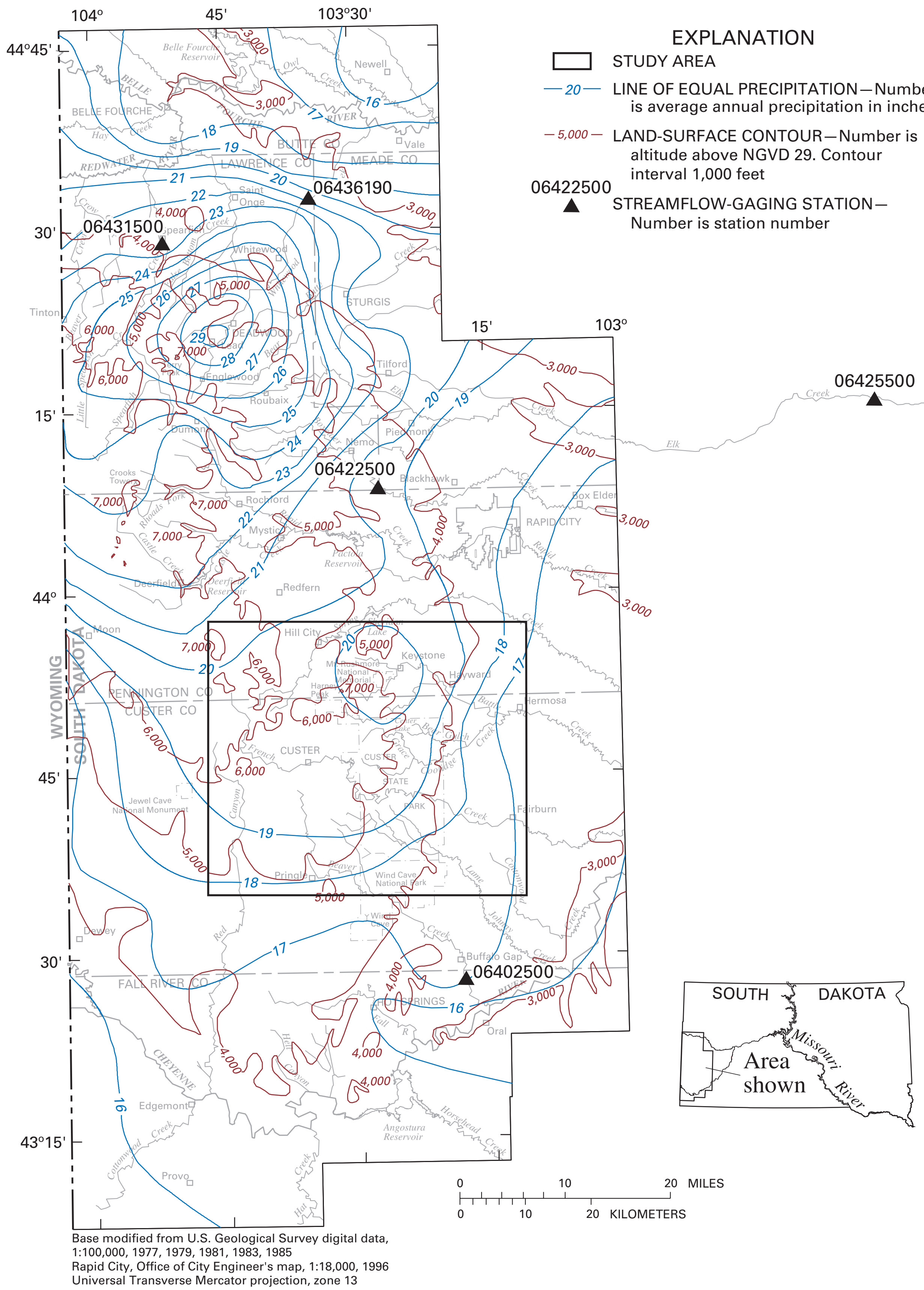


Figure 2. Isohyetal map showing distribution of average annual precipitation for the Black Hills area, water years 1961-90 (from Driscoll and others, 2000). Locations of streamflow-gaging stations outside the study area also are shown.

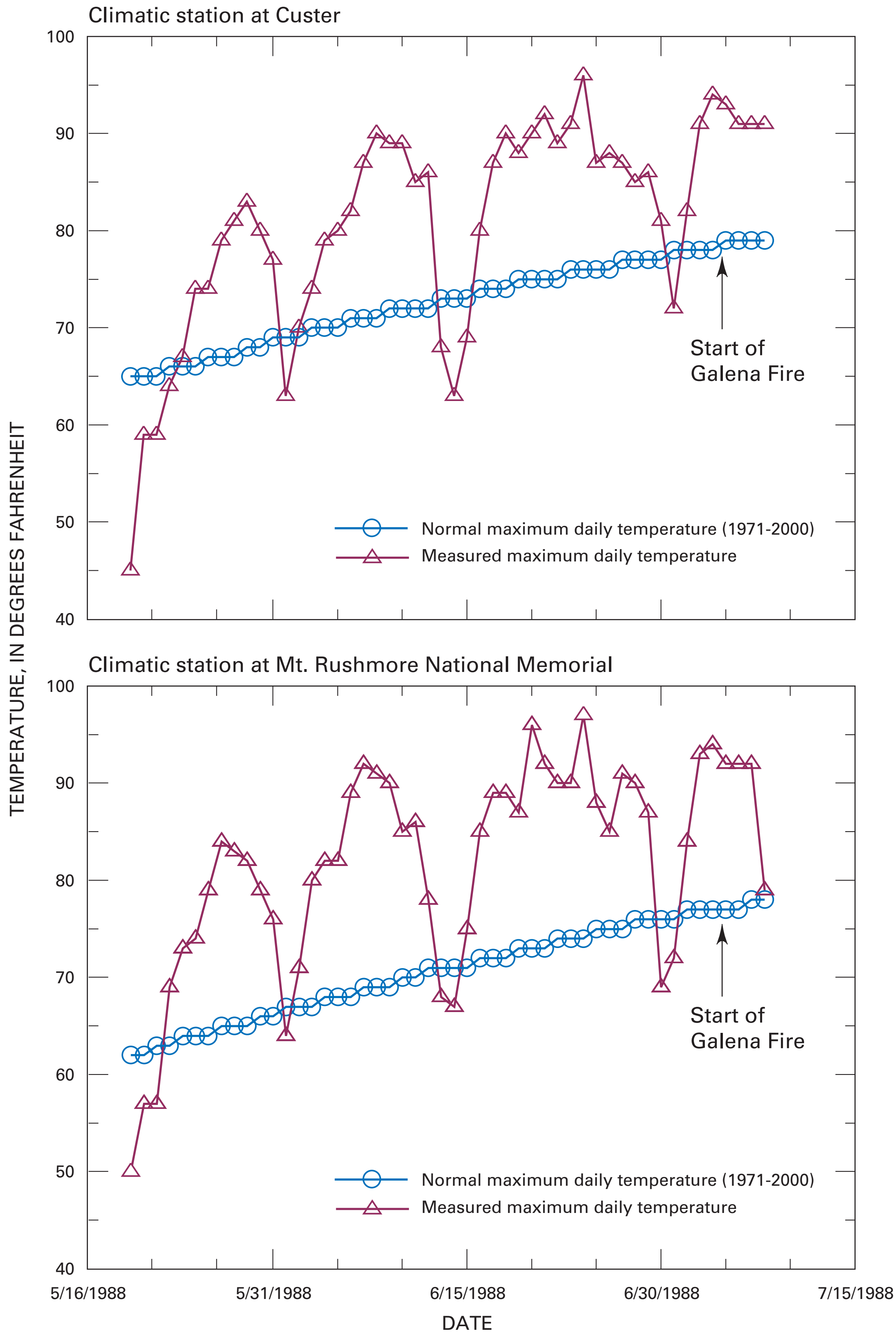


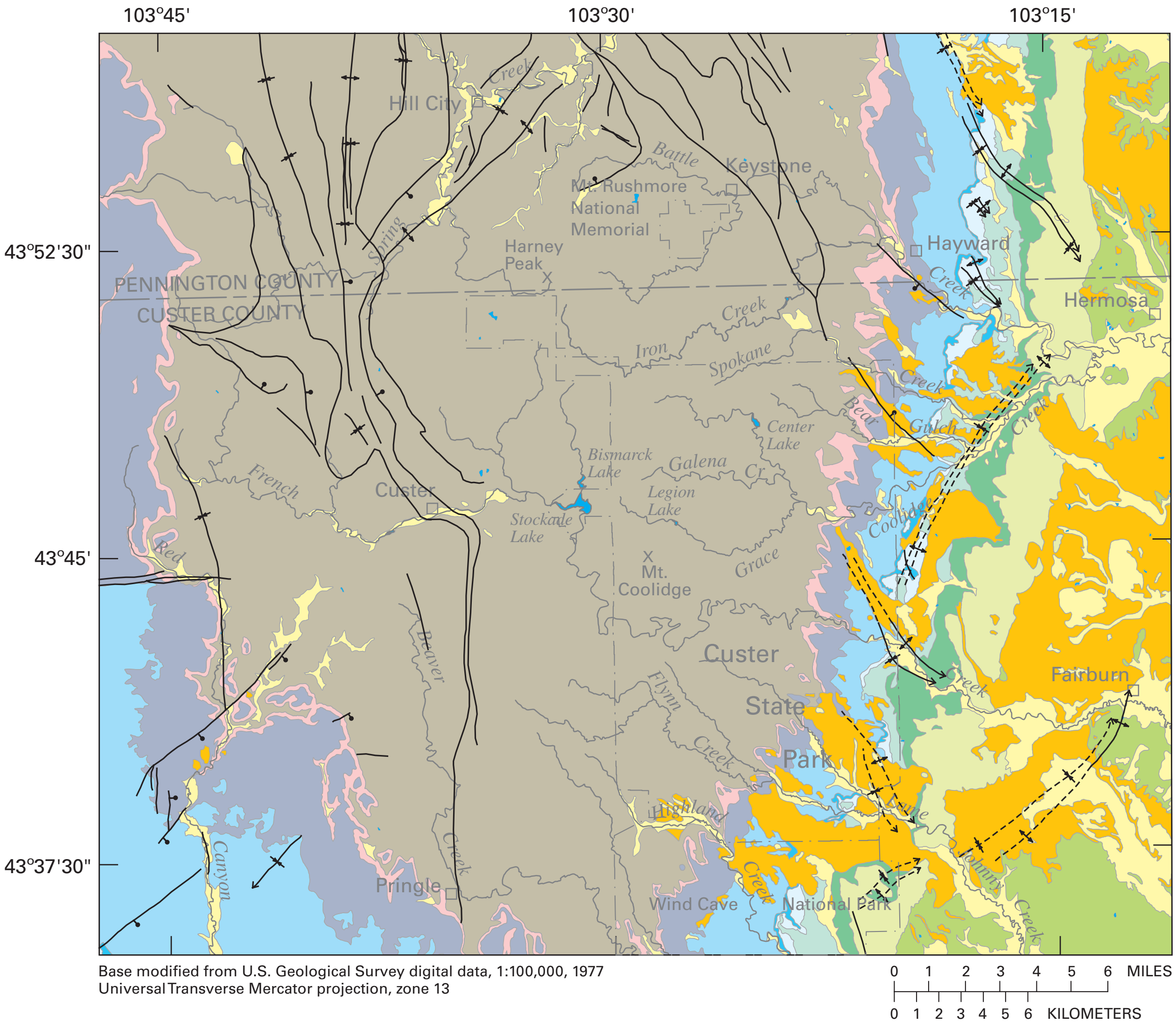
Figure 3. Air temperatures at Custer and Mt. Rushmore climatic stations prior to and during the Galena Fire. Data from South Dakota State University (2003) and National Oceanic and Atmospheric Association (1988).

ERATHEM	SYSTEM	ABBREVIATION FOR STRATIGRAPHIC INTERVAL	GEOLOGIC UNIT	THICKNESS IN FEET	DESCRIPTION
CENOZOIC	QUATERNARY & TERTIARY (?)	QTac	UNDIFFERENTIATED ALLUVIUM AND COLLUVIUM	0-50	Sand, gravel, boulder, and clay.
		Tw	WHITE RIVER GROUP	0-300	Light colored clays with sandstone channel fillings and local limestone lenses.
	TERTIARY	Tui	INTRUSIVE IGNEOUS ROCKS	--	Includes rhyolite, latite, trachyte, and phonolite.
MESOZOIC	CRETACEOUS	Kps	PIERRE SHALE	1,200-2,700	Principal horizon of limestone lenses forming teepee buttes. Dark-gray shale containing scattered concretions. Widely scattered limestone masses, forming small teepee buttes. Black fissile shale with concretions.
			NIOBRARA FORMATION	[1]80-300	Impure chalk and calcareous shale.
			CARLILE SHALE — Turner Sandy Member; Wall Creek Member	[1]350-750	Light-gray shale with numerous large concretions and sandy layers. Dark-gray shale
			GREENHORN FORMATION	225-380	Impure slabby limestone. Weathers buff. Dark-gray calcareous shale, with thin Orman Lake limestone at base.
			GRANEROS GROUP: BELLE FOURCHE SHALE	150-850	Gray shale with scattered limestone concretions. Clay spur bentonite at base.
			GRANEROS GROUP: MOWRY SHALE	125-230	Light-gray siliceous shale. Fish scales and thin layers of bentonite.
			GRANEROS GROUP: MUDDY SANDSTONE / NEWCASTLE SANDSTONE	0-150	Brown to light-yellow and white sandstone.
			GRANEROS GROUP: SKULL CREEK SHALE	150-270	Dark-gray to black siliceous shale.
		Kik	INYAN KARA GROUP: FALL RIVER FORMATION	10-200	Massive to thin-bedded, brown to reddish-brown sandstone.
			INYAN KARA GROUP: LAKOTA FM — Fuson Shale; Minnewaste Limestone; Chilson Member	10-190 0-25 25-485	Yellow, brown, and reddish brown massive to thinly bedded sandstone, pebble conglomerate, siltstone, and claystone. Local fine-grained limestone and coal.
	JURASSIC	Ju	MORRISON FORMATION	0-220	Green to maroon shale. Thin sandstone.
			UNKPAPA SS	0-225	Massive fine-grained sandstone.
			SUNDANCE FORMATION — Redwater Member; Lak Member; Hulett Member; Stockade Beaver Mem.; Canyon Spr Member	250-450	Greenish-gray shale, thin limestone lenses. Glauconitic sandstone; red sandstone near middle.
			GYPSUM SPRING FORMATION	0-45	Red siltstone, gypsum, and limestone.
	TRIASSIC	TRPs	SPEARFISH FORMATION — Goose Egg Equivalent	375-800	Red silty shale, soft red sandstone and siltstone with gypsum and thin limestone layers. Gypsum locally near the base.
PALEOZOIC	PERMIAN	Pmk	MINNEKAHTA LIMESTONE	[1]25-65	Thin to medium-bedded, fine-grained, purplish gray laminated limestone.
		Po	OPECHE SHALE	[1]25-150	Red shale and sandstone.
	PERMIAN / PENNSYLVANIAN	PIPm	MINNELUSA FORMATION	[1]375-1,175	Yellow to red cross-bedded sandstone, limestone, and anhydrite locally at top. Interbedded sandstone, limestone, dolomite, shale, and anhydrite. Red shale with interbedded limestone and sandstone at base.
	MISSISSIPPIAN / DEVONIAN	MDme	MADISON (PAHASAPA) LIMESTONE	[1]<200-1,000	Massive light-colored limestone. Dolomite in part. Cavernous in upper part.
			ENGLEWOOD FORMATION	30-60	Pink to buff limestone. Shale locally at base.
	ORDOVICIAN	Ou	WHITEWOOD (RED RIVER) FORMATION	[1]0-235	Buff dolomite and limestone.
			WINNIPEG FORMATION	[1]0-150	Green shale with siltstone.
	CAMBRIAN	O€d	DEADWOOD FORMATION	[1]0-500	Massive to thin-bedded buff to purple sandstone. Greenish glauconitic shale, flaggy dolomite, and flat-pebble limestone conglomerate. Sandstone, with conglomerate locally at the base.
PRECAMBRIAN		p€u	UNDIFFERENTIATED IGNEOUS AND METAMORPHIC ROCKS		Schist, slate, quartzite, and arkosic grit. Intruded by diorite, metamorphosed to amphibolite, and by granite and pegmatite.

[1]Modified based on drill-hole data

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

Figure 4. Stratigraphic section for the Black Hills area.



EXPLANATION

GEOLOGIC UNITS

- QTac — Alluvium and colluvium, undifferentiated
- Tw — White River Group
- Kps — Pierre Shale to Skull Creek Shale, undifferentiated
- Kik — Inyan Kara Group
- Ju — Morrison Formation to Sundance Formation, undifferentiated
- TrPs — Spearfish Formation
- Pmk — Minnekahta Limestone
- Po — Opeche Shale
- PIPm — Minnelusa Formation
- MDme — Madison (Pahasapa) Limestone and Englewood Formation
- O€d — Deadwood Formation
- p€u — Undifferentiated igneous and metamorphic rocks

FAULT—Bar and ball on downthrown side

ANTICLINE—Showing trace of axial plane and direction of plunge. Dashed where approximated

SYNCLINE—Showing trace of axial plane and direction of plunge. Dashed where approximated

MONOCLINE—Showing trace of axial plane. Dashed where approximated

Figure 5. Geology of the study area (modified from Strobel and others, 1999).

The study area is underlain primarily by Precambrian igneous and metamorphic rocks that consist mostly of the Harney Peak granite and quartzite, with lesser amounts of granitic pegmatite and schist (DeWitt and others, 1989; Strobel and others, 1999). The Deadwood, Madison, and Minnelusa Formations underlie a much smaller portion of the burned area than the Precambrian rocks.

Although geology within the study area is complex (fig. 5), streamflow records for analyses of annual-yield characteristics for this study are considered only for drainage areas upstream from outcrops of the Madison Limestone. These drainages are dominated by outcrops of Precambrian igneous and metamorphic rocks and are within the "crystalline core" hydrogeologic setting identified by Driscoll and Carter (2001). Streamflow characteristics for this setting are typified by relatively small base flow and strong correlations between annual streamflow and precipitation.

Most streams, including Grace Coolidge Creek, generally lose all or part of their flow as they cross the outcrop of the Madison Limestone (Rahn and Gries, 1973; Hortness and Driscoll, 1998). Large streamflow losses also occur in many locations within the outcrop of the Minnelusa Formation, and limited losses probably also occur within the outcrop of the Minnekahta Limestone (Hortness and Driscoll, 1998).

The Precambrian basement rocks generally have low permeability and form the lower confining unit for the series of aquifers in sedimentary rocks in the Black Hills area. Driscoll and others (2002) assumed negligible regional ground-water outflow for Precambrian rocks; however, localized aquifers within Precambrian rocks occur in many locations in the crystalline core of the Black Hills, where enhanced secondary permeability results from weathering and fracturing. Ground-water discharge from Precambrian rocks provides base flow for streams in the study area, especially at higher altitudes where moisture surpluses result from increased precipitation and reduced evapotranspiration. Base flow can diminish very quickly during particularly dry periods.

Within the Paleozoic rock interval, aquifers in the Deadwood Formation, Madison Limestone, Minnelusa Formation, and the Permian-age Minnekahta Limestone are used extensively and are considered to be major aquifers in the Black Hills area. These aquifers receive recharge from infiltration of precipitation on outcrops, and the Madison and Minnelusa aquifers also receive significant recharge from streamflow losses. These aquifers are collectively confined by the underlying Precambrian rocks and the overlying Spearfish Formation, where present (fig. 5). Individually, these aquifers are separated by minor confining units or by relatively impermeable layers within the individual units. In general, ground-water flow in these aquifers is radially outward from the crystalline core of the Black Hills.

Land Use

Although a wide variety of land ownership exists within the study area (fig. 6), hydrologic differences resulting from differing land uses within the drainages considered probably are relatively minor. Most of the burn area is within Custer State Park (fig. 1). Drainage basins used for comparisons consist of various combinations of land ownership; however, the U.S. Forest Service (USFS) is the majority landholder in all of the comparison basins. Private landholdings, which are excluded from the Black Hills National Forest, are common within parts of the comparison basins. The Battle Creek drainage includes Mt. Rushmore National Memorial, which is administered by the National Park Service.

Land use and vegetation patterns generally are similar throughout the study area, regardless of land ownership. The predominant tree species throughout the study area is ponderosa pine. Historically, ponderosa pine has been the primary species utilized by a timber industry that has existed since the earliest European settlement of the area, which began soon after the Custer Expedition of 1874 when gold was discovered in French Creek. White spruce, which are locally known as Black Hills spruce, occasionally are intermixed with ponderosa pine stands, most commonly in locations that are particularly damp or well shaded. Various deciduous species exist throughout the study area, most commonly in bottom areas. Bur oak and ironwood typically are found at lower altitudes and give way to aspen and paper birch at higher altitudes (Ron Walker, Custer State Park, oral commun., 1989).

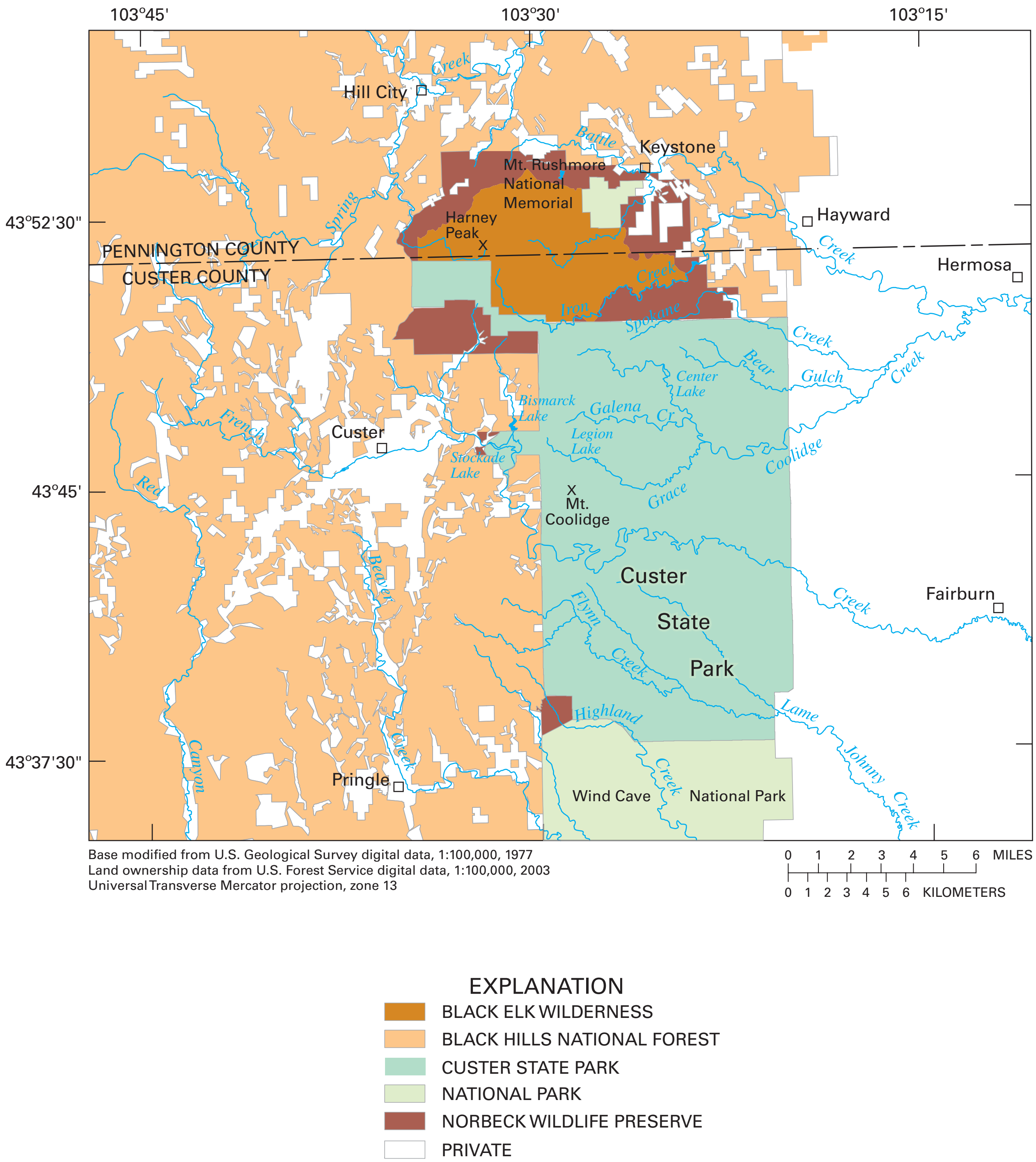


Figure 6. Land ownership in study area.

Land use within the study area historically has been dominated by timber harvesting and cattle grazing. One or both of these land uses have occurred to at least some extent throughout most of the study area since shortly after the Custer Expedition, in support of the mining industry. Grazing typically has been concentrated in the more heavily grassed bottom areas, many of which are in private ownership. Grassed understories within timber stands frequently are utilized during summer months, and private grazing permits are issued for many allotments within the Black Hills National Forest. An important focus of land management within Custer State Park is production of grasses for grazing by buffalo and a variety of big game.

Numerous other land uses have existed within the study area. Initial settlement of the area was during the gold rush, so in addition to mining, other support industries such as railroads and agriculture were common. Current mining activity is minimal, but most private lands exist on former mining claims or along relatively open bottom areas where agricultural activities (including grazing) were feasible. At the higher altitudes, cultivated cropland is uncommon and agricultural activities generally are limited to animal husbandry and hay production. Tourism has been a stable industry in the area since soon after the horseless carriage was invented. Outdoor recreation, including bicycling, fishing, hiking, and hunting, have become increasingly popular throughout the Black Hills area. During recent years, suburban growth has been increasing around the small communities in the study area. Although there are no urban areas within Custer State Park, tourist accommodations and facilities for Park staff are similar to many suburban areas throughout the study area.

Timber Management and Burn Characteristics

Most studies that have addressed the effects of timber harvest on water yield have utilized various indices of timber stand condition or density. Numerous records undoubtedly exist for various tracts of USFS land within the study area; however, documenting changes in timber stand conditions for numerous tracts of private land in the study area would not be practical. It is useful, however, to provide a general overview of the history of timber management in the area.

Streamflow records considered for this study could potentially be influenced by timber management dating back many decades. Various photographs taken during the 1874 Custer Expedition have been used to document long-term increases in ponderosa pine density (Progulske, 1974; Grafe and Horsted, 2002), and an example photograph pair is shown in figure 7. Increased density has resulted primarily from implementation of fire suppression since the arrival of European settlers in the area. Many parts of the French Creek drainage upstream from Stockade Lake have particularly large open areas that may result from a combination of fire effects before 1874 and subsequent human maintenance of open areas. In general, fire suppression can substantially reduce both the general percentages of open areas and ratios of mature to immature pines in typical stands. Fire suppression also causes reduced species diversity with increased dominance of ponderosa pine (Brown and Sieg, 1996).

Most studies of hydrologic effects of timber harvest have been conducted in small watersheds under highly controlled conditions. Hydrologic effects of timber management may be difficult to discern in large watersheds because timber stand conditions can be quite dynamic. Reduced timber stand density resulting from harvest or widespread mortality in a large watershed can be offset by ongoing timber growth in other parts of the watershed.

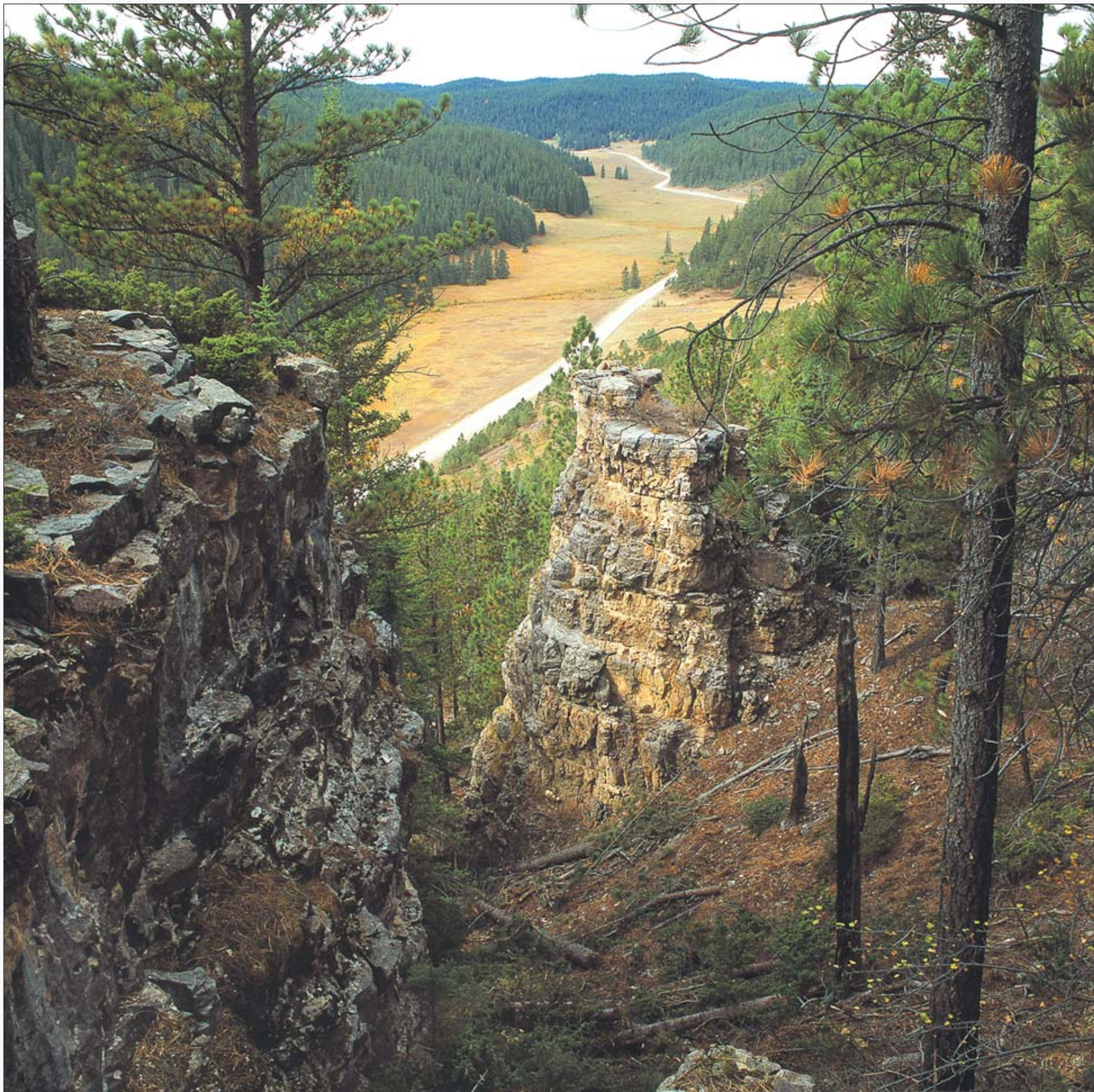
Timber Management

In spite of the wide variety in land ownership, timber management practices throughout the study area historically have been similar. Most parts of the study area with merchantable timber stands have been subject to selective-cut harvest practices during the last century and repeated rotational harvests have occurred in many locations. Logging methods in the study area have been largely independent of land ownership and over time have evolved from hand saws and animal-drawn equipment to complete mechanization, in many cases. Logging practices have evolved from high grading of the most desirable and accessible saw timber to highly controlled timber sales that can include pre-commercial thinning of non-merchantable timber throughout large areas. Large-scale clear cuts have been uncommon in the Black Hills area because of various factors including the particularly prolific germination characteristics of ponderosa pine in the area and propensity towards multi-story stands.

Wagon train passing through Castle Creek Valley, July 26, 1874

Figure 7. Photographs showing increase in pine forest between 1874 and 2000 in the Black Hills. (Photo pair is from the book, Exploring with Custer: The 1874 Black Hills Expedition, by Ernest Grafe and Paul Horsted. Published by Golden Valley Press, Custer, South Dakota. Information at www.custertrail.com. Used with permission.)

July 2000



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Local logging practices at any given time typically have been heavily influenced by standards established by the USFS, which administers the majority of forest lands in the study area. The Black Hills Forest Reserve was established in 1897 by President Grover Cleveland and in 1905 was transferred to the USFS, an agency of the U.S. Department of Agriculture, for management of forested lands in the Black Hills (U.S. Forest Service, 1994). It was renamed the Black Hills National Forest in 1907. The first commercial timber sale on Federal forested land in the United States was authorized in 1898 near the town of Nemo in the northern Black Hills (fig. 2).

In 1912, about 50,000 acres in Custer County were designated Custer State Forest, which was established as Custer State Park in 1919 through efforts by South Dakota Governor Peter Norbeck. Additional lands were acquired in the 1920s and in 1964. Custer State Park now encompasses about 71,000 acres and is one of the largest State parks in the United States.

From 1917 to 1927, approximately 45 million board feet of pine timber were harvested from Custer State Forest/Park (Walker and others, 1995). In 1927, the South Dakota Legislature limited harvesting in Custer State Park to 100,000 board feet per year. There are no records of timber sales from 1927-1951 (Walker and others, 1995).

Extensive non-commercial timber management occurred in Custer State Park during the 1930s through efforts by the Civilian Conservation Corps (CCC). The CCC also made many improvements throughout the park including campgrounds, lodges, roads, and bridges. Additionally, the CCC built the dams that created Stockade, Center, and Legion Lakes.

Timber harvesting in Custer State Park resumed in 1951; however, management activities generally were very limited until the late 1970s when an aggressive timber management program was initiated. Extensive pre-commercial thinning was performed in the northwestern part of Custer State Park as part of this program. Effects of thinning activities are visible in an aerial photograph from 1978 (fig. 8), in which the western boundary of Custer State Park is clearly apparent because of lower timber density east of the boundary. The boundary also is clearly apparent in an aerial photograph from 2000 (fig. 8), which shows a general reversal of relative timber densities that resulted from timber growth within Custer State Park and decreased density from timber harvest that occurred west of the boundary during the 1990s. Thus, the dynamic nature of timber stand density is well illustrated by these aerial photographs.

Relatively recent (last few decades) timber management in many parts of the drainages used for comparisons with Grace Coolidge Creek probably has been fairly similar to that which has occurred in Custer State Park. A general exception is the Norbeck Wildlife Preserve, which was established in 1920 by Congress. The preserve includes about 35,000 acres, of which 27,800 acres are managed by the USFS and most of the rest is part of Custer State Park (fig. 6). A relatively long period of logging inactivity in the Norbeck Wildlife Preserve occurred between the Cayauga Timber sale in the 1970s and the Needles 2 Timber sale that began in 2002 (Blaine Cook, U.S. Forest Service, oral commun., 2003) because of environmental challenges. The Norbeck Wildlife Preserve includes the 13,426-acre Black Elk Wilderness Area (fig. 6), which was established in 1980 and in which logging activity is precluded because mechanized equipment is not allowed.

Burn Characteristics

The Galena Fire (figs. 1 and 9), which burned 16,788 acres, stands out as the most notable recent change in forest cover within the study area. About 8,569 acres (13.4 mi^2) of the burned area were within the 26.8 mi^2 drainage area for gaging station 06404998, which represents about 50 percent of the drainage area. In 1990, the Cicero Peak Fire burned about 14,203 acres along both sides of the western boundary of Custer State Park, from the southwestern edge of the Galena Fire and extending to about 6 mi south of there (fig. 10). The Cicero Peak Fire was primarily within the Flynn Creek drainage and other drainages to the south, but also included a small part (about 9 mi^2) of the French Creek drainage, which is used for comparisons with burned drainages. Numerous other small fires with little potential for substantial hydrologic influence have occurred during recent decades; however, no documentation or evidence of other particularly large fires in the study area has been identified.

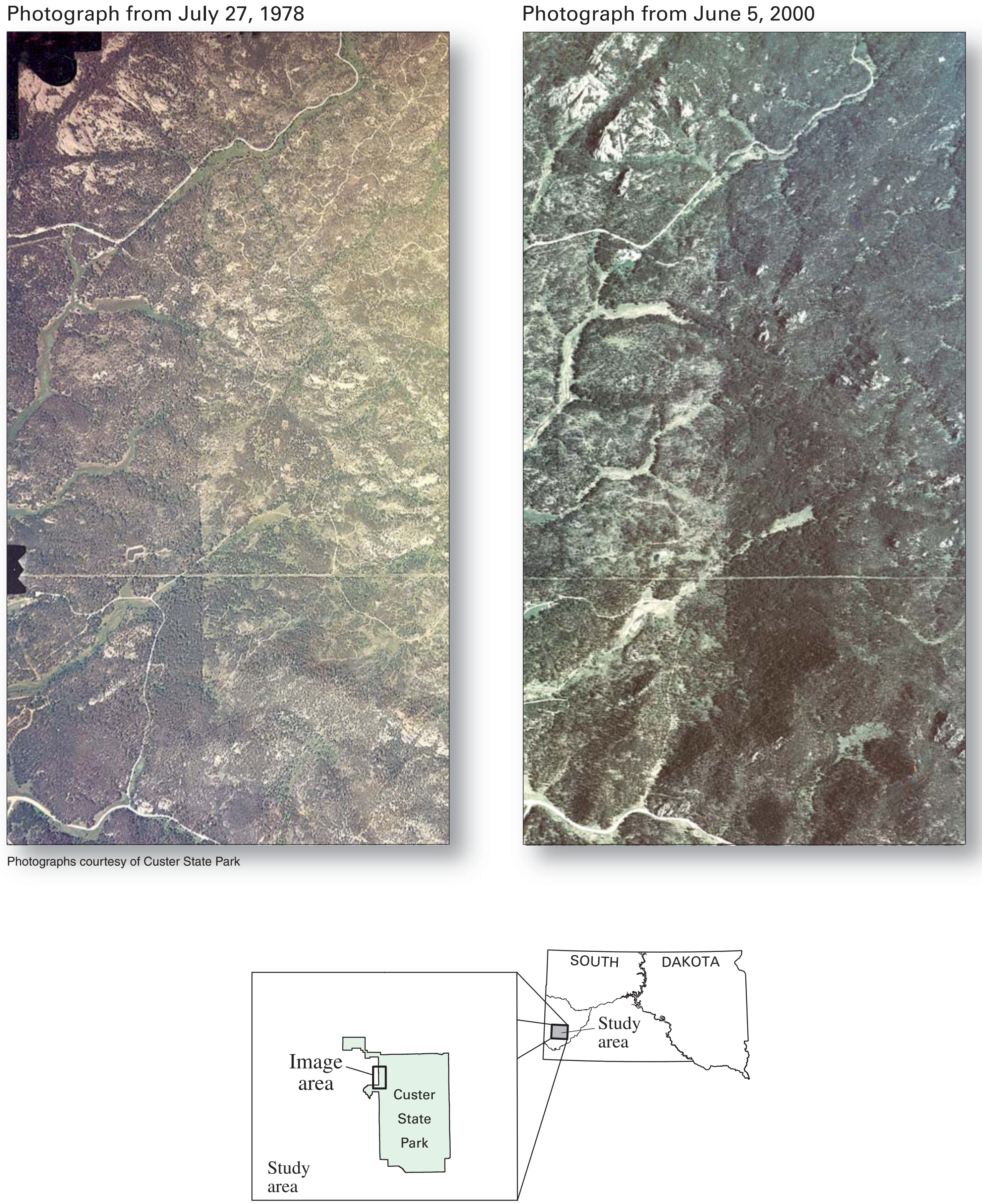
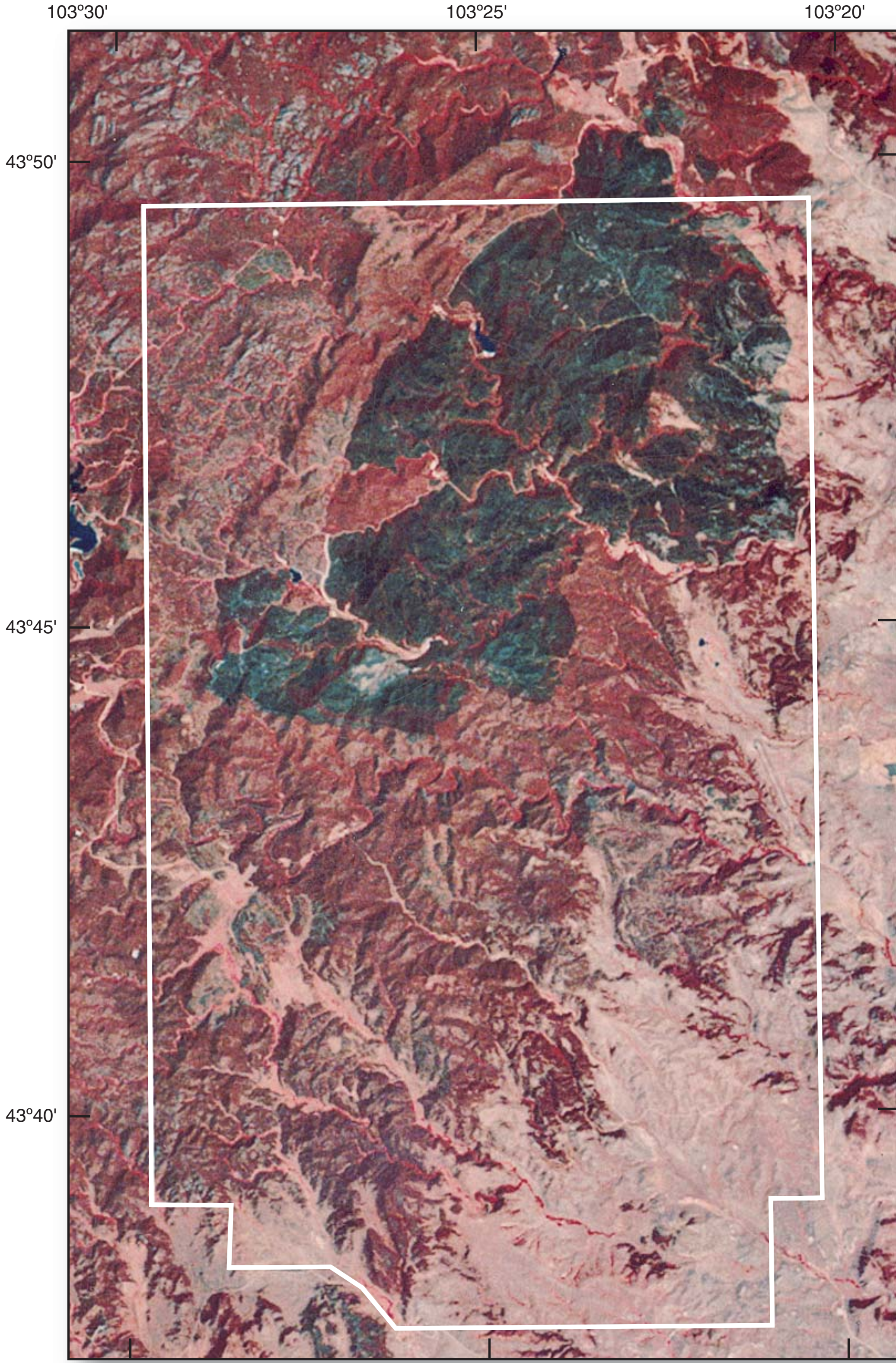


Figure 8. Aerial photographs showing changes in forest cover near northwestern corner of Custer State Park.



U.S. Geological Survey/Geography Discipline, EROS Data Center
LANDSAT Thematic Mapper, 7/27/1988
Modified from Scene ID: Y4220317055XO
Universal Transverse Mercator projection, zone 13

Figure 9. Landsat image of area burned by Galena Fire. Custer State Park boundary depicted on 1988 image is generalized.

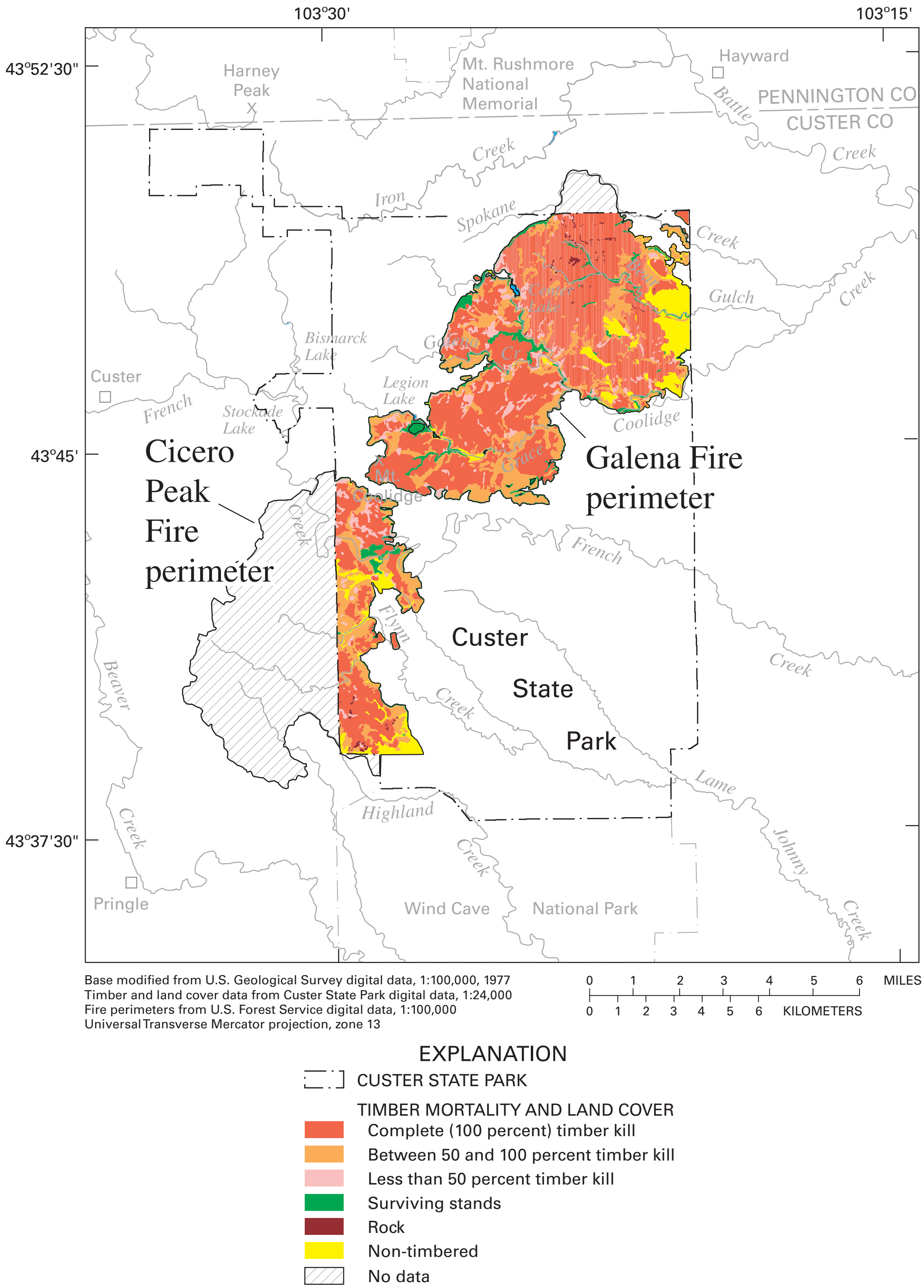


Figure 10. Timber mortality in Custer State Park following the Galena Fire in 1988 and the Cicero Peak Fire in 1990.

As with most forest fires, burn intensities of the Galena Fire varied immensely. A few limited areas suffered only partial consumption of surface fuels, usually within valley bottoms. Most hillslopes and hilltops burned much more intensely, however, because of generally drier fuels, better air circulation, and upward convection of massive heat generated. Total crown consumption was common in many such areas. Because of extreme fire conditions, particularly large tracts were burned very intensely, with total mortality of timber stands occurring in numerous and widespread areas (fig. 10), accounting for about 54 percent of the area within the fire perimeter. About 29 percent of the area within the fire perimeter had partial timber mortality, and only 7 percent of the area had surviving timber stands initially following the fire. Most of the sparse remaining surviving timber stands have suffered additional mortality from wind throw, breakage, and disease (Walker and others, 1995). About 10 percent of the area within the fire perimeter was non-timbered.

Available fuel in many of the severely burned areas was almost entirely consumed, with the general exception of standing tree boles, which typically do not burn completely. Such areas typically incurred crown consumption; near-total consumption of surface fuels, which include forest floor litter and fuels to a height of about 4 ft; and widespread consumption of ground fuels, which include duff, roots, punky wood, and peat located beneath the floor litter (Walker and others, 1995). Ground-surface temperatures were sufficient to cause spalling of rocks (fig. 11) in many locations.

Photograph by Dietrich H. Whitesides

Figure 11. Spalling of granite due to intense heat from Galena Fire.

One possible effect of forest fire is development of water repellent or "hydrophobic" soils (Doerr and others, 2000) that can increase runoff potential because of decreased permeability within the soil horizon. When surface and ground fuels burn, the types of volatile organic compounds that are released depend upon the temperature of the fire. Some of the compounds may condense on soil particles below the soil surface where temperatures are relatively cooler than at the soil surface. This process does not necessarily create a uniform hydrophobic layer below the soil surface because the fire-induced hydrophobicity reflects the mosaic distribution of surface and ground fuels that burn and the variable heat impulse from the fire into the soil (DeBano, 2000).

Initial post-fire remediation consisted of various components (South Dakota Department of Environment and Natural Resources, 1991). Logging operations that were performed by private contractors during 1988-89 salvaged virtually all accessible stands of merchantable timber within the burn area. The Soil Conservation Service participated in several watershed stabilization projects in various severely burned locations that were prioritized for erosion control measures. Sediment traps were constructed from straw bales in numerous small channels. Hillside terraces that were anchored with downslope log barriers were constructed using earth-moving equipment in selected locations. Cross-slope felling and slash spreading were implemented in some hillside areas, and occasional slash piling was emplaced in small channels. Various agencies participated in aerial seeding efforts during 1988, with yellow blossom sweet clover sown over about 5,000 acres of severely burned hillsides and annual rye grass sown over about 500 acres of drainage bottoms.

Additional remediation efforts included limited pine seeding (totaling about 300 acres) and seeding of grass mixes on logging roads (about 140 acres including about 20 acres of landings). Reseeding of grass mixes was done in a 970-acre area in the Bear Gulch drainage after a 1989 survey indicated failure to meet an established target of 20 percent ground cover (South Dakota Department of Environment and Natural Resources, 1991). A 1990 survey indicated exceedance of a 40 percent ground cover target in nearly all areas that were seeded (Walker and others, 1995); thus, no further seeding was performed.

Regeneration of woody vegetation, including ponderosa pine, has been particularly slow in the burned area. Regeneration of species such as bur oak, ironwood, aspen, and birch probably has been slow because root stock was entirely consumed in many locations. Regeneration of ponderosa pine has been slow in many locations because of sparsity and remoteness of seed stock. Pictures showing the aftermath (circa 1988-89) are presented in figure 12. The regrowth of vegetation following the fire is documented in a series of post-fire photographs taken from a site on the northeastern flank of Mt. Coolidge (fig. 13). Particularly heavy growth of yellow blossom sweet clover occurred during 1990. Various grasses and forbs, such as clover and dandelions, also began to re-establish, and vegetation has been dominated by grasses during subsequent years.

PREVIOUS INVESTIGATIONS

Numerous previous investigations have documented hydrologic effects of logging activities. Most of these studies have been in controlled settings and have indicated increased water yield associated with decreased forest cover (Bosch and Hewlett, 1982) because of decreased evapotranspiration potential. Hydrologic changes after logging in Oregon coastal watersheds were presented by Harris (1977) and Beschta (1978). During the 7 years following logging in the watershed, sediment yield increased about 180 percent and annual runoff increased 19 in. (Harris, 1977). More recently, Bowling and others (2000) reported on the hydrologic effects of logging on 23 watersheds in western Washington.

Locally, Anderson (1980) evaluated the effects of selective timber harvest on water yield in the Sturgis Watersheds, which was a small research site operated by the USFS in the northern Black Hills of South Dakota. For 8 years of post-harvest data, measured annual water yield in the harvested watershed averaged 8.05 in., relative to a predicted yield of 6.12 in., based on regression analysis with annual yield for a control watershed. Thus, annual yield increased 1.93 in., or about 30 percent, relative to preharvest conditions. The largest increases generally occurred during the wettest years; however, percentage increases were largest during dry years. No discernible decrease in yield characteristics occurred during the 8-year post-harvest period for which data were collected.

Various previous investigations also have addressed hydrologic effects of forest fire, which typically can include increased stormflow potential and associated erosion rates from removal of ground cover and development of water-repellent characteristics in the soil horizon. Local investigations are sparse; however, data for 1989-91 for Bear Gulch (within the area of the Galena Fire) were considered by Moody and Martin (2001), who explored post-fire relations between rainfall intensity and peak discharge for three mountainous watersheds in the western United States. This study showed that the change in the unit-area peak discharge for burned drainages is greater for the more frequent, lower intensity rainfall events than for the less frequent, higher intensity rainfall events.

August 1988

Photographs by Mark T. Anderson

May 1989

Figure 12. Aftermath of Galena Fire in severely burned areas.

Figure 13. Progression of post-fire vegetation recovery at a site on the northeastern flank of Mt. Coolidge (photographs taken during October, courtesy of Rollie Larson, retired Rapid City Central High School ecology teacher).

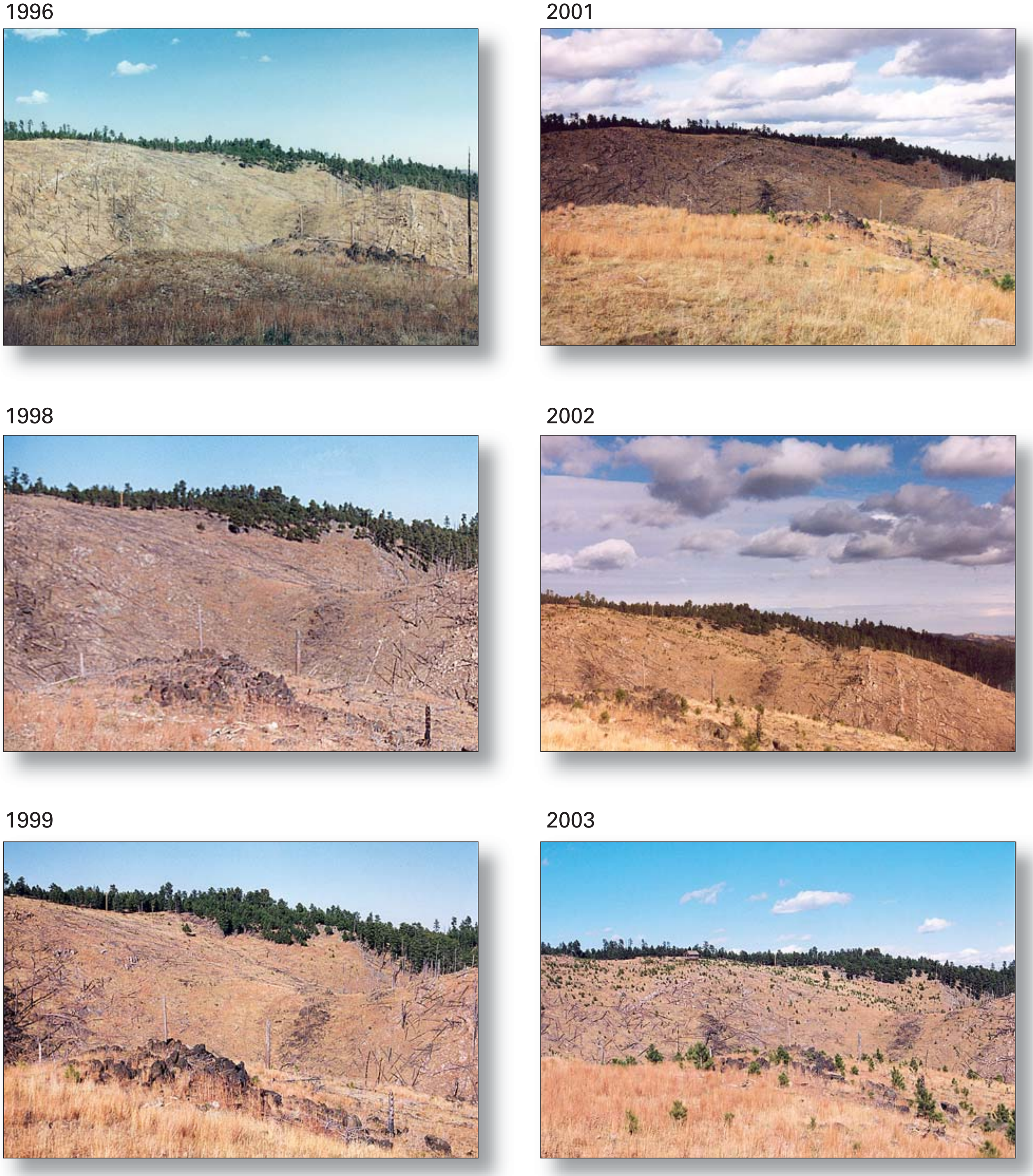


Figure 13. Progression of post-fire vegetation recovery at a site on the northeastern flank of Mt. Coolidge (photographs taken during October, courtesy of Rollie Larson, retired Rapid City Central High School ecology teacher).—Continued

Following studies of fire effects in southern California mountains, Colman (1953) reported that erosion rates remained above normal for at least 8 years following fire and that flood peaks of streams remained above normal for at least 20 years. Streamflow records from mountain streams in north-central Washington before, during, and after a fire in 1970 that burned over 120,000 acres showed that streamflow was greatly reduced while the fire was actively burning and that streamflow quickly increased to above-normal conditions following the fire (Berndt, 1971). Hydrologic effects in the years following the 1970 Washington fire were reported by Helvey (1973) and Helvey and others (1976).

The U.S. Forest Service (1979) summarized hydrologic effects of fire based on studies across the United States through 1978. The effects summarized included land stability, erosion, sedimentation, mass erosion, nutrient concentrations, and biological composition.

Flooding and debris flows were documented by Parrett (1987) for a small Missouri River tributary near Helena, Montana, following a forest fire and subsequent rainfall event in 1984. No significant runoff from unburned tributaries contributed to the documented flooding that yielded unit peak debris discharges ranging from 143 to 34,000 $(ft^3/s)/mi^2$ and moved an estimated 80,000 yd^3 of material.

Changes in water-quality characteristics for a reservoir in west-central California following a large fire in 1985 and a flood in 1986 are documented by Taylor and others (1993). Following the Yellowstone fires of 1988, the observed channel response of a spring-fed stream in eastern Idaho was documented by Simon (1999). Following a wildfire in 1996 near the mountain community of Buffalo Creek, Colorado, rainfall events over the next 3 years produced 10 floods larger than a 100-year (pre-fire conditions) flood and numerous smaller floods (Jarrett, 1999).

A study of infiltration rates following a prescribed fire in Northern Rocky Mountain forests showed greater runoff rates from areas with high-severity burn than unburned and low-severity burn areas, especially during the initial stages of the first simulated rainfall event (Robichaud, 2000). The results indicated hydrophobic or water repellent soil conditions, which temporarily caused a 10 to 40 percent reduction in hydraulic conductivity values when compared to a normal infiltrating soil condition.

The effects of wildfires in 1977 and 1996 on the hydrology of two watersheds in Bandelier National Monument, New Mexico, were documented by Veenhuis (2002). The peak flow at one streamflow-gaging station was about 160 times the maximum recorded flood prior to the fire. The hydrologic effects were most pronounced during the first 3 years following the fire; however, flood magnitudes had not completely returned to pre-fire conditions following the 1977 fire.

Drainage basin characteristics and initial channel response to storm rainfall for 95 recently burned drainage basins in Colorado, New Mexico, and southern California are documented by Cannon (2001). Debris flows were produced from about 40 percent of the basins examined. Sediment-laden streamflow was produced in most of the remaining basins, whereas a few basins showed no discernible response. The study concluded that drainage basin morphology and lithology and the presence or absence of water-repellent soils are the factors that control the generation of fire-related debris flows.

DATA SETS CONSIDERED AND HYDROLOGIC CONSIDERATIONS

The primary focus of this report is evaluation of effects of the Galena Fire on streamflow characteristics, including both annual-yield and peak-flow characteristics. Within this section, a description of data sets considered and an overview of various hydrologic considerations relevant to evaluating effects on streamflow characteristics is presented.

Data Sets Considered

Precipitation and streamflow records for numerous measurement sites have been considered in evaluating the hydrologic effects of the Galena Fire. Some of the measurement sites were installed specifically for this study; however, records for numerous other sites also are considered, as discussed in the following sections.

Precipitation Data

Many of the precipitation data sets that are used within this report are from Driscoll and others (2000), who summarized available precipitation data for water years 1931-98 for the Black Hills area. These investigators compiled monthly precipitation records for 52 long-term precipitation gages operated by National Oceanic and Atmospheric Administration and 42 short-term precipitation gages operated by the USGS. The precipitation gages that are within the study area are shown in figure 14 and selected site information for these gages is presented in table 1. Driscoll and others (2000) used a geographic information system (GIS) to generate spatial distributions of monthly precipitation data for 1,000-by-1,000-meter grid cells for the Black Hills area. Data sets and methods developed by these investigators were used for estimating precipitation amounts over drainage areas for selected streamflow-gaging stations using monthly precipitation distributions that were compiled by water year.

Most of the USGS precipitation gages listed in table 1 were installed and operated specifically for the study of fire effects. Many of these were nonrecording gages operated by observers, who reported daily precipitation totals. A number of recording gages, which can provide information regarding precipitation intensity, also were operated.

Streamflow Data

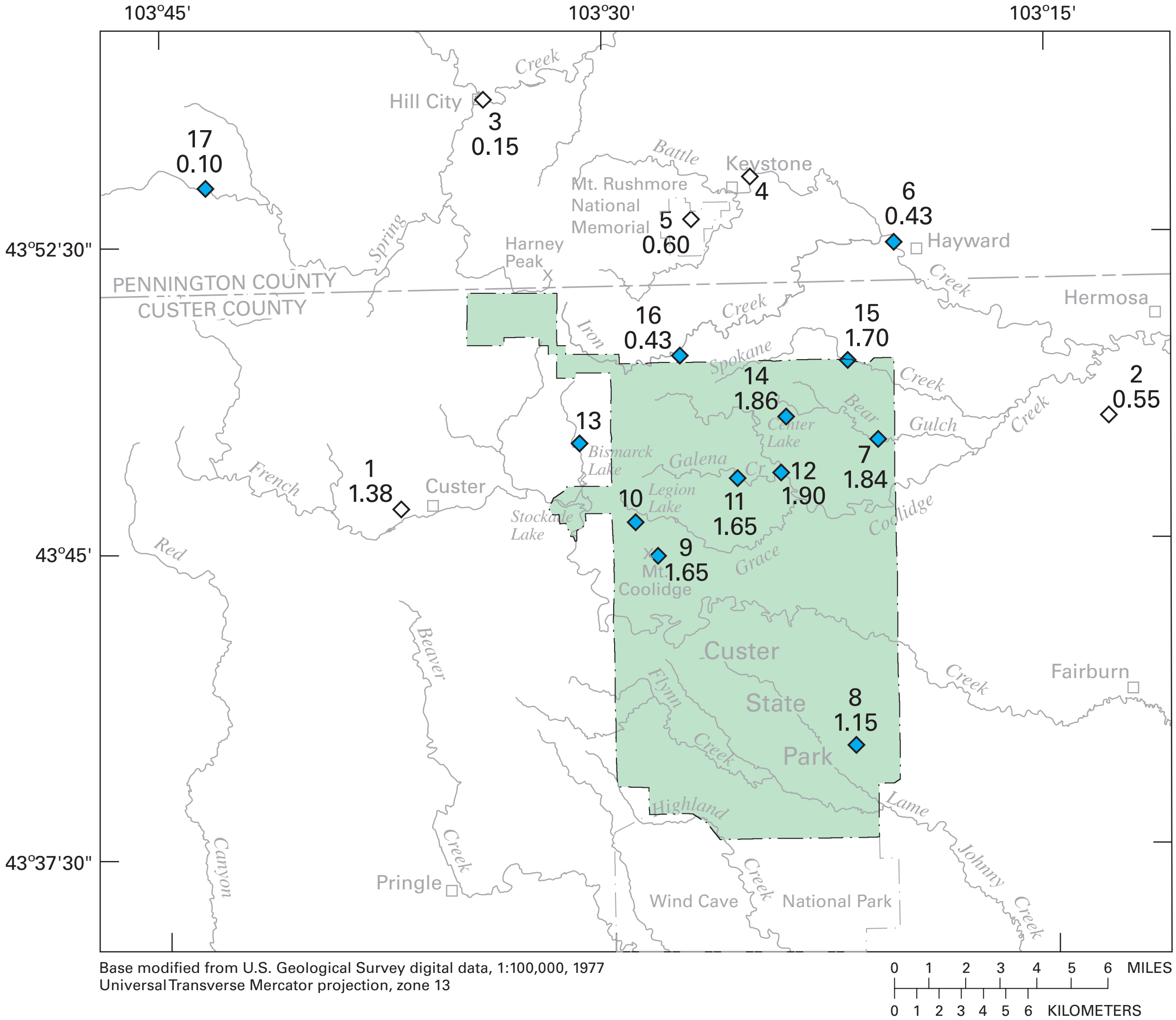
Streamflow-gaging stations used for analyses in this report that are located within the study area are shown in figure 1, and stations outside the study area are shown in figure 2. Selected site information for all gaging stations is presented in table 2. Data for the gaging stations that are used in analyses in this report have been published in USGS annual data reports (U.S. Geological Survey, 1968-99). About one-half of the drainage area for station 06404998 (Grace Coolidge Creek near Game Lodge) is within the burn area, with streamflow records dating back to 1977. Station 06405000 (Grace Coolidge Creek near Custer), which was located a short distance downstream, has records for 1967-76. This station was eventually discontinued and moved upstream to the current location when it was determined that the original station was located within the upstream part of the reach where streamflow losses occur to the Madison Limestone. Thus, low-flow records for the downstream station were not considered for analyses of annual-yield characteristics. High-flow records were used for analyses of peak-flow characteristics, however, because effects of streamflow losses on peak flows are negligible.

Table 1. Summary of selected site information for precipitation gages within study area

[Station type: N, Nonrecording gage (year-round); R, Recording gage (year-round); S, seasonal gage]

Site number (fig. 14)	Station number	Station name	Station type	Period of record (water years)
		National Oceanic and Atmospheric Administration stations		
1	392087	Custer	N	1931-98
2	393775	Hermosa 3SSW	N	1941-98
3	393868	Hill City	N	1955-98
4	394556	Keystone	N	1990-97
5	395870	Mt. Rushmore National Memorial	N	1962-98
		U.S. Geological Survey stations		
6	06404000	Battle Creek near Keystone	N	1988-98
7	06405800	Bear Gulch near Hayward	R	1989-98
8	434002103214500	Racetrack Butte near Fairburn	R	1984-98
9	434444103282000	Custer State Park at Mt. Coolidge	R	1984-90
10	434534103290500	Mt. Coolidge near Custer	R	1990-98
11	434638103253500	Road Camp at Custer State Park	N	1989-98
12	434645103240700	Water Treatment Plant at Custer State Park	S	1989-98
13	434732103305500	Bismark Lake near Custer	S	1989-98
14	434807103235400	Center Lake near Hayward	R	1989-98
15	434928103214800	North Farm at Custer State Park	S	1989-98
16	434939103272800	Camp Remington near Hayward	R	1989-98
17	435355103432800	Medicine Mountain near Custer	R[1]	1989-98

[1]Operated as nonrecording gage prior to 1994.



EXPLANATION

CUSTER STATE PARK

PRECIPITATION GAGE—Upper number is site number in table 1. Lower number is precipitation, in inches, for September 7, 1989, where available (data from National Oceanic and Atmospheric Administration, 1989, and U.S. Geological Survey, 1990)

2 0.55 — Operated by National Oceanic and Atmospheric Administration

8 1.15 — Operated by U.S. Geological Survey

Figure 14. Location of precipitation gages within study area. Precipitation amounts for a storm on September 7, 1989, also are shown.

Table 2. Selected site information for streamflow-gaging stations used in analyses

[B, burned; U, unburned; AY, annual yield; PF, peak flow]

Station number	Station name	Drainage area (square miles)	Period of record considered (water years)	Watershed condition		Analytic usage	
				B	U	AY	PF
[1]06402500	Beaver Creek near Buffalo Gap	130	1967-98		X		X
[2]06403300	French Creek above Fairburn	105	[3]1983-98		X	X	X
[2]06404000	Battle Creek near Keystone	[4]58.5	1967-98		X	X	X
[2]06404800	Grace Coolidge Creek near Hayward	7.48	1990-98		X		X
[2]06404998	Grace Coolidge Creek near Game Lodge, near Custer	[4]26.8	1977-87		X	X	X
			1989-98	X		X	
			1988-98	X			X
[2]06405000	Grace Coolidge Creek near Custer	[4]26.9	1967-76		X		X
[2]06405800	Bear Gulch near Hayward	4.23	1990-98	X			X
[1]06422500	Boxelder Creek near Nemo	96.0	1973-98		X		X
[1]06425500	Elk Creek near Elm Springs	540	1967-98		X		X
[1]06431500	Spearfish Creek at Spearfish	168	1967-98		X		X
[1]06436190	Whitewood Creek near Whitewood	77.4	1982-98		X		X

[1]Location shown in figure 2.
[2]Location shown in figure 1.
[3]Available partial record in water year 1982 (April-September) used for peak-flow analyses.
[4]Revised values.

Station 06404800 (Grace Coolidge Creek near Hayward) was installed after the fire, just upstream from the burn area (fig. 1). This station provides data for the unburned headwaters of the Grace Coolidge Creek drainage and, as such, serves as a control watershed for comparative purposes. Another streamflow-gaging station (06405800) was installed after the fire on Bear Gulch, which is tributary to Grace Coolidge Creek several miles downstream from station 06404998. The Bear Gulch drainage was severely burned, with complete deforestation occurring in nearly the entirety of the area upstream from the gaging station.

Several existing streamflow-gaging stations (table 2) also were considered for comparisons with streamflow data for the burned areas (Grace Coolidge Creek and Bear Gulch). Stations along French Creek and Battle Creek (fig. 1, table 2) were considered as control watersheds for analyses of effects on annual-yield characteristics, and various additional stations were considered for analyses of effects on peak-flow characteristics (fig. 2, table 2).

Hydrologic Considerations

Various hydrologic considerations have been important in evaluating effects of the Galena Fire on streamflow characteristics. Selection of appropriate streamflow records for comparisons between burned and unburned areas has required consideration of various factors. For analysis of annual-yield characteristics, pre-fire and post-fire comparisons are possible using records for station 06404998, Grace Coolidge Creek near Game Lodge, of which about one-half of the drainage area was burned (fig. 1). For this station, 11 years of pre-fire data (WY 1977-87) and 10 years of post-fire data (WY 1989-98) are available (table 2). Data for WY 1988, which is when the Galena Fire occurred, are not considered for analysis of annual-yield characteristics. Bear Gulch (station 06405800) is not considered for analysis of annual-yield characteristics because pre-fire data are not available.

Unburned drainages considered for analysis of annual-yield characteristics include French Creek and Battle Creek, which are located immediately south and north, respectively, of Grace Coolidge Creek. For the

French Creek station (06403300), only 5 years of data are available for the pre-fire period (WY1983-87); however, records for Battle Creek (station 06404000) are much longer and pre-date records for Grace Coolidge Creek (table 2). Thus, comparisons with Battle Creek are most useful for analysis of effects of fire on annual-yield characteristics in Grace Coolidge Creek. Furthermore, both of these drainages have very similar hydrogeologic characteristics. Large outcrop areas of the Harney Peak Granite and other similar rocks occur in both drainages (DeWitt and others, 1989). Precipitation patterns also are very similar (fig. 2) and are influenced by a topographic high that is generally centered around Harney Peak and extending from about Mount Coolidge to Mount Rushmore.

A number of drainages are considered for analysis of peak-flow characteristics. Consideration of both pre- and post-fire records are possible for Grace Coolidge Creek near Game Lodge (station 06404998) and comparisons are made with various stations along the eastern flank of the Black Hills (fig. 2) for which pre- and post-fire records are available. Peak-flow characteristics for Bear Gulch (station 06405800) can be considered only for the post-fire period. The size of the severely burned drainage area for this station (table 2) is comparable to that for Grace Coolidge Creek near Hayward (station 06404800), which is upstream from the burn area and also was installed after the fire.

Comparability of precipitation patterns between drainage basins is another important consideration in evaluating streamflow characteristics. Peak-flow events often result from relatively short-term, high-intensity precipitation events, which generally tend to have extremely large spatial variability in precipitation amounts and intensities. Thus, for consideration of peak-flow characteristics, comparability of annual precipitation patterns may not be particularly important. Annual-yield characteristics, however, are highly influenced by annual precipitation amounts (Driscoll and Carter, 2001), as shown by relations between annual yield efficiency and precipitation (fig. 15) for the

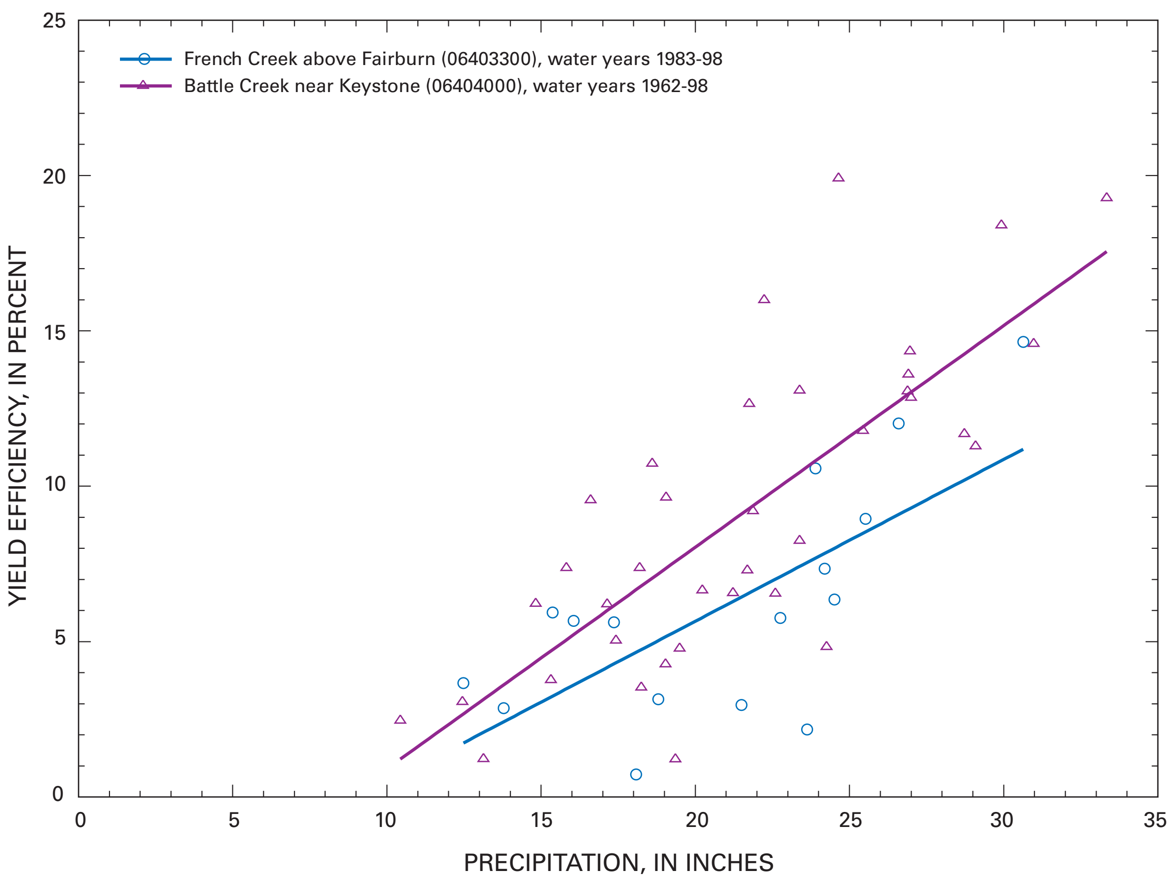


Figure 15. Relations between annual yield efficiency and precipitation for selected drainage basins.

unburned control watersheds (French Creek and Battle Creek). Data sets for these stations are provided in table 8 in the Supplemental Information section at the back of the report. For these basins, annual yield efficiencies (ratios of annual streamflow yield, in inches, to annual precipitation, in inches) have varied by as much as an order of magnitude over the range of measured conditions.

A comparison of annual precipitation amounts for the drainage areas associated with stations 06403300 (French Creek), 06404000 (Battle Creek), and 06404998 (Grace Coolidge Creek near Game Lodge), is presented in figure 16; data considered are provided in table 8. Annual precipitation for periods of overlapping streamflow record are shown for Battle and Grace Coolidge Creeks. For French Creek, annual precipitation is shown for the entire period of available streamflow record. Annual means (WY 1977-98) for Battle and Grace Coolidge Creeks are nearly identical (21.24 and 21.37 in., respectively). The annual mean (WY 1983-98) for French Creek (20.95 in.) is notably lower than for Grace Coolidge Creek for the same period (22.66 in.), which is consistent with the long-term spatial patterns indicated by figure 2.

An important trend in precipitation patterns is shown by the plots of cumulative annual precipitation departures for WY 1977-98 for the Battle and Grace Coolidge Creek drainages (fig. 17). These plots clearly indicate a pattern of generally average to below-average precipitation through WY 1988 and average to above-average precipitation during the post-fire period. Climatic conditions during WY 1995-98 were particularly wet, with annual precipitation substantially above average in the French, Battle, and Grace Coolidge Creek drainages (fig. 16).

The above-average precipitation trends during the late 1990s are an extremely important consideration in evaluating the effects of forest fire on streamflow characteristics. Because yield efficiencies generally increase with increasing annual precipitation (fig. 15), distinctions between climatic and fire-related effects are confounded, as illustrated in figure 18, which shows daily duration hydrographs for pre- and post-fire periods for Battle and Grace Coolidge Creeks. Flow characteristics for both drainages are consistently higher for the post-fire period, for all but the largest exceedance percentiles (which represent extreme low-flow characteristics).

Low-flow characteristics are nearly identical for pre- and post-fire periods for Battle Creek, with zero-flow conditions occurring about 7 percent of the time for both periods (fig. 18). For Grace Coolidge Creek, extreme low-flow conditions are less common than for Battle Creek, with zero-flow conditions occurring only about 0.2 percent of the time during the pre-fire period and 0.8 percent of the time during the post-fire period. The post-fire, low-flow characteristics for both stations are predominantly affected by conditions during WY 1989, near the end of the drought conditions during which the Galena Fire occurred. Figure 18 excludes flow records for WY 1988, for which mean annual flow is the lowest year of record for both stations (U.S. Geological Survey, 1999).

HYDROLOGIC EFFECTS OF THE GALENA FIRE

Hydrologic effects of the Galena Fire have included effects on geomorphology, water quality, and streamflow. This section of the report includes a brief summary of effects on geomorphology and water quality, and a detailed description of effects on streamflow characteristics.

Effects on Geomorphology and Water Quality

The USGS was involved with cursory studies of geomorphologic and water-quality effects immediately following the Galena Fire. These studies were performed in conjunction with the South Dakota School of Mines and Technology, and were completed by 1990. Results were described in two unpublished M.S. theses and are summarized within this section.

Whitesides (1989) described geomorphologic effects of the Galena Fire, including effects on erosion and sedimentation. Moderately burned areas did not experience substantial increases in rates of surface erosion. Severely burned areas, however, underwent surficial erosion nearly twice that of the unburned areas, with south-facing slopes experiencing more erosion than north-facing slopes in both severely burned and unburned areas. The increased erosion was caused by a combination of sheet erosion and wind erosion. The sediment production rate of Bear Gulch estimated 8 to 14 months after the fire was 870 ft^3/acre (44 tons/acre).

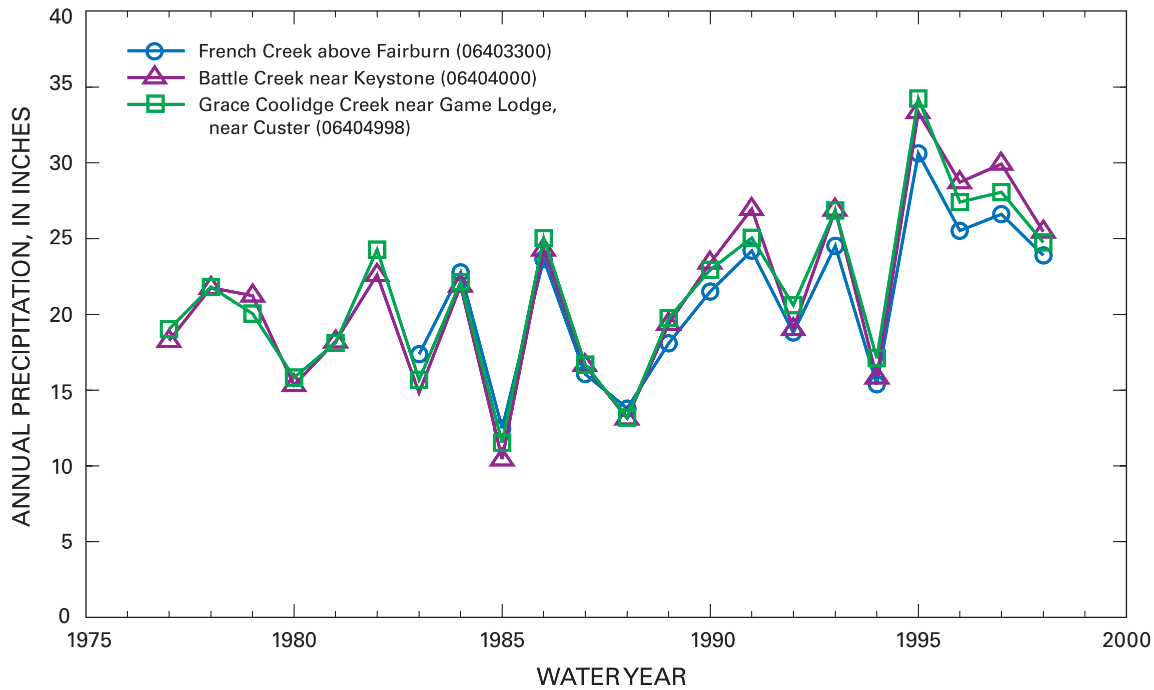


Figure 16. Annual precipitation for drainage areas of selected streamflow-gaging stations.

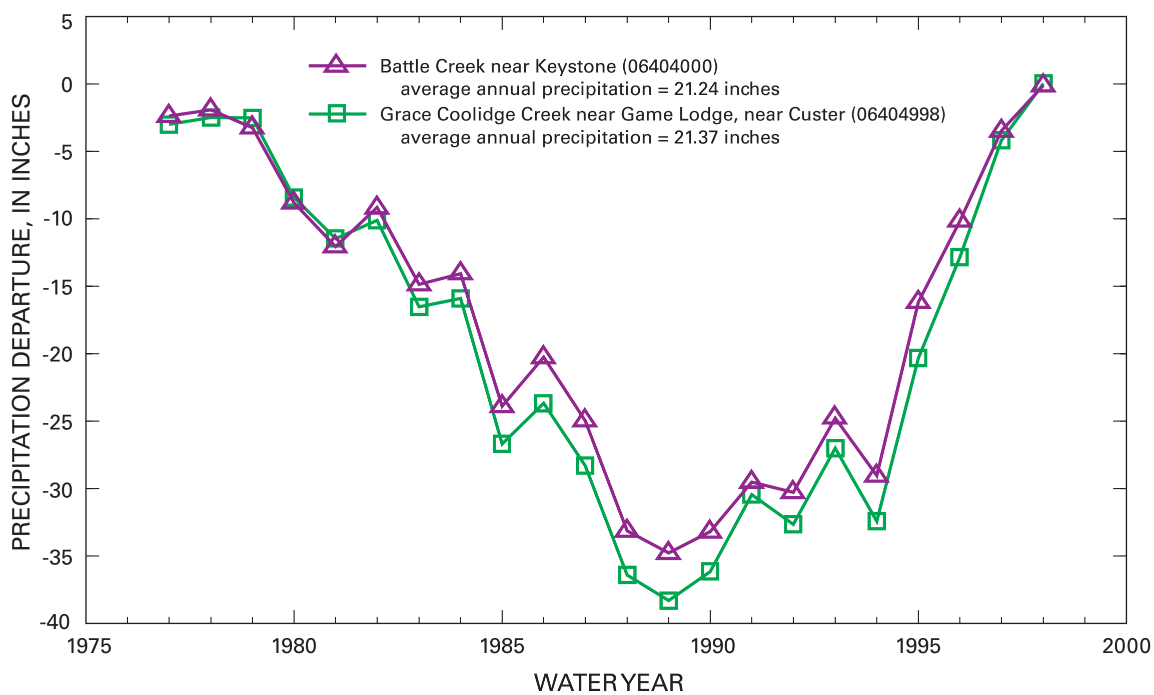


Figure 17. Cumulative departure from long-term average annual precipitation for selected drainage areas, water years 1977-98.

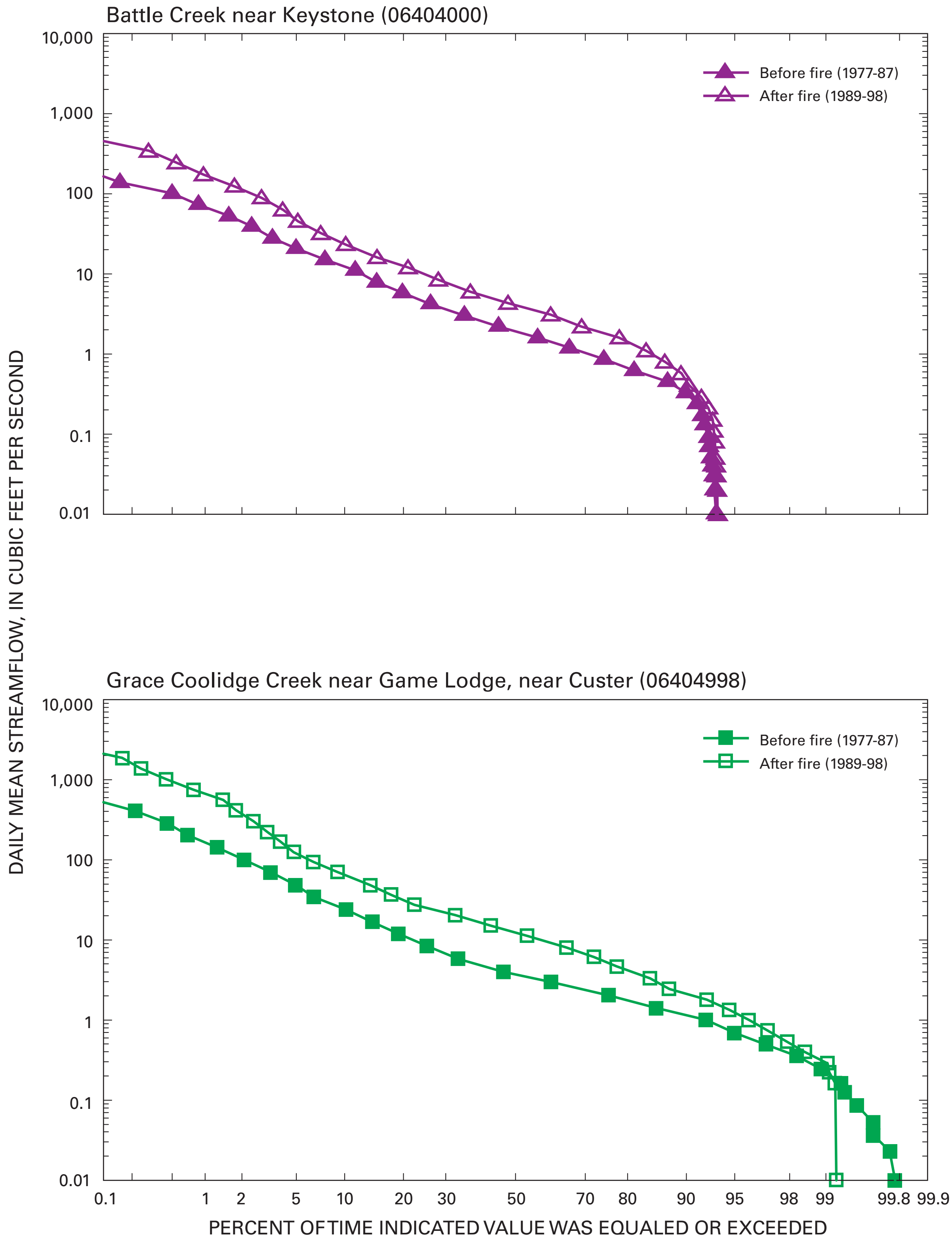


Figure 18. Duration hydrographs for selected streamflow-gaging stations.

Whitesides (1989) also described effects of the Galena Fire on stream-channel morphology. Substantial degradation of stream channels within the severely burned headwater areas of Bear Gulch was documented. Farther downstream, channel aggradation resulted from deposition of sediments transported from the headwater areas. Movement of large quantities of sediment associated with several high-flow events that occurred soon after the fire also was described by Whitesides (1989).

Gundarlahalli (1990) described effects of the Galena Fire on water quality. Sampling locations (fig. 1) included Grace Coolidge Creek upstream (station 06404800) and downstream (station 06404998) of the burn area and Bear Gulch (station 06405800), which was extensively burned. The most notable effect was on concentrations of suspended sediment, which were orders of magnitude higher for Bear Gulch than for the unburned area. Concentrations of suspended sediment were intermediate for the downstream site on Grace Coolidge Creek, which was considered representative of a moderately burned area.

Effects on several other water-quality constituents, such as organic carbon and nitrogen and phosphorus nutrient constituents, probably were influenced by the large concentrations of suspended matter that were documented in initial post-fire, stormflow events (Gundarlahalli,1990). The first post-fire stormflow produced the highest measured concentrations of specific conductance, nitrogen, phosphorus, organic carbon, calcium, magnesium, potassium, manganese, and sulfate in the burned areas. For most constituents sampled, differences in concentrations between burned and unburned areas were no longer discernible within about 1 year following the Galena Fire.

Large sediment loads resulting from the Galena Fire may have influenced streamflow losses to the Madison aquifer that occur along Grace Coolidge Creek downstream from station 06404998 (fig. 1). In an unrelated study, Hortness and Driscoll (1998) reported that calculated loss rates along Grace Coolidge Creek were consistently smaller for water years (WY) 1990-95 than calculated losses during WY 1978 and WY 1996. Deposition of fine-grained sediment within the stream channel following the Galena Fire was hypothesized as the cause for the decrease in the loss rate.

Effects on Streamflow Characteristics

Within this section, effects of the Galena Fire on streamflow characteristics are evaluated. Evaluations of effects on both annual-yield and peak-flow characteristics are described.

Effects on Annual-Yield Characteristics

Numerous previous studies have indicated increased water yield following timber harvests; thus, increased yields also might be expected from decreased timber density resulting from forest fire, especially in areas with low to moderate burn intensity. Alternatively, one might hypothesize that in areas of high-intensity burns, decreased shading from denuding of forest cover could result in increased evaporation. In this section, a variety of approaches are utilized to evaluate potential changes in annual-yield characteristics for Grace Coolidge Creek.

As discussed in the previous section, potential effects of the 1988 Galena Fire on annual-yield characteristics of Grace Coolidge Creek are evaluated using comparisons between station 06404998 (burned area) and stations on French Creek (06403300) and Battle Creek (06404000). Hydrographs showing annual yield (in inches) for these three stations are presented in figure 19. All three hydrographs clearly show trends of substantially increased yields in response to the particularly wet years of the 1990s (fig. 16).

Mass analysis (Linsley and others, 1982) is a simple plotting procedure that can be useful for examination of trend data. Plots of cumulative annual yield versus time are presented in figure 20 for periods of overlapping streamflow record between Grace Coolidge Creek and each of the two comparison basins (French Creek and Battle Creek). Increased trends in annual yield resulting from increased precipitation trends (fig. 16) are clearly indicated for all three basins by inflection points around 1990. Another change in slope reflecting the especially wet conditions during 1995-98 also is apparent for each of the three basins.

Graphs of cumulative annual yield versus cumulative annual precipitation (double mass analysis) are presented in figure 21. Close examination of the upper plot in figure 21 indicates that contrary to the long-term regional pattern (fig. 2), cumulative precipitation for the French Creek drainage was slightly, but consistently, greater than or equal to cumulative precipitation for the Grace Coolidge Creek drainage for the first few years of overlapping streamflow record. Annual

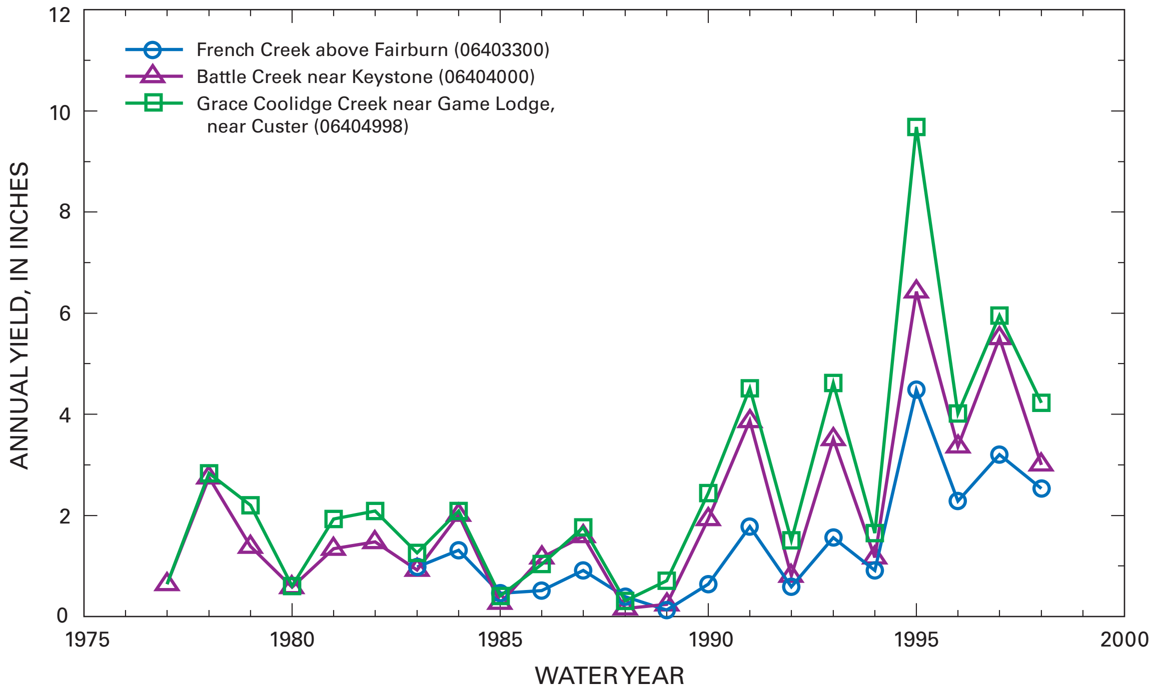


Figure 19. Annual yield for French Creek, Battle Creek, and Grace Coolidge Creek.

precipitation during the pre-burn period (WY 1983-87) averaged 18.46 and 18.21 in. for French Creek and Grace Coolidge Creek, respectively, compared with annual means of 22.91 and 24.67 in. for WY 1989-98. This subtle change in precipitation patterns contributes substantially to the large difference in annual yield patterns for the two drainages during these two periods (fig. 21). Thus, potential effects resulting from the Galena Fire cannot be distinguished from climatic effects, and no further comparisons are made between French Creek and Grace Coolidge Creek for analysis of annual-yield characteristics.

The lower plot in figure 21 indicates that subtle changes in precipitation patterns also occurred for the Battle Creek and Grace Coolidge Creek drainages; however, close examination of these data supports a conclusion of increased post-burn water yield for Grace Coolidge Creek. For the pre-burn period (WY 1977-87), cumulative annual precipitation for Grace Coolidge Creek was slightly larger than for Battle Creek (fig. 21). Mean annual precipitation was about 2 percent larger for Grace Coolidge Creek than for Battle Creek during this period (table 3). Mean annual yield and yield efficiency during the pre-burn period also were slightly larger for Grace Coolidge Creek than for Battle Creek (table 3), which is consistent with larger precipitation (fig. 15). During WY 1989-94, mean annual precipitation for Grace Coolidge Creek was less than 1 percent larger than for Battle Creek (table 3); however, divergence of the cumulative yield plots is much larger than divergence during the pre-burn period (fig. 21). During WY 1995-98, mean annual yields and yield efficiencies for Grace Coolidge Creek were substantially larger than for Battle Creek, in spite of slightly smaller mean annual precipitation (table 3). For the entire post-burn period (WY 1989-98), when most of the divergence in cumulative yield occurred, mean annual precipitation for Grace Coolidge Creek was about 1 percent smaller than for Battle Creek. During the post-burn period, mean yield efficiency for Grace Coolidge Creek was 32 percent larger than for Battle Creek, compared with a 16 percent differential for the pre-burn period.

Standard approaches to evaluation of increased yields typically would include determination of the statistical significance of yield increases. Because the distribution of mean annual precipitation between Grace Coolidge Creek and Battle Creek changed slightly during the pre-burn and post-burn periods, statistical evaluations described in the following paragraphs were performed using comparisons of yield efficiencies, which account for differences in annual precipitation.

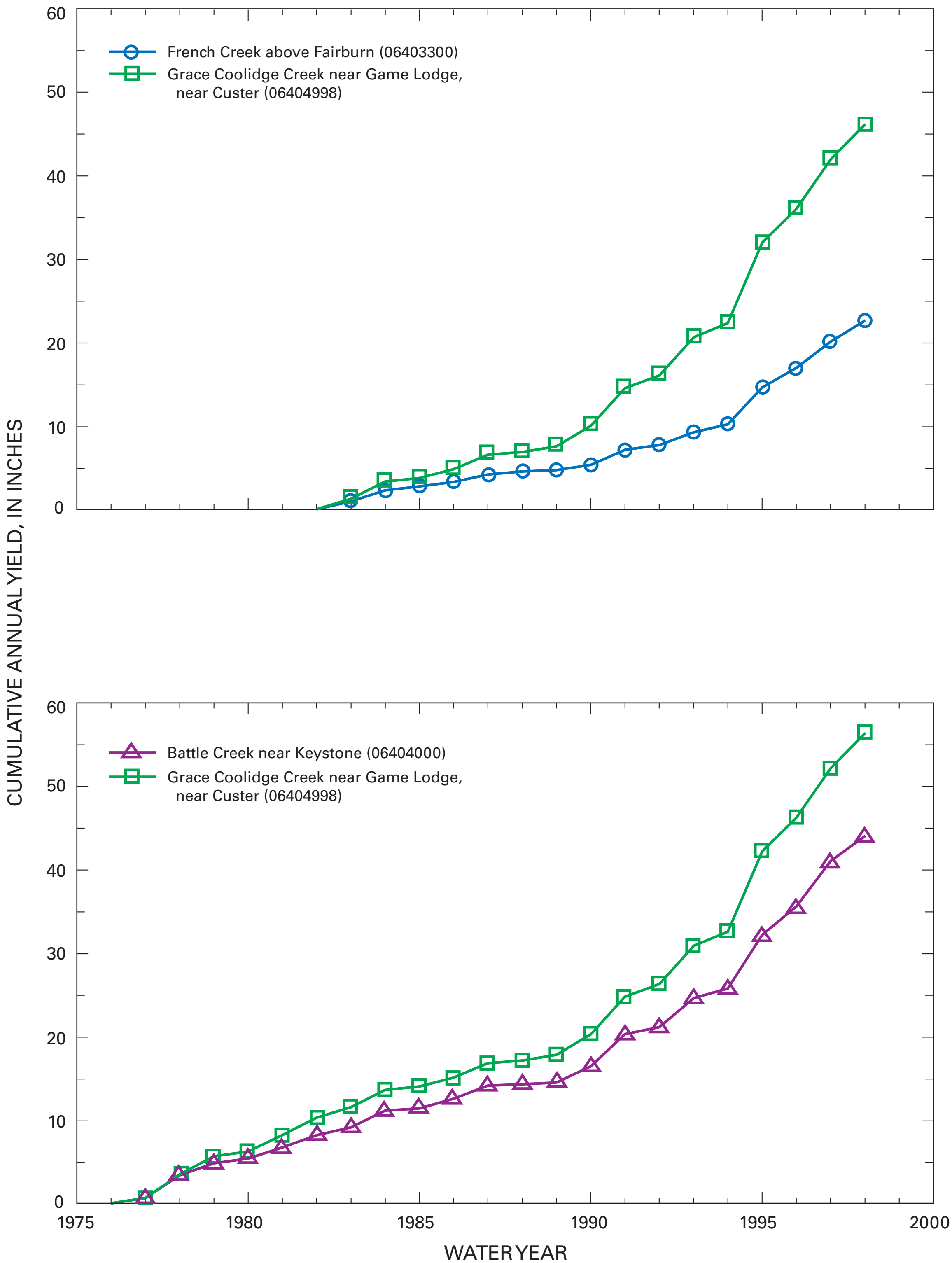


Figure 20. Mass analysis for selected streams in comparison to Grace Coolidge Creek.

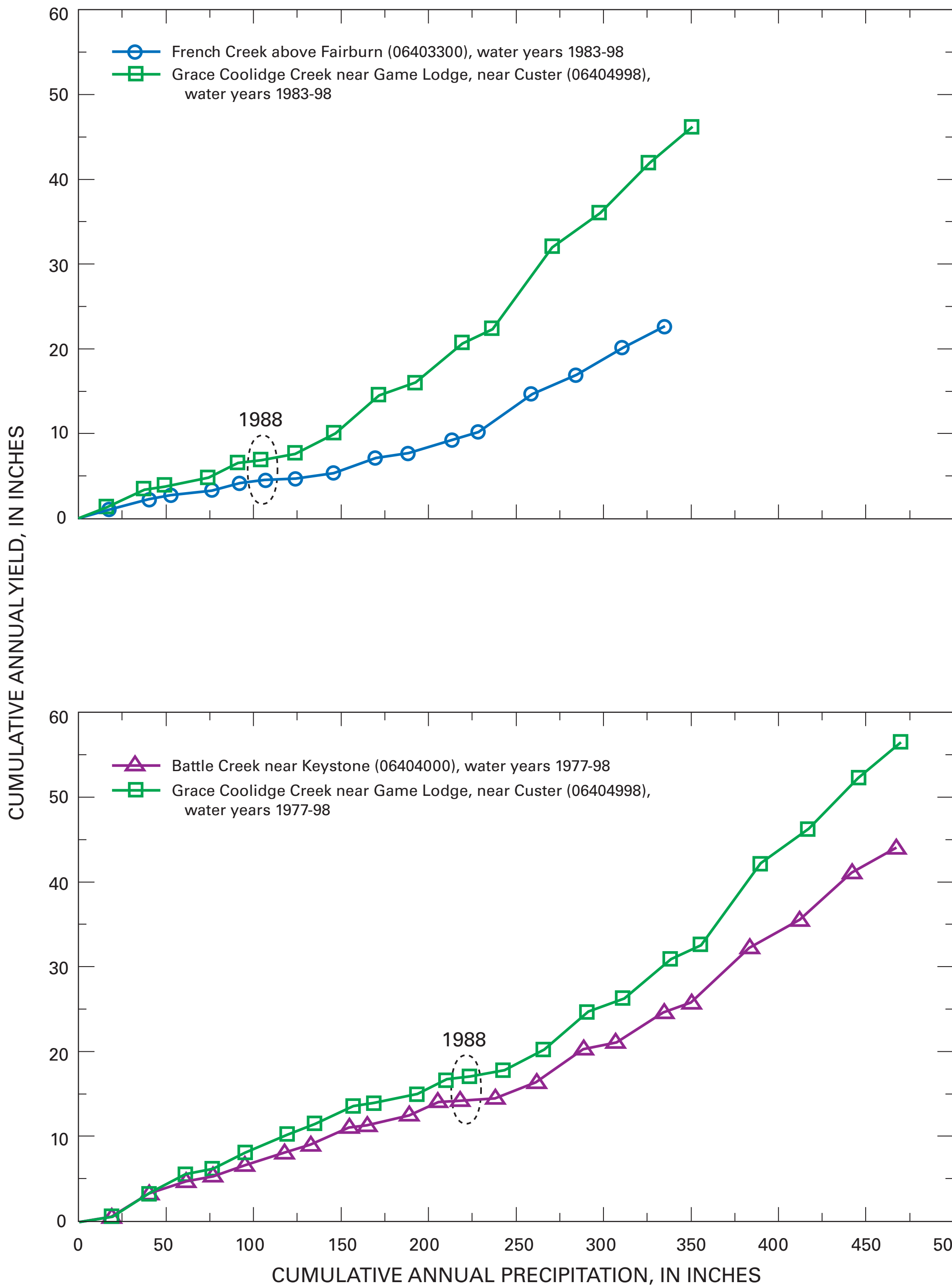


Figure 21. Double mass analysis for selected streams in comparison to Grace Coolidge Creek.

Table 3. Summary of precipitation and yield data for selected periods for Battle Creek and Grace Coolidge Creek

Period (water years)	Battle Creek (06404000)			Grace Coolidge Creek (06404998)		
	Mean annual precipitation (inches)	Mean annual yield (inches)	Mean yield efficiency (percent)	Mean annual precipitation (inches)	Mean annual yield (inches)	Mean yield efficiency (percent)
1977-87	18.67	1.29	6.9	19.10	1.53	8.0
1989-94	21.90	1.92	8.8	22.05	2.57	11.7
1995-98	29.36	4.57	15.6	28.60	5.97	20.9
1989-98	24.89	2.98	12.0	24.67	3.93	15.9

A one-sided comparison of pre- and post-burn yield efficiencies for Grace Coolidge Creek using the Wilcoxon rank-sum test (Helsel and Hirsch, 1992) confirms that the post-burn increase is statistically significant (p-value = 0.012), which indicates a 98.8 percent probability that the increase is not a chance occurrence. The same test for Battle Creek indicates that because of increased yield efficiency associated with increased precipitation (fig. 15), yield efficiency for the control watershed also increased during the post-burn period, but at a lower confidence level (p-value = 0.029).

A one-sided comparison of paired post-burn yield efficiencies using the Wilcoxon signed-rank test (Helsel and Hirsch, 1992) provides strongly significant confirmation (p-value = 0.001) that post-burn efficiencies for Grace Coolidge Creek are larger than for Battle Creek. The same test for the paired pre-burn efficiencies indicates that pre-burn efficiencies for Grace Coolidge Creek also are significantly larger (p-value = 0.013) than for Battle Creek, which again limits the capability of making a definitive statistical inference that yield efficiencies have increased because of deforestation.

The preceding discussions indicate that statistical interpretations are not conclusive, but do not necessarily indicate that yield efficiencies have not increased because of deforestation. Another perspective is obtained from a somewhat intuitive approach. As discussed previously, mean annual post-burn yield for Grace Coolidge Creek increased substantially relative to yield for Battle Creek, despite a small relative decrease in mean annual precipitation (table 3). A comparison of annual yield efficiencies (table 8) indicates that yield efficiency for Battle Creek equalled or exceeded that for Grace Coolidge Creek for 3 of 11 pre-burn years (one year was a tie); however, yield efficiency for Grace Coolidge Creek was not exceeded during any of the 10 post-fire years.

The sign test (Helsel and Hirsch, 1992), which compares strictly non-zero differences in paired data, is similar to the Wilcoxon signed-rank test, but has less power because magnitudes of differences are not considered. A one-sided sign test comparing post-burn yield efficiencies (p-value = 0.001) indicates a 99.9 percent probability that 10 consecutive exceedances of Battle Creek by Grace Coolidge Creek is a non-chance occurrence. The same test for the pre-burn period (p-value = 0.055) indicates only a 94.5 percent probability of non-chance occurrence for the 8 of 10 non-tied exceedances of Battle Creek by Grace Coolidge Creek. This is justification for acceptance of the null hypothesis (no difference in pre-burn yield efficiencies between Grace Coolidge Creek and Battle Creek) and rejection of the one-sided alternative hypothesis (pre-burn efficiency larger for Grace Coolidge Creek than Battle Creek) at a significance level of 0.05 that typically is used for hypothesis testing (Helsel and Hirsch, 1992).

Plots of annual yield versus precipitation for pre- and post-burn periods for both Battle Creek and Grace Coolidge Creek (fig. 22) provide another graphical perspective on the post-burn change in yield characteristics for Grace Coolidge Creek. The pre-burn regression lines indicate very similar yield characteristics for both drainages, and clearly reflect the slightly higher yield characteristics for Grace Coolidge Creek. The effect of slightly higher pre-burn precipitation for Grace Coolidge Creek is evaluated by substituting the mean pre-burn precipitation value of 18.67 in. for Battle Creek (table 3) into the regression equation for Grace Coolidge Creek. The resulting (calculated) annual yield of 1.49 in. is about 97 percent of the actual mean annual yield of 1.53 in/yr, and also is substantially larger than the actual mean of 1.29 in/yr for Battle Creek. Thus, the effect of slightly larger pre-burn precipitation for Grace Coolidge Creek is considered negligible.

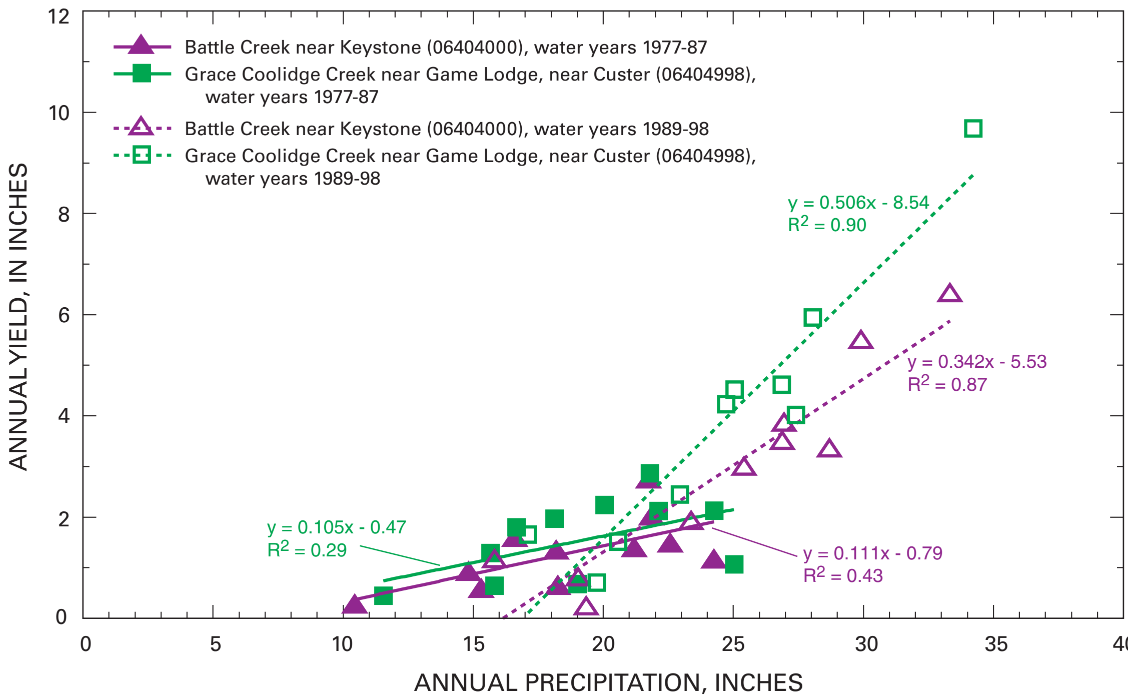


Figure 22. Relations between annual yield and annual precipitation for Battle Creek and Grace Coolidge Creek before and after the Galena Fire.

Complications associated with quantification of post-burn yield characteristics for Grace Coolidge Creek also are well illustrated in figure 22. Divergence of the post-burn regression lines indicates increased post-burn yield for Grace Coolidge Creek, relative to Battle Creek; however, it also is apparent that substantial increases in yield have resulted from increased precipitation during the post-burn period for both drainages. The absence of high-yield data points during the pre-burn period is another apparent problem.

Relations between annual yield for Grace Coolidge Creek and Battle Creek (fig. 23) are used to quantify increased yield for Grace Coolidge Creek. As discussed, many of the post-burn data points are well beyond the range of the pre-burn data, which requires extrapolation of the pre-burn regression equation to obtain estimates of annual yield for an "unburned" condition for Grace Coolidge Creek for the upper range of the yield values.

Estimates of increased yield for Grace Coolidge Creek derived from comparisons between the post-burn and unburned regression equations from figure 23 are presented in table 4. The estimates for both unburned and post-burn conditions for Grace Coolidge Creek are obtained by substituting hypothetical values of annual yield for Battle Creek into the regression equations. For most of the range of annual yield values, the estimates indicate increased yields of about 20 percent for the post-burn condition, relative to predicted yields for the unburned condition. Estimated increases are somewhat less than 20 percent for hypothetical values of annual yield for Battle Creek that are less than about 3.0 in.

Table 4. Estimates of increased annual yield for Grace Coolidge Creek, based on comparison of regression equations from figure 23

Hypothetical yield for Battle Creek (inches per year)	Predicted unburned yield for Grace Coolidge Creek (inches per year)	Predicted post-burn yield for Grace Coolidge Creek (inches per year)	Predicted yield increase for Grace Coolidge Creek (percent)
0.50	0.72	0.80	11.1
1.00	1.24	1.43	15.3
2.00	2.27	2.69	18.5
3.00	3.31	3.96	19.6
4.00	4.35	5.22	20.0
5.00	5.38	6.48	20.4
6.00	6.42	7.75	20.7
7.00	7.46	9.01	20.8

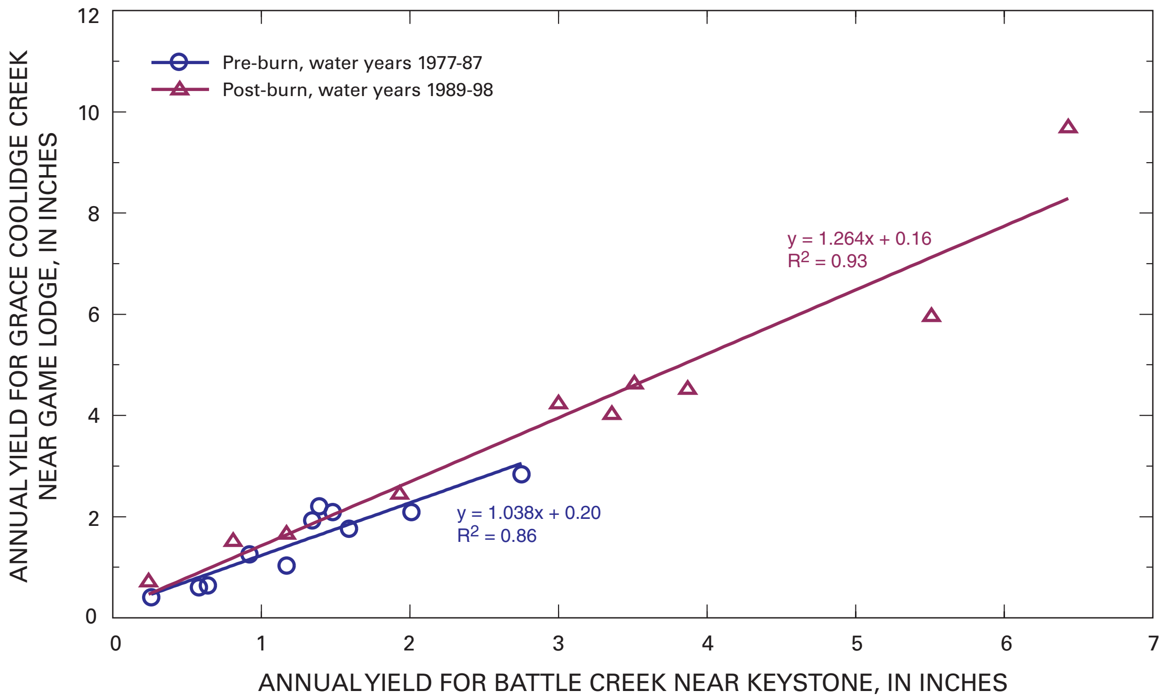


Figure 23. Relations between annual yield for Battle Creek and Grace Coolidge Creek for pre-burn and post-burn periods.

Estimates of increased yield also can be derived by comparing measured post-burn yields for Grace Coolidge Creek with predicted yields for the unburned condition (table 5), which are obtained by substituting measured post-burn yields for Battle Creek into the unburned regression equation from figure 23. For this analysis, the predicted yield increases (in percent) for individual years demonstrate considerable variability because they reflect the variability of the measured post-burn values for Grace Coolidge Creek about the post-burn regression line.

Another useful perspective is obtained by consideration of the mean values that are summarized in table 5. The arithmetic mean increase in yields for the individual years is 23.8 percent; however, the mean increase calculated from the totals for all years is 19.5 percent. An inherent characteristic of the least-squares regression method is that the regression line passes through the mean of the data sets for both the dependent and independent variables. Thus, substitution of the post-burn mean yield of 2.98 in. for Battle Creek (table 5) into the unburned and post-burn regression equations (fig. 23) would result in predicted yields of 3.29 in. and 3.93 in., respectively, which are the means for the unburned and post-burn conditions for Grace Coolidge Creek (table 5). These are the calculations that were summarized in table 4, and results are very closely approximated by the value of 3.00 in. for Battle Creek that was used as one of the hypothetical input values. Therefore, the mean increase of 19.5 percent truly represents the central tendency for the data sets and provides a better estimate of increased yield than the arithmetic mean of 23.8 percent.

Because annual precipitation is not considered in the "yield versus yield" regression equations (fig. 23), an inherent assumption in the approach is that differences in annual precipitation for Battle Creek and Grace Coolidge Creek are negligible. As discussed previously, mean annual precipitation for Grace Coolidge Creek was slightly larger than for Battle Creek during the pre-burn period, but was slightly smaller during the post-burn period (table 3). Thus, the post-burn increase in annual yield for Grace Coolidge Creek could actually be slightly larger than estimated.

As discussed, many of the post-burn data points are well beyond the range of the pre-burn data, which requires extrapolation of the pre-burn regression equation to obtain estimates of annual yield for the unburned condition for Grace Coolidge Creek for the upper range of the yield values (fig. 23). The possibility of substantially disproportionate differences in yield characteristics (either smaller or larger) between Battle Creek and Grace Coolidge Creek, for a higher range of yield values than what occurred during the pre-burn period, cannot be discounted. This possibility is the largest source of uncertainty in estimating post-burn yield increases for Grace Coolidge Creek. The strong correlations between annual yield data for the two basins for both the pre-burn ($r^2 = 0.86$) and post-burn ($r^2 = 0.93$) periods (fig. 23) provide confidence, however, that reasonable estimates are obtained by extrapolation of the regression equation for the pre-burn period.

It is possible that estimated yield increases for Grace Coolidge Creek may have been influenced by timber management activities in addition to the Galena Fire. Possible influences could have included increased timber density in the Battle Creek drainage or decreased timber density in the unburned part of the Grace Coolidge Creek drainage. These potential influences are evaluated in the following discussions.

Logging activity in the Norbeck Wilderness Area, which composes much of the Battle Creek drainage area, has been relatively minimal during recent years, as was discussed in the Timber Management section of this report. Thus, potential has existed for relatively slow, but steady increases in timber density, which could result in decreased water yield over time. This potential is evaluated by examination of figure 24, which shows cumulative annual yield and cumulative annual precipitation departure for the entire period of streamflow record available for the Battle Creek drainage (WY 1962-98). Trend lines for annual yield during three short periods of approximately average precipitation trend have been constructed in figure 24 using an “eyeball” fit. Very slight cumulative precipitation deficits occurred during 1965-70 and 1975-79, and slopes for annual yield are essentially identical during these periods. A slight precipitation surplus occurred during 1990-95, and the slope for the corresponding yield trend is slightly steeper than the slopes for the other two periods. Thus, it is concluded that there is no evidence of measurably declining yield for the Battle Creek drainage.

Table 5. Estimates of increased annual yield for Grace Coolidge Creek, based on comparison of actual post-burn values with unburned regression equation from figure 23

[NA, not applicable]

Water year	Measured yield for Battle Creek (inches)	Predicted unburned yield for Grace Coolidge Creek (inches)	Measured post-burn yield for Grace Coolidge Creek (inches)	Predicted post-burn yield increase for Grace Coolidge Creek	
				(inches)	(percent)
1989	0.24	0.45	0.71	0.26	58.9
1990	1.93	2.20	2.44	.24	10.9
1991	3.87	4.21	4.51	.30	7.1
1992	.81	1.04	1.51	.47	45.5
1993	3.51	3.84	4.62	.78	20.4
1994	1.17	1.41	1.65	.24	16.9
1995	6.43	6.87	9.68	2.81	41.0
1996	3.36	3.68	4.02	.34	9.2
1997	5.51	5.91	5.95	.04	.6
1998	3.00	3.31	4.23	.92	27.8
Total	29.83	32.91	39.32	6.40	NA
Mean	2.98	3.29	3.93	.64	[1]19.5
Arithmetic mean of predicted increases for individual years					23.8

[1]Mean percent increase based on totals for 10-year period.

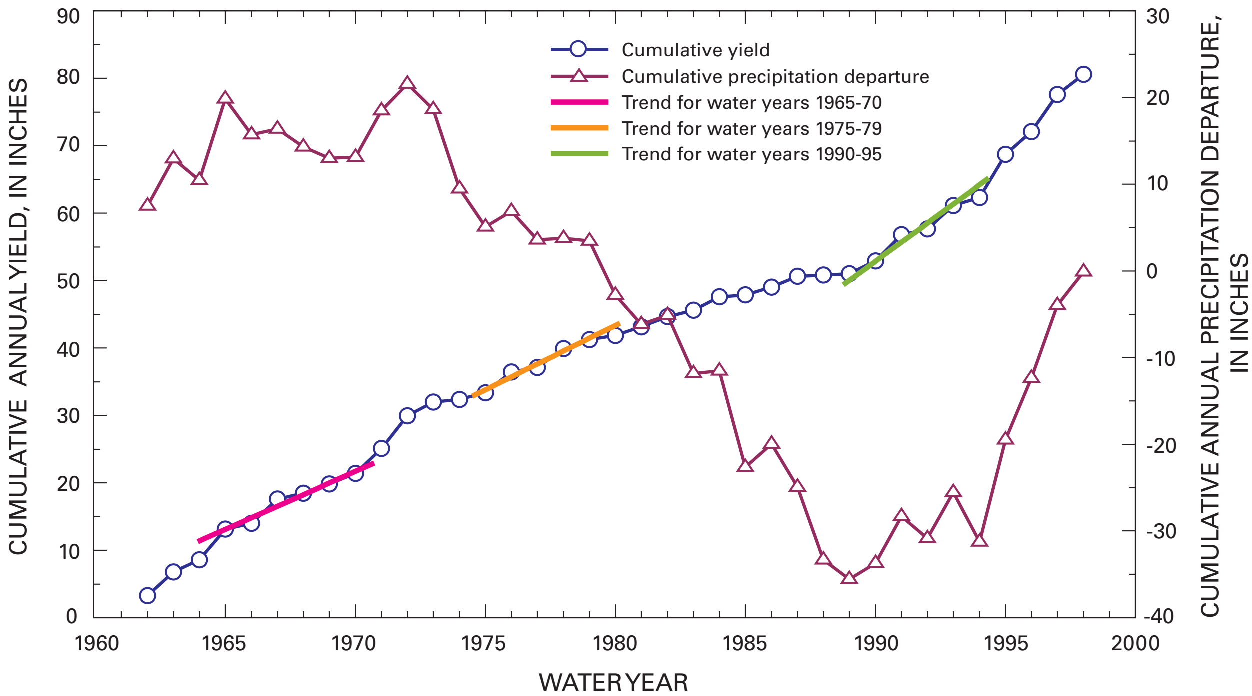


Figure 24. Cumulative annual yield and cumulative annual precipitation departure from long-term average for Battle Creek near Keystone (06404000). Trends for three periods of generally average precipitation also are shown.

Evaluation of various additional information indicates that the estimated increases in water yield have not been influenced by decreased timber stand density within unburned parts of the Grace Coolidge Creek drainage during the post-burn period. Walker and others (1995) reported timber harvest from 13,618 acres within Custer State Park of 22,541 thousand board feet (MBF) during 1981-87 and 8,383 MBF during 1989-94. Non-commercial thinning consisted of 5,780 acres during 1981-87 and 728 acres during 1989-94. About one-half of the reported timber treatment occurred within the Grace Coolidge Creek drainage, most of which was in the unburned part of the drainage in the northwest part of Custer State Park. The reported acreages are for unburned areas; however, the extent of the Galena Fire did include very minor areas where harvest or thinning treatments had previously occurred (Ron Walker, Custer State Park, oral commun., 2003). With the exception of post-fire salvage operations, timber management within the Grace Coolidge Creek drainage during 1989-98 has been very minimal (Ron Walker, Custer State Park, oral commun., 2003). Thus, timber stand density within the unburned part of the Grace Coolidge Creek drainage probably did not decrease substantially during the post-burn period, and may in fact have increased, as evidenced by the aerial photographs provided in figure 8.

Evaluation of all available information supports a conclusion of increased annual yield of about 20 percent for Grace Coolidge Creek as a result of the Galena Fire, which is consistent with a preponderance of literature that indicates increased yields associated with deforestation from both timber harvest and fire effects. The fire-induced timber treatment included about one-half of the Grace Coolidge Creek drainage area, and consisted of nearly 100 percent timber removal from about 54 percent of the burn area and about 50 percent removal from about 29 percent of the burn area. About 7 percent of the burn area had predominantly surviving timber stands, and about 10 percent of the area was non-timbered prior to the fire. The resulting overall timber treatment might approximate 20 to 25 percent timber removal from the entire basin. Pre-burn timber stand densities in the Grace Coolidge Creek drainage probably were not uniformly distributed because of extensive timber management activities in the generally unburned northwest part of Custer State Park during the late 1970s and early to mid 1980s. Thus, the overall net effect of the Galena Fire on timber density cannot necessarily be generalized.

Effects on Peak-Flow Characteristics

Numerous previous studies have documented increased peak-flow characteristics following forest fire. Various physical factors contribute to the potential for increased stormflows. Increased stormflow volumes could result from several factors, including: (1) reduced interception from removal of pine canopy; (2) reduced interception from removal of ground litter and grasses; and (3) reduced infiltration rates from development of water repellent layers within the soil horizon. Increased antecedent soil-moisture storage resulting from decreased evapotranspiration also could be expected for some percentage of storm events, based on results of the analysis of effects on annual-yield characteristics. In addition, reduced traveltimes from hillslopes to channels resulting from removal of ground cover would be expected to contribute to generally steeper hydrographs with larger peak discharges.

Substantial increases in peak-flow characteristics for severely burned drainages were visually apparent after the Galena Fire from numerous post-fire field observations that were obtained in collecting data for studies of geomorphologic effects (Whitesides, 1989) and water-quality effects (Gundarlahalli, 1990). Evidence of frequent, minor runoff events from burned drainages was readily apparent because stream banks were coated with fine ash mobilized from burned areas. Somewhat larger runoff events also occurred frequently, and would mobilize large volumes of woody debris, including pine needles, charred pine bark, and tree limbs. Clogging of culverts occurred frequently, and typically resulted in deposition of large volumes of woody debris upstream from roads (fig. 25). Mobilization of sediment for large events was apparent from sediment deposits formed in numerous locations (fig. 26). Dramatic evidence of a particularly extreme runoff event from a small, intensively burned drainage was provided by a deposit of boulders emplaced as a small alluvial fan at the base of an extremely steep channel (fig. 27).

September 1989

August 1988

Photographs by Mark T. Anderson

Figure 25. Culverts occasionally became clogged with debris following large runoff events.

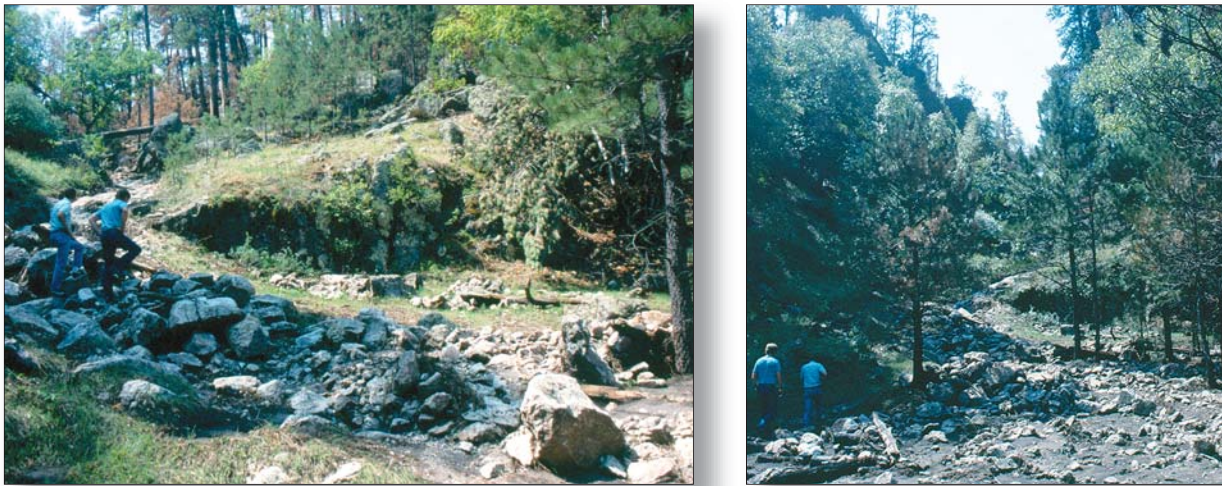
Available streamflow records support the evidence from visual observations of increased stormflow potential from burned areas; however, quantification of effects is complicated by various factors. A primary difficulty is an inability to accurately account for extremely large variability in precipitation intensities and totals that can occur over very small distances during short-duration, high-intensity storms that often are influential in driving peak-flow events. Effects from differences in antecedent precipitation conditions probably are relatively minor because of the generally similar trends in longer term precipitation conditions in the proximity of drainage basins used for comparisons.

Figure 26. Numerous sediment deposits formed as a result of heavy erosion.

A qualitative perspective regarding effects of the Galena Fire on peak-flow characteristics is provided by a graphical comparison of maximum daily instantaneous streamflow values (April through October during post-fire years) for selected sites (fig. 28). In spite of smaller drainage area (table 2), numerous peaks for Bear Gulch during 1989 are substantially larger than for Grace Coolidge Creek (near Hayward). The steepness of many of these peaks for Bear Gulch is consistent with the anticipated post-fire response, and the relative frequency of occurrence is consistent with the field observations discussed previously. Substantially fewer peaks for Bear Gulch are larger than for Grace Coolidge Creek during 1990, with the number of exceeding peaks generally declining during subsequent years.

Various data for selected peaks from figure 28 for Bear Gulch and Grace Coolidge Creek (near Hayward) are presented in table 9 (in the Supplemental Information section). The selected peaks include all peaks where the maximum daily instantaneous streamflow equalled or exceeded 10.0 ft^3/s for at least one of the sites, and the data set presented includes the maximum value for associated peaks for both sites. Most of the matched peaks occurred on the same dates; however, several peaks are lagged by one day.

Boxplots showing distributions of peak discharges from table 9 are presented in figure 29. These



Photographs by C.J. Winter

Figure 27. Boulders were deposited following an extreme runoff event.

boxplots confirm the previous observation that peaks for Bear Gulch routinely exceeded associated peaks for Grace Coolidge Creek (near Hayward) during 1989 and 1990, and that peak-flow potential for Bear Gulch decreased dramatically after 1990. Differences in drainage areas between Grace Coolidge Creek (7.48 mi^2) and Bear Gulch (4.23 mi^2) are an important consideration in comparing the data in figure 29. Peak-flow estimates for ungaged areas commonly are obtained by factoring estimates for gaged areas by the drainage-area ratio raised to an exponent of 0.5 (Burr and Korkow, 1996). Application of this method would yield a coefficient of 0.75 for estimating peaks for Bear Gulch on the basis of the control watershed (Grace Coolidge Creek). This coefficient closely approximates the ratios between Bear Gulch and Grace Coolidge Creek for both median and mean values for the 46 peaks during 1991-98 period (table 9). This comparison indicates general similarities in peak-flow characteristics for the two drainages after 1990.

Peak discharges per unit area for the selected peaks also are presented in table 9, in addition to ratios of the unit-area peak discharges (Bear Gulch to Grace Coolidge Creek). Boxplots of this data set are presented in figure 30. Unit-peak discharges for Bear Gulch would be expected to exceed those for Grace Coolidge Creek (near Hayward) by a factor of about 1.33 (the inverse of 0.75) because of the drainage area considerations discussed in the preceding paragraph. The median of the 46 values for 1991-98 is 1.6, which again indicates similar peak-flow characteristics for the two drainages for this period. The mean value of 4.6 is not representative of the central tendency for the data set because it is heavily skewed by a large outlier for August 5, 1995, with a ratio of 98.24 (table 9). In comparison, mean and median values for 1990 and 1989 are about one and two orders of magnitude larger, respectively, than the median for 1991-98. These ratios are influenced primarily by the numerous, but relatively small, peaks that occurred frequently within the first several years of the fire and are not representative of the magnitude of effects that might occur for larger events.

Comparisons of maximum daily instantaneous streamflow for Grace Coolidge Creek (near Game Lodge) and Battle Creek also are provided in figure 28. Increased peak-flow response for Grace Coolidge Creek is apparent only for 1988-89. The most notable responses are the particularly large peaks in August of 1988 and September of 1989. Minor responses also are apparent for a series of small peaks for Grace Coolidge Creek during September and October of 1989, when corresponding responses for Battle Creek were minimal, with the exception of a single large peak during late September that was an order of magnitude larger than the corresponding peak for Grace Coolidge Creek.

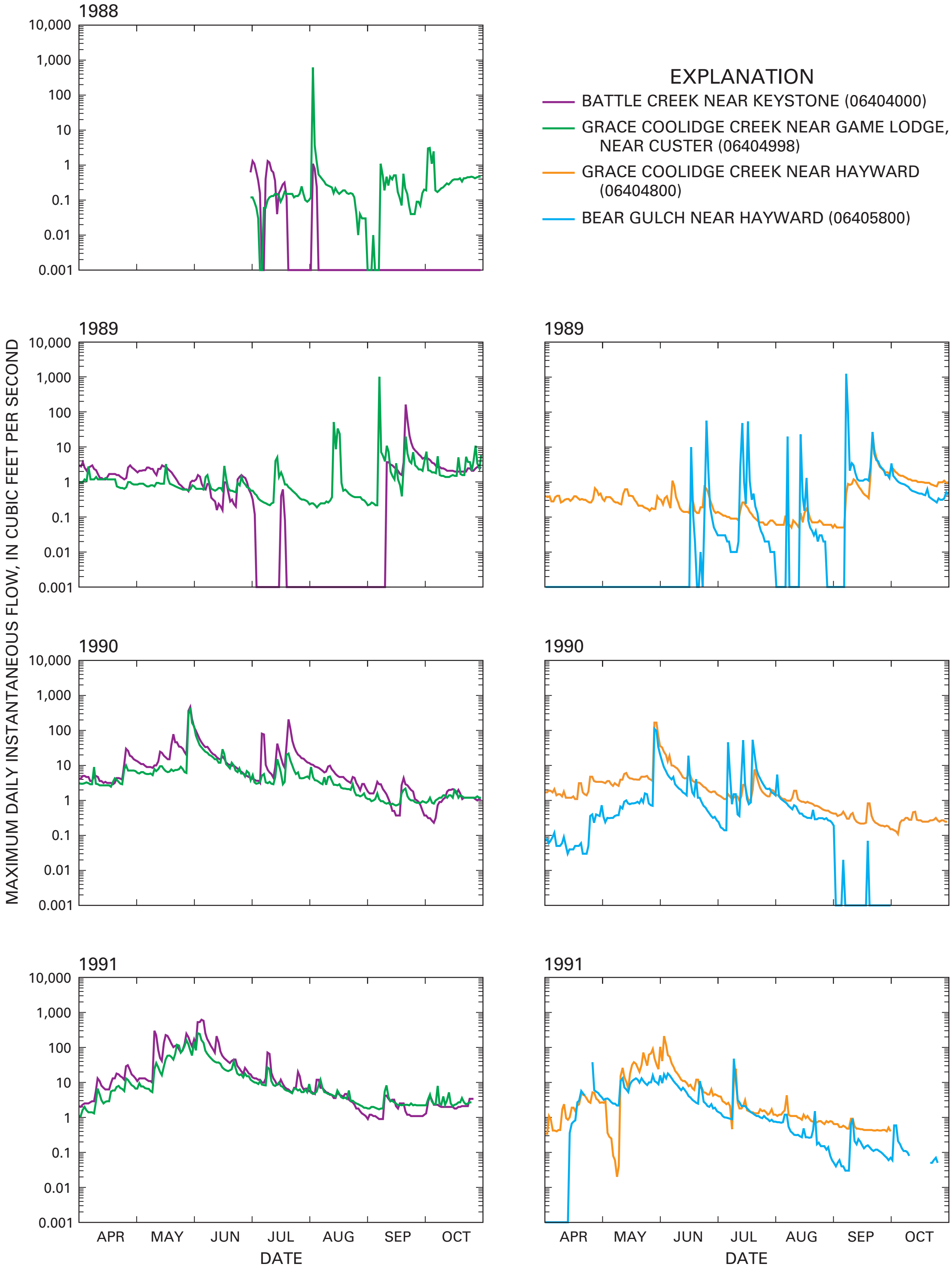


Figure 28. Maximum daily streamflow (April-October) for Battle Creek, Grace Coolidge Creek, and Bear Gulch. Zero-flow values are plotted as 0.001 cubic feet per second.

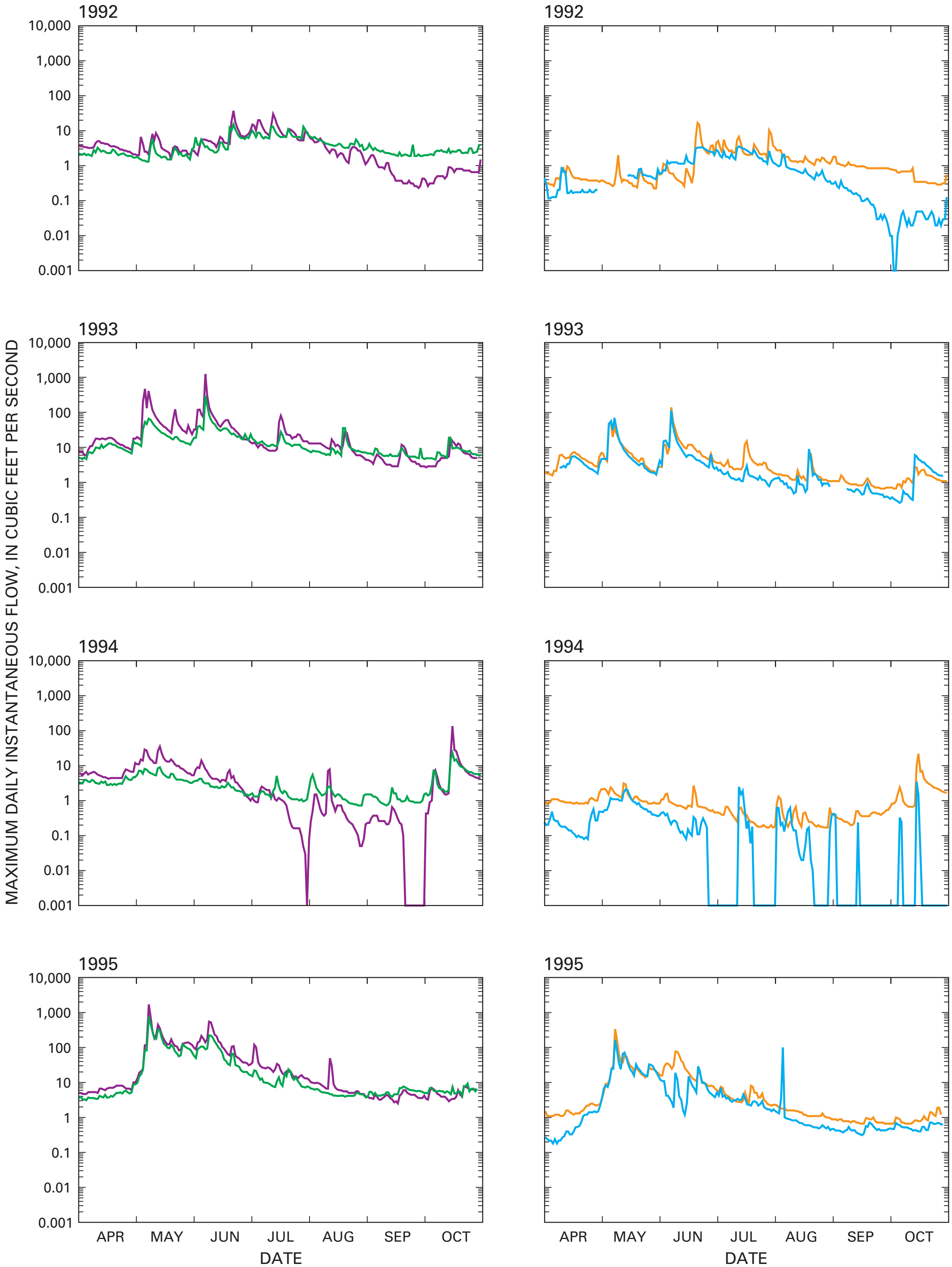


Figure 28. Maximum daily streamflow (April-October) for Battle Creek, Grace Coolidge Creek, and Bear Gulch. Zero-flow values are plotted as 0.001 cubic feet per second.—Continued

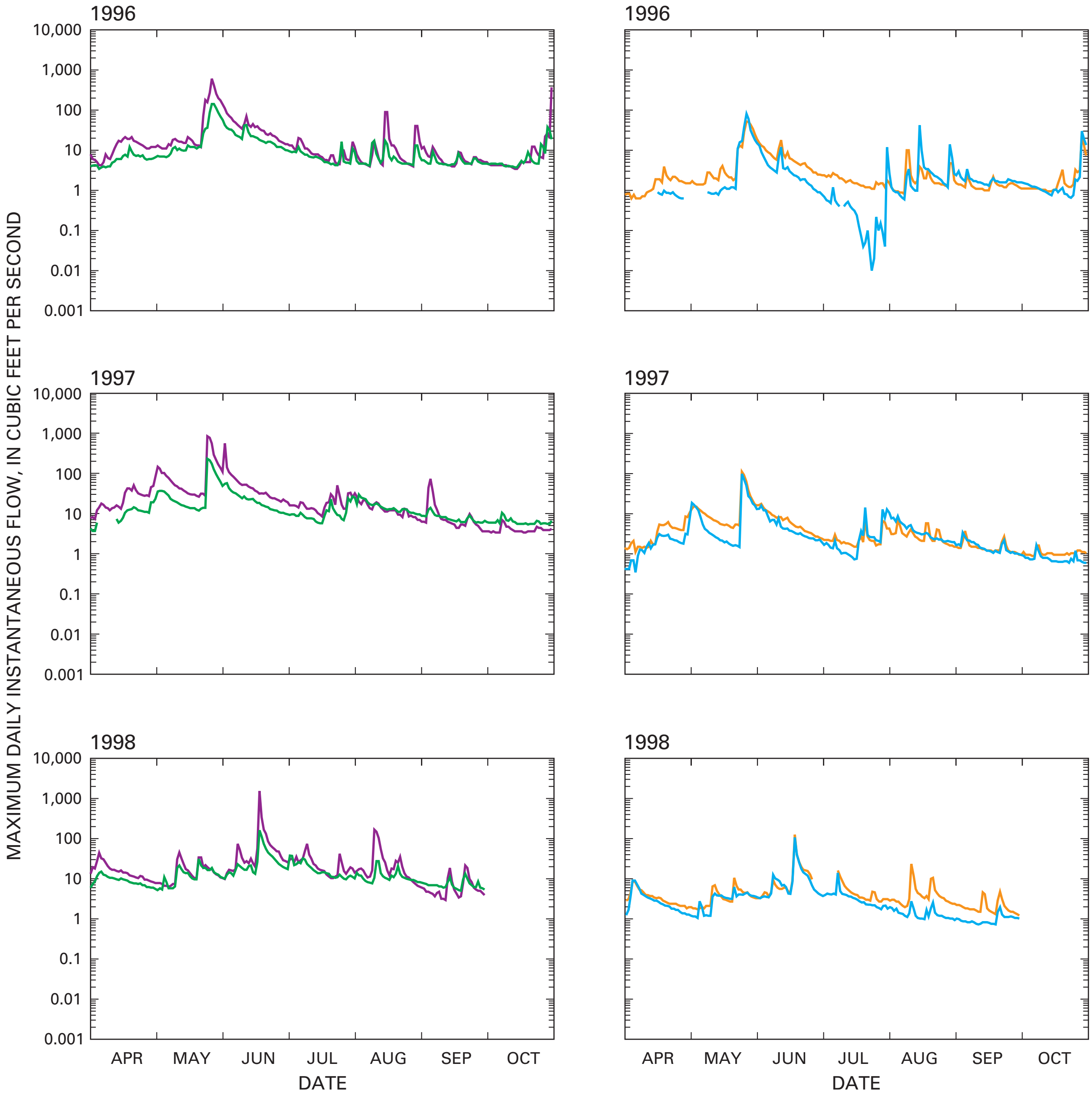


Figure 28. Maximum daily streamflow (April-October) for Battle Creek, Grace Coolidge Creek, and Bear Gulch. Zero-flow values are plotted as 0.001 cubic feet per second.—Continued

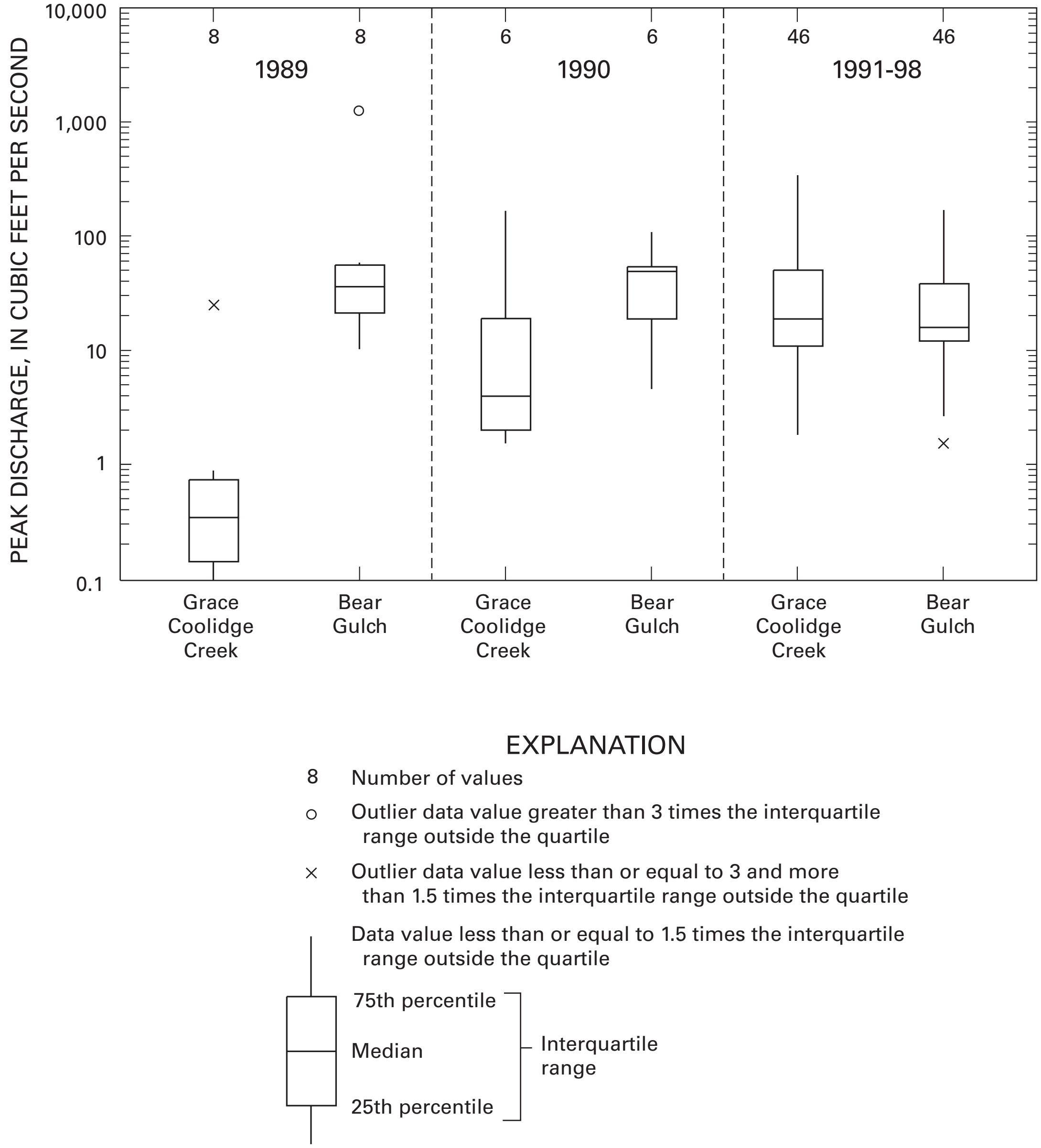


Figure 29. Peak discharges for Grace Coolidge Creek near Hayward (06404800) and Bear Gulch near Hayward (06405800).

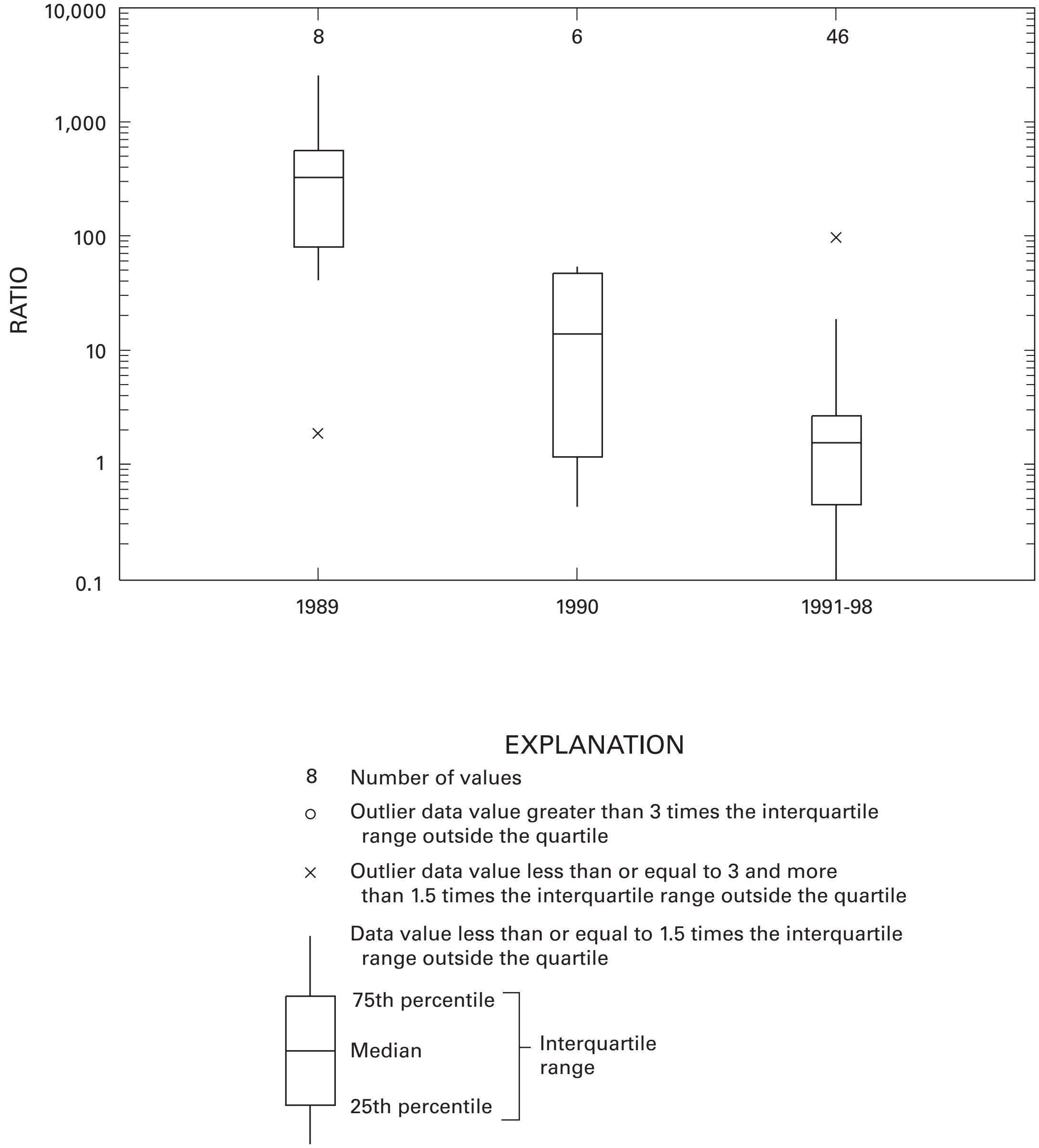


Figure 30. Ratio of peak discharges per unit area for Bear Gulch near Hayward (06405800) to Grace Coolidge Creek near Hayward (06404800).

The preponderance of information considered thus far strongly supports a conclusion of increased stormflow potential in burned areas during the first 2 to 3 years following the Galena Fire, after which peak-flow response decreased substantially. Additional supporting evidence is provided by double mass analyses of cumulative annual peak flows for selected long-term streamflow-gaging stations (table 10 in Supplemental Information section). Plots of cumulative annual peaks for Grace Coolidge Creek (near Game Lodge) versus cumulative annual peaks for other selected gages are presented in figure 31. Locations of other gages were shown previously in figures 1 and 2. Gaging stations considered include relatively long-term stations along the eastern flank of the Black Hills that are appropriate for this analysis. Several long-term gages were excluded because of influences such as reservoir regulation. Peak-flow records for Grace Coolidge Creek include records for WY 1967-76 for station 06405000 (Grace Coolidge Creek near Custer), as discussed previously in the Streamflow Data section of this report. The resulting, combined period of peak-flow record for Grace Coolidge Creek (WY 1967-98) is used for many of the plots in figure 31. For stations with shorter records, only the period of overlapping record can be considered. Records for WY 1967-72 are excluded for Battle Creek and Boxelder Creek because of the influence of a massive storm that occurred during 1972 and resulted in a flood peak with a recurrence interval in excess of 100 years (U.S. Geological Survey, 1975).

All of the plots in figure 31 indicate large annual peaks for Grace Coolidge Creek during the first several post-fire years (generally WY 1988-89 or 1990), relative to annual peaks for other stations during this period. Plots for several stations (Beaver, French, and Whitewood Creeks) have substantially steeper slopes for subsequent outyears (generally 1991-98) than for the pre-burn period, which could be interpreted as indicative of a longer term increase in stormflow potential, but at a reduced level. For all other stations, however, slopes for the subsequent outyears are similar to or less steep than slopes for the pre-burn period. Thus, it is concluded that stormflow potential for Grace Coolidge Creek increased substantially for the first several years after the Galena Fire, but then diminished to a generally pre-burn condition.

Diminishment of peak-flow potential can be explained by vegetation recovery that is documented by remotely sensed imagery available for the study area. LANDSAT Thematic Mapper data contain a wealth of information about earth features. Each spectral band responds in unique ways to terrain features, which enhances the ability to distinguish the identity and condition of these features, such as vegetation type, structure, and water content.

The normalized difference vegetation index (NDVI), which provides an estimate of vegetation condition (greenness), was used as a means for evaluating relative changes in vegetation density over time for the area burned by the Galena Fire. NDVI is a ratio of measured intensities from the visible and near-infrared spectral bands as measured by bands 3 (0.63-0.69 micrometers) and 4 (0.76-0.90 micrometers) on the LANDSAT Thematic Mapper sensor. Healthy vegetation absorbs most of the visible light and reflects a large portion of the near-infrared light. Unhealthy or sparse vegetation reflects more visible light and less near-infrared light. NDVI is calculated using the following formula (from Weier and Herring, 2001):

$$NDVI = (NIR-VIS)/(NIR+VIS)$$

where
NIR = near-infrared radiation, and
VIS = visible radiation.

NDVI values range between -1 and 1. Very low values of NDVI (less than 0.1) correspond to barren areas; moderate values (0.2 to 0.3) represent shrub and grassland; and high values (0.6 to 0.8) indicate temperate and tropical rainforests (Weier and Herring, 2001).

The establishment of grasses and forbs in the burned area occurred much more quickly than regrowth of the ponderosa pine forest, as shown by the succession of photographs in figure 13. Maximum greenness from grasses and forbs generally occurs during June in the Black Hills area. Thus, LANDSAT Thematic Mapper images showing negligible or minimal cloud cover for the Custer State Park area were acquired for a day in June (or as close to June as possible) for each year from 1988 through 2002 (table 6); adequate (cloud-free) images were not available in 1994, 1995, and 1999. LANDSAT images from 2000-02 are included in analyses to provide additional information about the Galena Fire beyond the general study period (through water year 1998). Each selected annual image was processed to obtain the NDVI data for the study area.

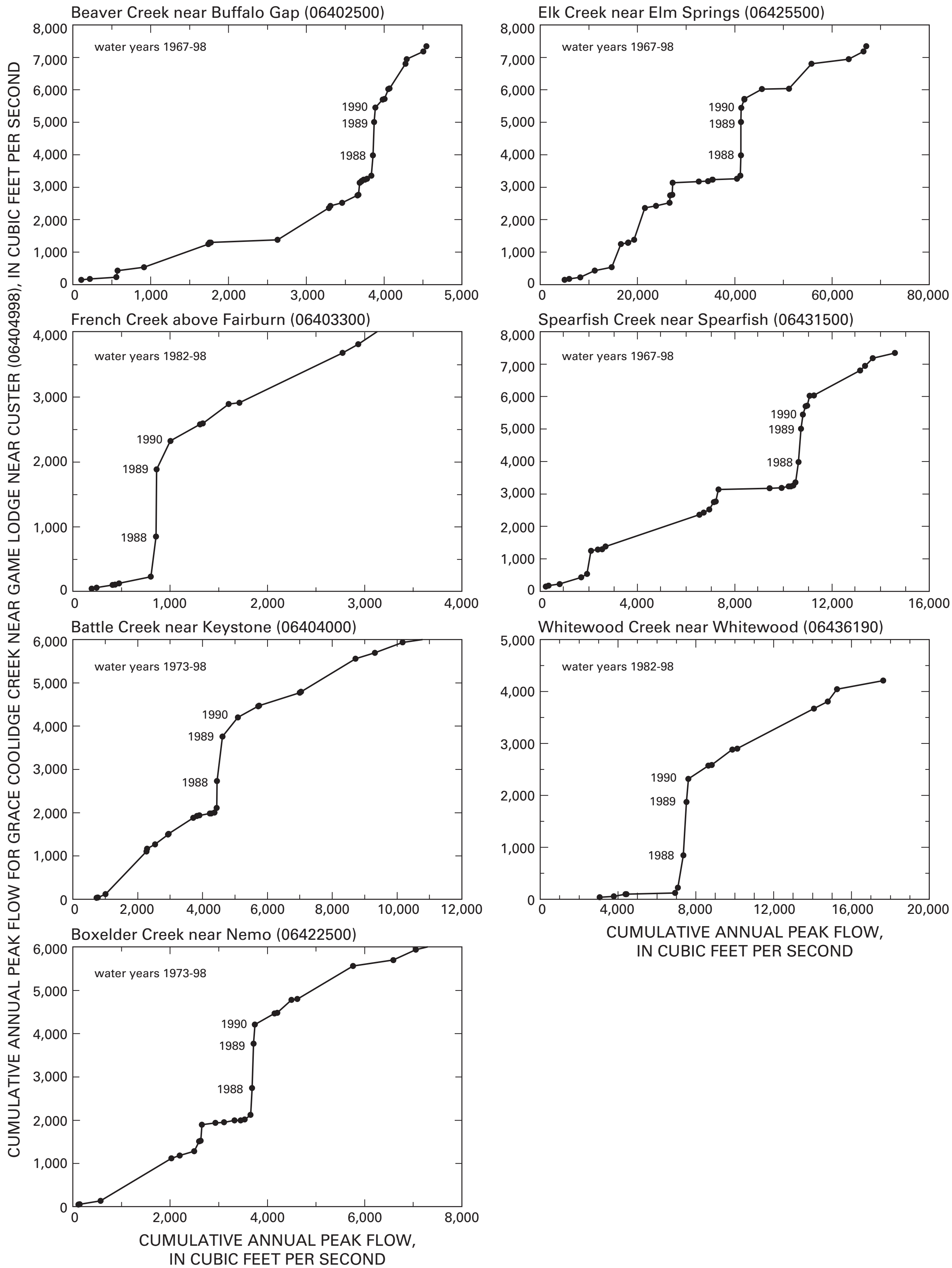


Figure 31. Cumulative annual peak flows for selected streamflow-gaging stations in comparison to Grace Coolidge Creek.

Table 6. Mean normalized difference vegetation index values for selected areas

Image date	Areas within perimeter of Galena Fire			Control area in northwest corner of Custer State Park (fig. 32)
	All areas	Moderate-low to high-severity burn areas (fig. 32)	Unburned to low-severity burn areas (fig. 32)	
7/3/1988	0.515	0.517	0.511	0.473
6/20/1989	.199	.145	.299	.389
6/23/1990	.391	.367	.434	.454
7/12/1991	.401	.365	.467	.497
6/12/1992	.369	.342	.421	.449
5/14/1993	.281	.250	.339	.403
6/7/1996	.370	.336	.433	.516
6/26/1997	.443	.414	.500	.533
7/15/1998	.478	.454	.522	.553
6/2/2000	.340	.306	.404	.488
6/5/2001	.351	.316	.418	.489
5/31/2002	.268	.227	.346	.437

LANDSAT images also were used to determine the burn severity of areas within the fire perimeter using methods presented by Key and Benson (2003). The methods employ a scaled index that gauges the magnitude of ecological change caused by fire and groups areas within the fire perimeter into the following five categories: unburned, low severity, moderate-low severity, moderate-high severity, and high severity. Figure 32 shows the Galena Fire perimeter and burn severity as determined from comparisons between pre-fire (July 3, 1988) and post-fire (June 29, 1989) images. The data shown in figure 32 were not calibrated with field measurements, but compare reasonably well with the timber mortality and fire perimeter shown in fig. 10. Figure 32 also shows an area in the northwest corner of Custer State Park that was considered to represent an unburned control area within the study area for subsequent NDVI analyses.

Mean NDVI values were calculated for areas with selected burn severities (table 6) using the processed data for each year for which an adequate image was available. The 1988 image was taken only 2 days before the Galena Fire began and provides a baseline for pre-fire conditions. In 1988, the mean NDVI for all areas within the fire perimeter was 0.515 (table 6), which indicates healthy vegetation prior to the fire. It should be noted that NDVI values probably were slightly lower in 1988 than previous years due to the extended drought conditions in 1988.

Figure 33 shows the temporal changes in NDVI values for the images listed in table 6 for the different burn-severity categories within the burned area and for the control area. As expected, the NDVI values for all of the burn-severity categories are much lower for 1989 than for 1988, with much lower values for the higher severity burn areas than for the lower severity burn areas. The NDVI value for the control area also is somewhat lower for 1989 than for 1988 because of the prolonged effects of drought conditions on vegetative condition. A very large increase in NDVI values for the burn areas is apparent for 1990, with the largest increase occurring for the higher severity areas. Much of the large increase for the higher severity areas probably resulted from particularly heavy stands of yellow blossom sweet clover, which was the primary seed stock used for post-fire remedial seeding during 1988 (South Dakota Department of Environment and Natural Resources, 1991; Walker and others, 1995). The sweet clover was widely established as seedlings by 1989, and developed particularly heavy growth during 1990, but generally phased out very quickly thereafter (Ron Walker, Custer State Park, oral commun., October 2003). This general progression is visible in the photograph sequence of figure 13, which shows numerous sweet-clover stalks in background areas during 1990. The disturbed area in the foreground (fig. 13) also had relatively heavy sweet clover during 1992 (presumably because sweet clover is a biennial); however, various grasses are the predominant species apparent for all other years.

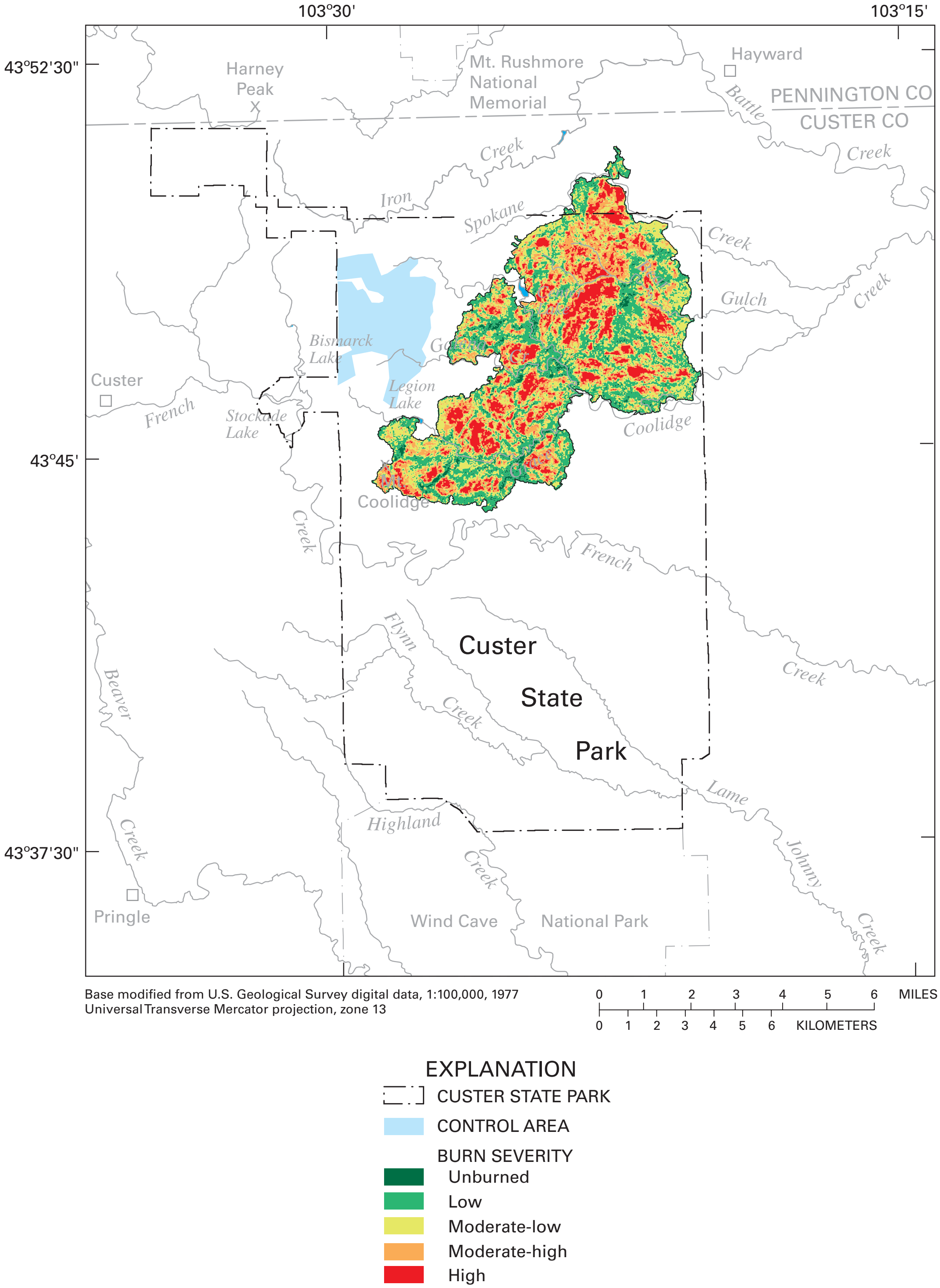


Figure 32. Burn severity of the Galena Fire determined on the basis of remotely sensed data from July 3, 1988, and June 20, 1989. Control area used to represent an unburned area also is shown.

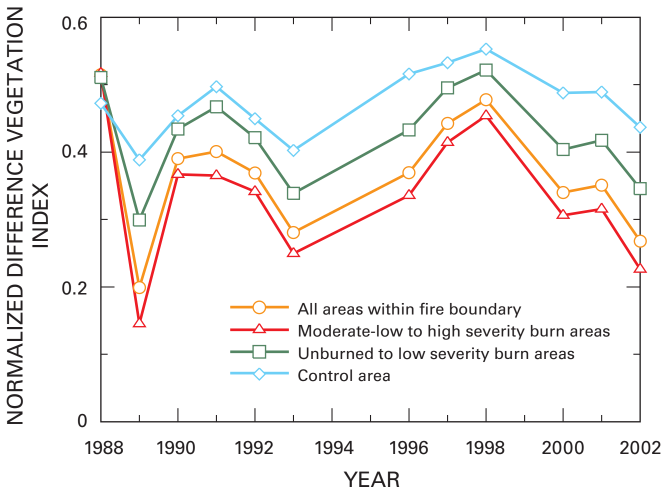


Figure 33. Mean normalized difference vegetation index values for selected areas during or near June.

During 1991, the NDVI value for the lower severity burn areas increased moderately; however, the value for the higher severity areas decreased slightly (fig. 33). NDVI values for all subsequent years track similarly. The decrease during 1991 for the higher severity areas may have resulted from a general transition from sweet-clover dominance to somewhat lighter stands of various grasses in many areas. Much of the variability in NDVI values for subsequent years probably reflects vegetation response to differences in climatic conditions. The maximum mean post-fire NDVI value for the burned area (0.478) occurred in 1998 following several years of wet climatic conditions.

The regrowth of vegetation following the Galena Fire could be identified visually in the NDVI images for post-fire years in comparison to the pre-fire image in 1988. Only selected images from post-fire years (1989, 1990, and 1998) are shown in figure 34, but all available images were considered in the following discussion. In figure 34, the dark tones within the area burned by the Galena Fire in the 1989 image indicate relatively low quantities of green vegetation. The light tones in other areas indicate relatively high quantities of green vegetation. Within the area burned by the Galena Fire, the tones became progressively lighter from 1989 to 1998, which correspond to increases in green vegetation. The largest annual increase to lighter tones within the burned area of the Galena Fire occurred between the 1989 and 1990 NDVI images. Areas burned intensively during the 1990 Cicero Peak Fire also are readily apparent in the 1998 image.

The NDVI analyses provide evidence that establishment of grasses and forbs as a replacement for the previous stands of ponderosa pine had largely occurred by 1990. Although NDVI analyses indicate that post-fire vegetation density has remained generally smaller than pre-fire vegetation density, analyses of streamflow data indicate that peak-flow characteristics subsequent to 1990 are approximately similar to peak-flow characteristics prior to the Galena Fire. Thus, these data indicate that the grasses and forbs that replaced the ponderosa pine forest are approximately equally effective in suppressing peak flows.

As discussed previously, quantification of increased stormflow potential is difficult because of various factors. Peak-flow frequency analyses for selected sites and periods of record are presented in table 7 for consideration of various quantitative aspects of increased stormflow potential. These peak-flow frequency estimates were derived using the log-Pearson Type III procedure recommended in Bulletin 17B of the Hydrology Subcommittee of the U.S. Interagency Advisory Committee on Water Data, 1982, “Guidelines for Determining Flood Flow Frequency” (United States Water Resources Council, 1982). Annual peak flows used in the analyses are provided in table 10. Readers are cautioned that the peak-flow estimates provided in table 7 are heavily influenced by conditions during the short periods of record considered, and should not be considered representative of long-term peak-flow characteristics for these sites.

Peak-flow frequency estimates for pre- and post-burn periods for Battle Creek and Grace Coolidge Creek (near Game Lodge) are presented in table 7. The pre-burn period considered excludes data prior to 1973 because of the influence of a massive storm that occurred during 1972 and resulted in a flood peak in excess of 26,000 ft^3/s for Battle Creek (table 8). The corresponding peak, however, was less than 1,000 ft^3/s for Grace Coolidge Creek, which was on the south fringe of the storm. The post-burn (1988-98) peak-flow estimates for Grace Coolidge Creek (table 7) generally are about twice as large as the pre-burn (1973-87) estimates for corresponding recurrence intervals; however, post-burn estimates for Battle Creek are about three to four times larger than the corresponding pre-burn estimates. Thus, it is apparent that the influence of the Galena Fire on peak-flow frequency estimates for Grace Coolidge Creek is minor, relative to the influence of episodic rainfall events that caused a series of large peaks for Battle Creek during 1993-98 (table 8) and resulted in the particularly large peak-flow frequency estimates for the post-burn period for this station.

Table 7. Peak-flow frequency estimates for selected recurrence intervals for selected streamflow-gaging stations

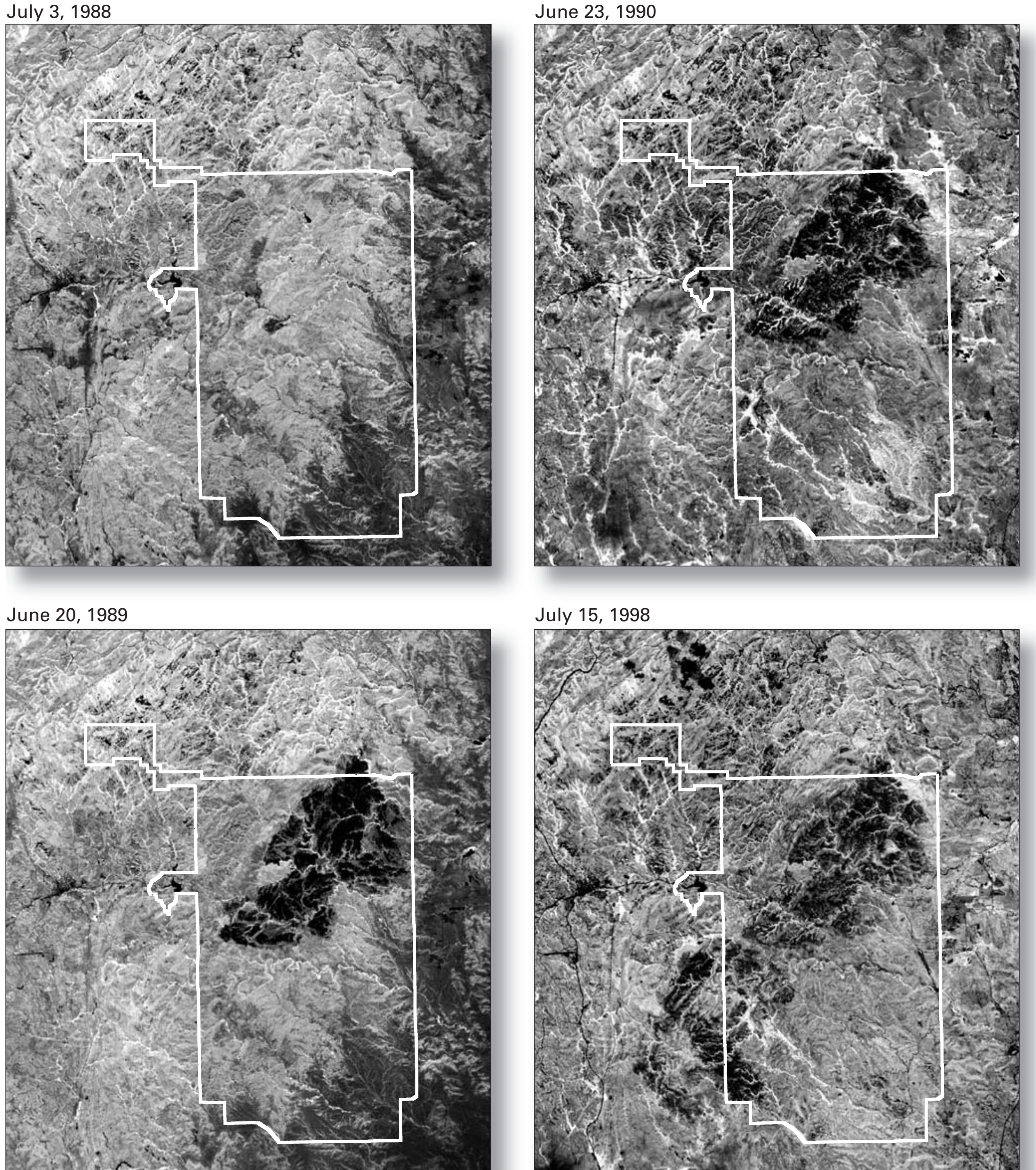
Station number	Station name	Period of analysis (water years)	Peak flow, in cubic feet per second, for recurrence interval, in years							
			2	5	10	25	50	100	200	500
06404000	Battle Creek near Keystone	1973-87	137	425	788	1,550	2,420	3,660	5,350	8,570
		1988-98	297	1,270	2,660	5,730	9,310	14,300	21,100	33,500
06404998	Grace Coolidge Creek near Game Lodge near Custer	1973-87	48	181	371	809	1,350	2,160	3,320	5,640
		1988-98	211	657	1,170	2,120	3,100	4,330	5,860	8,410
06404800	Grace Coolidge Creek near Hayward	1989-98	81	201	320	522	713	942	1,210	1,640
06405800	Bear Gulch near Hayward	1989-98	69	276	573	1,260	2,100	3,310	5,040	8,420

Most peak-flow frequency estimates for Bear Gulch (table 7) are considerably larger than for Grace Coolidge Creek (near Hayward), despite smaller drainage area (table 2). The peak-flow estimates for Bear Gulch are roughly comparable to estimates for three of the four periods considered for Battle Creek and Grace Coolidge Creek (near Game Lodge), both of which have drainage areas that are about an order of magnitude larger than Bear Gulch. The peak-flow frequency estimates for Bear Gulch are heavily influenced by the peak of 1,250 ft^3/s on September 7, 1989, which is about an order of magnitude larger than any of the other peaks for Bear Gulch (tables 9 and 10).

Data summarized in figures 29 and 30 provided strong evidence of increased stormflow potential for Bear Gulch through 1990. With the exception of the peak of 1,250 ft^3/s for Bear Gulch, however, other peaks for Bear Gulch and Grace Coolidge Creek (near Hayward) during 1989-90 were of relatively small magnitude. Peaks exceeding the estimated magnitude for a 2-year recurrence interval (table 7) did occur for both streams on May 29, 1990 (table 10). The relative magnitudes of these peaks, and the associated unit-area discharges (table 9), however, are approximately commensurate with the predicted ratios based on drainage areas that were discussed previously. Thus, increased stormflow response for Bear Gulch is not indicated for this event, although increased response is apparent for several other smaller events that occurred later in 1990. Measured precipitation totals (U.S. Geological Survey, 1991) for this storm generally were in the range of 3 to 4 in. for applicable precipitation gages (table 1); however, rainfall intensities were low for this long-duration storm (Moody and Martin, 2001).

Extremely high precipitation intensities occurred during the storm that resulted in large peaks (1,030 and 1,250 ft^3/s, respectively) on September 7, 1989, for Grace Coolidge Creek (near Game Lodge) and Bear Gulch (table 10). Precipitation amounts for these drainages (fig. 14) were much larger than for Battle Creek and Grace Coolidge Creek (near Hayward); thus, valid comparisons between burned and unburned conditions cannot be made for this storm. Moody and Martin (2001) reported a maximum 30-minute intensity of about 2.6 in/hr (1.3 in. per 1/2 hour) for Bear Gulch, which constituted most of the storm total for that day. Additional rainfall in the range of 1 to 2 in. occurred during the next 1 to 2 days throughout the burned area, but failed to produce substantial runoff.

Moody and Martin (2001) investigated relations between peak discharge and rainfall intensity for three severely burned watersheds, including Bear Gulch, in the western United States. These investigators estimated a recurrence interval of about 10 years for the September 7, 1989, rainstorm. These investigators concluded that precipitation intensity is a particularly important factor in driving the occurrence of large-discharge events. Comparison of peak discharges for Bear Gulch for the two storms discussed in detail supports this conclusion (the high-intensity storm yielded a peak discharge that was an order of magnitude larger than the high-volume storm with low intensity).



U.S. Geological Survey/Geography Discipline, EROS Data Center
Universal Transverse Mercator projection, zone 13

EXPLANATION

Dark tones—Low quantites of green vegetation
Light tones—High quantites of green vegetation

Figure 34. Normalized difference vegetation index images for selected years.

Although available data sets are insufficient for complete quantification of effects on peak-flow characteristics, various conclusions can be made. One reason that available data are sparse is that the window of opportunity for determination of effects is short. Increased peak-flow response was readily apparent through 1990, but diminished substantially during subsequent years. This conclusion is consistent with photographic evidence (fig. 13), vegetation surveys (Walker and others, 1995), and NDVI analyses, all of which indicate that establishment of grasses and forbs as a replacement for the ponderosa pine forest had primarily occurred by about 1991. Readers are cautioned that reduced peak-flow potential does not necessarily equate to a return to pre-fire conditions. Although peak-flow potential diminished quickly, it cannot necessarily be ascertained that increased peak-flow potential was completely eliminated by 1991. It also should be pointed out that peak-flow potential may not diminish as quickly for other burn areas, where factors such as differences in soil types, post-fire climatic conditions, or the aggressiveness of remedial revegetation efforts could influence establishment of grasses and forbs.

Peak flows for Bear Gulch were shown to be as much as two (or more) orders of magnitude larger than for Grace Coolidge Creek (near Hayward) for numerous stormflow events during 1989-90 (figs. 29 and 30) that generally were smaller than 2-year recurrence interval events. The primary reason for such large differences is that peak-flow responses for Grace Coolidge Creek were essentially non-existent for these relatively small events. For larger events, smaller relative differences between the two drainages would be expected, as was the case for the May 29, 1990, storm, for which peak-flow responses for the two drainages were similar. Results of peak-flow frequency analyses (table 7) indicate a much smaller relative level of increased peak-flow response (generally much less than an order of magnitude) for all of the recurrence intervals that are listed. These results are not definitive because of important differences in storm patterns during the short periods of record considered and because the post-fire response diminished substantially within several years of the fire. Thus, potential for increased peak-flow response during the first several post-fire years probably is somewhat larger than what may be inferred from examination of table 7.

Although quantification of increased peak-flow response cannot be accomplished from the available data, a conceptualized model is presented in figure 35. This model is consistent with numerous small peaks that equate to large percentage increases for small recurrence-interval events. Conversely, for large recurrence-interval events, the magnitudes of increased responses should be much larger; however, the percentage increases would be relatively small.

Precipitation intensity is an especially important factor in driving the occurrence of relatively low-recurrence interval events, as noted by Moody and Martin (2001). It is readily apparent that precipitation intensities that cause negligible to minimal runoff in unburned drainages can cause substantially larger runoff in burned drainages. Opportunities for measurement of runoff resulting from the combination of large precipitation intensity following large precipitation volume were not available during the critical first few years following the Galena Fire. The documented response for the high-intensity storm of September 7, 1989, certainly indicates that progressively larger runoff could be expected with increasing amounts of antecedent rainfall.

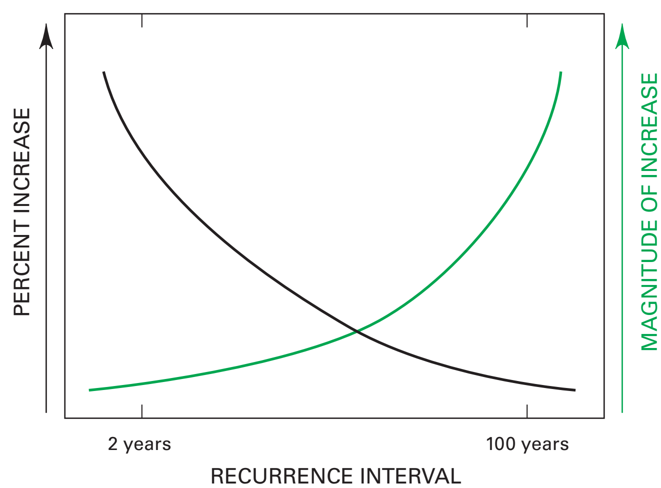


Figure 35. Conceptual model of hypothetical peak-flow response for increasing recurrence intervals.

SUMMARY

The Galena Fire burned about 16,788 acres of primarily ponderosa pine forest during July 5-8, 1988, in the Black Hills area of South Dakota. The fire burned primarily within the Grace Coolidge Creek drainage basin and almost entirely within the boundaries of

Custer State Park. A U.S. Geological Survey (USGS) gaging station with streamflow records dating back to 1977 was located along Grace Coolidge Creek within the burned area. About one-half of the gaging station's 26.8-square-mile drainage area was burned. The drainage basin for Bear Gulch, which is tributary to Grace Coolidge Creek, was burned particularly severely, with complete deforestation occurring in nearly the entirety of the area upstream from a gaging station that was installed in 1989.

The existence of long-term, pre-burn streamflow data provided a unique opportunity to evaluate the hydrologic effects of forest fire. In 1988, a study to evaluate effects on streamflow, geomorphology, and water-quality was initiated by the USGS in cooperation with the South Dakota Department of Environment and Natural Resources and the South Dakota Department of Game, Fish and Parks. The geomorphologic and water-quality components of the study were completed by 1990. A data-collection network consisting of streamflow- and precipitation-gaging stations was operated through water year 1998 for evaluation of effects on streamflow characteristics, including both annual-yield and peak-flow characteristics. Additional cooperators that have supported this continuing component of the study included the South Dakota Department of Agriculture (Forestry Division), West Dakota Water Development District, and U.S. Department of Agriculture (Forest Service).

Moderately burned areas did not experience a substantial increase in the rate of surface erosion; however, severely burned areas underwent surficial erosion nearly twice that of the unburned areas. The increased erosion was caused by a combination of sheet erosion and wind erosion. The sediment production rate of Bear Gulch estimated 8 to 14 months after the fire was 870 ft^3/acre (44 tons/acre). Substantial degradation of stream channels within the severely burned headwater areas of Bear Gulch was documented. Further downstream, channel aggradation resulted from deposition of sediments transported from the headwater areas.

The most notable water-quality effect was on concentrations of suspended sediment, which were orders of magnitude higher for Bear Gulch than for the unburned control area. Effects on several other water-quality constituents, such as organic carbon and nitrogen and phosphorus nutrient constituents, probably were influenced by the large concentrations of suspended matter that were documented in initial post-fire, stormflow events. The first post-fire stormflow produced the highest measured concentrations of specific conductance, nitrogen, phosphorus, organic carbon, calcium, magnesium, potassium, manganese, and sulfate in the burned areas. For most constituents sampled, differences in concentrations between burned and unburned areas were no longer discernible within about 1 year following the Galena Fire.

The effects of the Galena Fire on annual-yield characteristics of Grace Coolidge Creek were evaluated primarily from comparisons with long-term streamflow records for Battle Creek, which is hydrogeologically similar and is located immediately to the north. Analyses were complicated by climatic conditions, which were considerably wetter during the post-burn period than during the pre-burn period. Thus, statistically significant increases in annual yield occurred during the post-burn period for both drainages. Various analyses indicated larger increases for Grace Coolidge Creek than for Battle Creek. Between the pre- and post-burn periods, the mean annual yield increased from 1.53 to 3.93 in. for Grace Coolidge Creek compared to an increase from 1.29 to 2.98 in. for Battle Creek. Relations between annual yield for Grace Coolidge Creek and Battle Creek for pre- and post-burn periods were used to estimate increased annual yield of about 20 percent for Grace Coolidge Creek. Many of the post-burn data points are well beyond the range of the pre-burn data, which required extrapolation of the pre-burn regression equation used in estimating yield increases, and is a source of uncertainty for the estimates.

Substantial increases in peak-flow characteristics for severely burned drainages were visually apparent from numerous post-fire field observations. Evidence of frequent, minor runoff events from burned drainages was readily apparent because stream banks were coated with fine ash mobilized from burned areas. Somewhat larger runoff events also occurred frequently, and would mobilize large volumes of woody debris, including pine needles, charred pine bark, and tree limbs. Mobilization of sediment was apparent for particularly large runoff events in several locations, with mobilization of large boulders documented in one small, intensively burned drainage.

Various analyses of streamflow data indicated substantial increases in peak-flow response for burned drainage areas; however, quantification of effects was particularly difficult because peak-flow response diminished quickly and returned to a generally pre-burn condition by about 1991. Field observations of vegetation and analysis of remotely sensed data indicated that establishment of grasses and forbs in the burn area occurred within a similar timeframe. Comparison of pre-fire peak flows to post-1991 peak flows indicates that these grasses and forbs were equally effective in suppressing peak flows as the predominantly ponderosa pine forest was prior to the Galena Fire. Peak-flow potential may not diminish as quickly for other burn areas where various factors could influence revegetation.

Numerous peak-flow events with small recurrence intervals occurred within burned areas through 1990. Peak-flow events for Bear Gulch during this period were about one to two orders of magnitude larger than corresponding peaks for a small control drainage located along Grace Coolidge Creek upstream from the burn area. The small peaks do not provide quantitative information applicable to estimation of peak-flow magnitudes for larger events, however. Peak-flow events for Bear Gulch that occurred during 1991-98 were generally similar to those for the control drainage. A short-term increase in peak-flow potential also was documented for the longer-term gaging station located along Grace Coolidge Creek; however, peak-flow response was less pronounced than for Bear Gulch, which had nearly complete deforestation within a much smaller drainage area.

One particularly high-intensity storm (recurrence interval of about 10 years) occurred during 1989 within the burned areas for both Grace Coolidge Creek and Bear Gulch, but produced minimal rainfall in the two primary control drainages. Especially large peaks occurred from the burned areas; however, representative comparisons with unburned areas could not be made.

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SUPPLEMENTAL INFORMATION

Table 8. Annual flow and precipitation data for selected streamflow-gaging stations

[Precipitation data are for drainage area upstream of streamflow-gaging station. Precip, precipitation; YE, yield efficiency; ft^3/s, cubic feet per second; acre-ft, acre-feet; --, no data]

Water year	French Creek above Fairburn (06403300)					Battle Creek near Keystone (06404000)					Grace Coolidge near GL (06404998)				
	Flow			Precip (inches)	YE (percent)	Flow			Precip (inches)	YE (percent)	Flow			Precip (inches)	YE (percent)
	ft^3/s	acre-ft	inches			ft^3/s	acre-ft	inches			ft^3/s	acre-ft	inches		
1962	--	--	--	--	--	14.2	10,250	3.29	29.09	11.30	--	--	--	--	--
1963	--	--	--	--	--	15.0	10,830	3.47	27.00	12.86	--	--	--	--	--
1964	--	--	--	--	--	7.90	5,730	1.84	19.05	9.64	--	--	--	--	--
1965	--	--	--	--	--	19.5	14,100	4.52	30.98	14.59	--	--	--	--	--
1966	--	--	--	--	--	3.79	2,740	.88	17.43	5.04	--	--	--	--	--
1967	--	--	--	--	--	15.3	11,100	3.56	22.23	16.00	--	--	--	--	--
1968	--	--	--	--	--	4.01	2,910	.93	19.49	4.79	--	--	--	--	--
1969	--	--	--	--	--	5.80	4,200	1.35	20.23	6.65	--	--	--	--	--
1970	--	--	--	--	--	6.83	4,940	1.58	21.69	7.30	--	--	--	--	--
1971	--	--	--	--	--	15.8	11,420	3.66	26.91	13.60	--	--	--	--	--
1972	--	--	--	--	--	21.1	15,310	4.91	24.65	19.91	--	--	--	--	--
1973	--	--	--	--	--	8.61	6,230	2.00	18.60	10.73	--	--	--	--	--
1974	--	--	--	--	--	1.65	1,190	.38	12.45	3.06	--	--	--	--	--
1975	--	--	--	--	--	4.58	3,320	1.06	17.14	6.21	--	--	--	--	--
1976	--	--	--	--	--	13.2	9,550	3.06	23.39	13.09	--	--	--	--	--
1977	--	--	--	--	--	2.78	2,010	.64	18.25	3.53	1.27	918	0.64	19.02	3.38
1978	--	--	--	--	--	11.9	8,590	2.75	21.75	12.66	5.58	4,040	2.83	21.80	12.97
1979	--	--	--	--	--	6.00	4,350	1.39	21.22	6.57	4.33	3,140	2.20	20.05	10.96
1980	--	--	--	--	--	2.48	1,800	.58	15.32	3.77	1.17	852	0.60	15.82	3.77
1981	--	--	--	--	--	5.79	4,190	1.34	18.20	7.38	3.82	2,760	1.93	18.12	10.66
1982	--	--	--	--	--	6.38	4,620	1.48	22.60	6.55	4.13	2,990	2.09	24.27	8.62
1983	7.55	5,470	0.98	17.36	5.63	3.98	2,880	.92	14.83	6.23	2.48	1,800	1.26	15.67	8.04
1984	10.1	7,340	1.31	22.76	5.76	8.64	6,280	2.01	21.87	9.20	4.12	2,990	2.09	22.13	9.45
1985	3.53	2,560	.46	12.48	3.66	1.11	803	.26	10.44	2.47	.81	588	.41	11.54	3.56

Table 8. Annual flow and precipitation data for selected streamflow-gaging stations–Continued

[Precipitation data are for drainage area upstream of streamflow-gaging station. Precip, precipitation; YE, yield efficiency; ft³/s, cubic feet per second; acre-ft, acre-feet; --, no data]

Water year	French Creek above Fairburn (06403300)					Battle Creek near Keystone (06404000)					Grace Coolidge near GL (06404998)				
	Flow			Precip (inches)	YE (percent)	Flow			Precip (inches)	YE (percent)	Flow			Precip (inches)	YE (percent)
	ft^3/s	acre-ft	inches			ft^3/s	acre-ft	inches			ft^3/s	acre-ft	inches		
1986	3.97	2,870	0.51	23.63	2.17	5.05	3,660	1.17	24.26	4.84	2.03	1,470	1.03	25.02	4.11
1987	7.03	5,090	.91	16.05	5.66	6.84	4,950	1.59	16.60	9.55	3.49	2,520	1.76	16.67	10.58
1988	3.04	2,210	.39	13.79	2.86	.69	503	.16	13.13	1.23	.61	442	.31	13.19	2.34
1989	1.01	734	.13	18.09	.72	1.02	736	.24	19.36	1.22	1.40	1,020	.71	19.75	3.61
1990	4.94	3,570	.64	21.50	2.97	8.32	6,020	1.93	23.38	8.25	4.82	3,490	2.44	22.94	10.64
1991	13.7	9,950	1.78	24.20	7.34	16.7	12,070	3.87	26.96	14.35	8.89	6,440	4.51	25.05	17.99
1992	4.57	3,310	.59	18.80	3.14	3.50	2,540	.81	19.03	4.28	2.98	2,160	1.51	20.60	7.33
1993	12.0	8,720	1.56	24.51	6.35	15.1	10,950	3.51	26.88	13.06	9.12	6,600	4.62	26.86	17.19
1994	7.06	5,110	.91	15.38	5.93	5.03	3,640	1.17	15.82	7.38	3.26	2,360	1.65	17.11	9.65
1995	34.7	25,110	4.48	30.63	14.64	27.7	20,050	6.43	33.34	19.28	19.1	13,840	9.68	34.23	28.29
1996	17.6	12,790	2.28	25.52	8.95	14.4	10,470	3.36	28.72	11.68	7.93	5,750	4.02	27.40	14.68
1997	24.7	17,900	3.20	26.60	12.02	23.7	17,180	5.51	29.92	18.40	11.8	8,510	5.95	28.05	21.23
1998	19.5	14,140	2.53	23.89	10.57	12.9	9,360	3.00	25.44	11.79	8.35	6,040	4.23	24.73	17.09

Table 9. Peak discharges for selected dates for Grace Coolidge Creek and Bear Gulch

[ft^3/s, cubic feet per second; $(ft^3/s)/mi^2$, cubic feet per second per square mile]

Date[1]	Grace Coolidge Creek near Hayward (06404800)		Bear Gulch near Hayward (06405800)		Ratio of peak discharge per unit area of Bear Gulch to Grace Coolidge Creek
	Maximum daily instantaneous streamflow (ft^3/s)	Peak discharge per unit area [$(ft^3/s)/mi^2$]	Maximum daily instantaneous streamflow (ft^3/s)	Peak discharge per unit area [$(ft^3/s)/mi^2$]	
6/17/1989	0.4	0.1	10.0	2.4	41.1
6/25/1989	.6	.1	57.0	13.5	158
7/14/1989	.3	.0	49.0	11.6	333
7/17/1989	.2	.0	54.0	12.8	531
8/7/1989	.1	.0	20.0	4.7	589
8/14/1989	.1	.0	23.0	5.4	313
9/7-8/1989	.9	.1	1,250	296	2,480
9/21/1989	25.0	3.3	27.0	6.4	1.91
5/29/1990	168	22.5	111	26.2	1.17
6/6/1990	19.0	2.5	4.6	1.1	.43
6/16/1990	5.7	.8	19.0	4.5	5.89
7/7/1990	1.5	.2	46.0	10.9	54.2
7/15/1990	2.8	.4	53.0	12.5	33.5
7/20/1990	2.0	.3	54.0	12.8	47.7
4/26/1991	5.2	.7	38.0	9.0	12.9
5/12/1991	26.0	3.5	13.0	3.1	.88
5/18/1991	38.0	5.1	12.0	2.8	.56
5/22-23/1991	72.0	9.6	13.0	3.1	.32
5/28/1991	91.0	12.2	16.0	3.8	.31
6/1/1991	104	13.9	16.0	3.8	.27
6/3/1991	210	28.1	17.0	4.0	.14
6/21-22/1991	12.0	1.6	11.0	2.6	1.62
7/10-11/1991	25.0	3.3	48.0	11.3	3.40
6/21/1992	18.0	2.4	3.5	.8	.34
7/29/1992	11.0	1.5	2.8	.7	.45
5/6/1993	50.0	6.7	57.0	13.5	2.02
5/8/1993	37.0	4.9	71.0	16.8	3.39
6/4/1993	12.0	1.6	16.0	3.8	2.36
6/7/1993	141	18.9	115	27.2	1.44
6/17/1993	12.0	1.6	6.1	1.4	.90
7/17/1993	15.0	2.0	3.0	.7	.35
10/16/1994	22.0	2.9	1.5	.4	.12
5/8/1995	337	45.1	169	40.0	.89
5/13/1995	59.0	7.9	72.0	17.0	2.16

Table 9. Peak discharges for selected dates for Grace Coolidge Creek and Bear Gulch–Continued

[ft^3/s, cubic feet per second; $(ft^3/s)/mi^2$, cubic feet per second per square mile]

Date[1]	Grace Coolidge Creek near Hayward (06404800)		Bear Gulch near Hayward (06405800)		Ratio of peak discharge per unit area of Bear Gulch to Grace Coolidge Creek
	Maximum daily instantaneous streamflow (ft^3/s)	Peak discharge per unit area [$(ft^3/s)/mi^2$]	Maximum daily instantaneous streamflow (ft^3/s)	Peak discharge per unit area [$(ft^3/s)/mi^2$]	
5/19/1995	26.0	3.5	33.0	7.8	2.24
5/26/1995	28.0	3.7	33.0	7.8	2.08
6/4/1995	35.0	4.7	4.2	1.0	.21
6/9/1995	77.0	10.3	19.0	4.5	.44
6/16/1995	19.0	2.5	15.0	3.5	1.40
6/21/1995	19.0	2.5	29.0	6.9	2.70
8/5/1995	1.8	.2	100	23.6	98.2
5/24/1996	13.0	1.7	16.0	3.8	2.18
5/27/1996	52.0	7.0	81.0	19.1	2.75
6/12/1996	18.0	2.4	12.0	2.8	1.18
7/31/1996	1.8	.2	12.0	2.8	11.8
8/15/1996	3.9	.5	42.0	9.9	19.0
8/29/1996	4.8	.6	14.0	3.3	5.16
10/29/1996	23.2	3.1	30.0	7.1	2.28
5/2-3/1997	15.4	2.1	18.7	4.4	2.14
5/25/1997	112	14.9	98.3	23.2	1.55
6/3/1997	17.6	2.3	15.9	3.8	1.60
7/21/1997	7.0	.9	14.4	3.4	3.64
7/29/1997	6.7	.9	12.8	3.0	3.35
7/31/1997	4.3	.6	13.0	3.1	5.38
5/21/1998	10.5	1.4	6.2	1.5	1.04
6/8/1998	9.4	1.3	12.6	3.0	2.36
6/18/1998	126	16.8	108	25.6	1.52
7/8/1998	16.1	2.2	14.0	3.3	1.53
8/11/1998	23.7	3.2	2.7	.6	.20
8/21/1998	10.5	1.4	2.6	.6	.43
Mean 1989	3.4	.5	186	44.0	556
Median 1989	.3	.0	38.0	9.0	323
Mean 1990	33.2	4.4	47.9	11.3	23.8
Median 1990	4.3	.6	49.5	11.7	19.7
Mean 1991-98	43.0	5.7	31.7	7.5	4.6
Median 1991-98	19.0	2.5	15.9	3.8	1.6

[1]Selected dates are those when peak discharge for either station equalled or exceeded 10 ft^3/s. For consecutive days with discharges exceeding 10 ft^3/s, the day with the largest discharge was used.

Table 10. Annual peak flows for selected streamflow-gaging stations, water years 1967-98

[ft³/s, cubic feet per second; --, no data]

Water year	Beaver Creek near Buffalo Gap (06402500)		French Creek above Fairburn (06403300)		Battle Creek near Keystone (06404000)		Grace Coolidge Creek near Hayward (06404800)		Grace Coolidge Creek near Game Lodge, near Custer (06404998)	
	Date	Peak flow (ft³/s)	Date	Peak flow (ft³/s)	Date	Peak flow (ft³/s)	Date	Peak flow (ft³/s)	Date[2]	Peak flow (ft³/s)
1967	06/23/1967	109	--	--	06/15/1967	[1]533	--	--	06/12/1967	151
1968	06/07/1968	111	--	--	06/25/1968	[1]103	--	--	06/09/1968	29
1969	07/17/1969	340	--	--	07/17/1969	[1]551	--	--	07/05/1969	52
1970	03/10/1970	15	--	--	06/12/1970	[1]680	--	--	08/06/1970	196
1971	05/04/1971	340	--	--	06/01/1971	[1]429	--	--	05/21/1971	109
1972	06/10/1972	829	--	--	06/09/1972	[1]26,200	--	--	06/10/1972	709
1973	03/14/1973	13	--	--	04/19/1973	737	--	--	04/20/1973	46
1974	04/11/1974	16	--	--	07/19/1974	35	--	--	10/13/1974	6.0
1975	07/24/1975	861	--	--	07/19/1975	239	--	--	06/19/1975	83
1976	07/31/1976	660	--	--	06/15/1976	1,260	--	--	06/15/1976	980
1977	05/05/1977	16	--	--	04/12/1977	27	--	--	07/27/1977	63
1978	03/10/1978	157	--	--	05/18/1978	230	--	--	05/18/1978	102
1979	07/23/1979	192	--	--	07/04/1979	409	--	--	07/04/1979	226
1980	10/29/1980	15	--	--	06/17/1980	21	--	--	10/11/1980	15
1981	10/20/1981	14	--	--	05/17/1981	763	--	--	05/18/1981	370
1982	05/20/1982	19	06/24/1982	194	06/04/1982	101	--	--	06/03/1982	41
1983	12/09/1983	12	05/05/1983	50	05/07/1983	80	--	--	05/07/1983	16
1984	06/14/1984	21	07/15/1984	166	06/11/1984	327	--	--	05/10/1984	41
1985	12/04/1985	13	09/12/1985	23	03/18/1985	34	--	--	10/05/1985	2.3
1986	04/26/1986	31	06/10/1986	41	05/09/1986	105	--	--	06/10/1986	22
1987	05/27/1987	56	03/07/1987	329	10/03/1987	75	--	--	03/21/1987	102
1988	01/12/1988	19	07/16/1988	53	06/23/1988	9.2	--	--	08/03/1988	621
1989	01/22/1989	18	08/14/1989	4.6	09/21/1989	166	09/21/1989	25	09/07/1989	1,030

Table 10. Annual peak flows for selected streamflow-gaging stations, water years 1967-98–Continued

[ft³/s, cubic feet per second; --, no data]

Water year	Beaver Creek near Buffalo Gap (06402500)		French Creek above Fairburn (06403300)		Battle Creek near Keystone (06404000)		Grace Coolidge Creek near Hayward (06404800)		Grace Coolidge Creek near Game Lodge, near Custer (06404998)	
	Date	Peak flow (ft^3/s)	Date	Peak flow (ft^3/s)	Date	Peak flow (ft^3/s)	Date	Peak flow (ft^3/s)	Date[2]	Peak flow (ft^3/s)
1990	06/21/1990	12	05/30/1990	141	05/30/1990	473	05/29/1990	168	05/30/1990	442
1991	06/03/1991	97	06/04/1991	304	06/05/1991	620	06/03/1991	210	06/03/1991	254
1992	09/08/1992	23	06/22/1992	32	06/22/1992	37	06/21/1992	18	06/22/1992	15
1993	08/20/1993	49	06/08/1993	266	06/07/1993	1,250	06/07/1993	141	06/07/1993	298
1994	11/25/1994	17	03/03/1994	110	05/14/1994	35	05/13/1994	3.1	10/14/1994	19
1995	07/03/1995	203	05/08/1995	1,060	05/08/1995	1,690	05/08/1995	337	05/08/1995	765
1996	10/02/1996	14	05/28/1996	162	05/27/1996	595	05/27/1996	52	05/27/1996	140
1997	07/29/1997	216	05/25/1997	239	05/25/1997	854	05/25/1997	112	05/25/1997	236
1998	07/25/1998	43	06/19/1998	323	06/18/1998	1,520	06/18/1998	126	06/18/1998	162

Table 10. Annual peak flows for selected streamflow-gaging stations, water years 1967-98—Continued

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

Water year	Bear Gulch near Hayward (06405800)		Boxelder Creek near Nemo (06422500)		Elk Creek near Elm Springs (06425500)		Spearfish Creek at Spearfish (06425500)		Whitewood Creek near Whitewood (06436190)	
	Date	Peak flow (ft^3/s)	Date	Peak flow (ft^3/s)	Date	Peak flow (ft^3/s)	Date	Peak flow (ft^3/s)	Date[2]	Peak flow (ft^3/s)
1967	--	--	06/12/1967	[1]950	06/16/1967	4,960	06/16/1967	230	--	--
1968	--	--	06/09/1968	[1]62	06/07/1968	1,020	06/25/1968	106	--	--
1969	--	--	05/04/1969	[1]144	07/17/1969	2,300	05/15/1969	466	--	--
1970	--	--	06/12/1970	[1]648	04/26/1970	2,920	06/12/1970	884	--	--
1971	--	--	04/25/1971	[1]221	05/23/1971	3,510	05/10/1971	234	--	--
1972	--	--	06/09/1972	[1]30,100	06/11/1972	1,880	05/13/1972	163	--	--
1973	--	--	04/20/1973	117	04/22/1973	1,440	05/31/1973	287	--	--
1974	--	--	04/19/1974	23	04/09/1974	54	01/01/1974	175	--	--
1975	--	--	07/30/1975	427	04/27/1975	1,210	05/07/1975	143	--	--
1976	--	--	06/15/1976	1,460	06/17/1976	2,230	06/15/1976	3,870	--	--
1977	--	--	04/17/1977	170	06/14/1977	2,270	05/02/1977	167	--	--
1978	--	--	05/11/1978	301	03/18/1978	2,830	05/11/1978	230	--	--
1979	--	--	07/04/1979	97	03/17/1979	92	08/07/1979	182	--	--
1980	--	--	03/13/1980	35	06/15/1980	437	04/21/1980	85	--	--
1981	--	--	05/18/1981	26	08/13/1981	124	07/01/1981	102	--	--
1982	--	--	05/20/1982	272	05/21/1982	5,300	05/22/1982	2,110	05/20/1982	3,050
1983	--	--	05/07/1983	178	10/10/1983	1,940	05/08/1983	500	05/07/1983	736
1984	--	--	06/15/1984	215	05/04/1984	890	06/17/1984	285	06/09/1984	611
1985	--	--	03/18/1985	129	03/20/1985	73	04/17/1985	89	03/15/1985	39
1986	--	--	05/09/1986	82	02/27/1986	4,960	04/28/1986	104	09/24/1986	2,490
1987	--	--	03/06/1987	123	05/27/1987	718	04/18/1987	86	05/23/1987	158
1988	--	--	05/09/1988	33	03/24/1988	101	05/14/1988	118	05/08/1988	277
1989	09/07/1989	1,250	03/10/1989	30	03/22/1989	11	05/09/1989	106	05/05/1989	161
1990	05/29/1990	111	05/05/1990	29	09/02/1990	47	05/05/1990	82	05/04/1990	95

Table 10. Annual peak flows for selected streamflow-gaging stations, water years 1967-98—Continued

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

Water year	Bear Gulch near Hayward (06405800)		Boxelder Creek near Nemo (06422500)		Elk Creek near Elm Springs (06425500)		Spearfish Creek at Spearfish (06425500)		Whitewood Creek near Whitewood (06436190)	
	Date	Peak flow (ft^3/s)	Date	Peak flow (ft^3/s)	Date	Peak flow (ft^3/s)	Date	Peak flow (ft^3/s)	Date[2]	Peak flow (ft^3/s)
1991	07/10/1991	48	06/06/1991	401	05/28/1991	620	05/22/1991	106	06/05/1991	1,030
1992	07/13/1992	4.0	06/13/1992	53	06/21/1992	27	04/29/1992	70	06/14/1992	172
1993	06/07/1993	115	06/07/1993	293	05/08/1993	3,660	06/08/1993	100	05/05/1993	1,050
1994	10/14/1994	6.1	05/06/1994	125	06/08/1994	5,570	04/25/1994	175	04/23/1994	261
1995	05/08/1995	169	05/09/1995	1,140	05/10/1995	4,580	05/08/1995	1,900	05/08/1995	3,930
1996	05/27/1996	81	05/30/1996	826	05/28/1996	7,660	05/30/1996	204	05/27/1996	718
1997	05/25/1997	98	06/02/1997	463	02/18/1997	3,000	05/08/1997	322	07/24/1997	473
1998	06/18/1998	108	06/18/1998	607	06/19/1998	592	06/18/1998	899	06/18/1998	2,380

[1]Records for water years 1967-72 are excluded from peak-flow analyses for Battle Creek and Boxelder Creek because of the influence of a massive storm that occurred during 1972 and resulted in a flood peak with a recurrence interval in excess of 100 years.

[2]Peaks for water years 1967-76 are for station 06405000, which was located just downstream.