P

Monitoring Changes in Geothermal Activity at Norris Geyser Basin by Satellite Telemetry, Yellowstone National Park, Wyoming

By Irving Friedman

Chapter P *of*

Integrated Geoscience Studies in the Greater Yellowstone Area—Volcanic, Tectonic, and Hydrothermal Processes in the Yellowstone Geoecosystem

Edited by Lisa A. Morgan

Professional Paper 1717

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

About the Author

It is perhaps fitting that the last paper in this volume is also the last of over 200 scientific papers to be written by Irving Friedman whose scientific career began in the mid-1940s and ended with his death at the age of 85 on June 28, 2005. Irving was a member of the famed group of postdoctoral researchers in Nobel laureate Harold Urey's laboratory at the Institute for Nuclear Studies at the University of Chicago. There he built the first mass spectrometer for routine measurement of the hydrogen isotope composition of water. As a research chemist with the USGS for over 43 years, Irving pursued the understanding of every aspect of the water cycle with studies of water in oceans, rivers, lakes, glaciers, hot springs, the atmosphere, magmas, minerals, rocks, meteorites, plants, animals, and the Moon. For his contributions to our understanding of the water cycle, Irving is called the "father of isotope hydrology." Irving had a career-long interest in scientific studies at Yellowstone beginning with his first visit while an undergraduate student at Montana State University in Bozeman. He significantly advanced the scientific knowledge of the Park for decades. His work on the geochemistry of obsidian allowed huge advances in archeology and anthropology in the Park and worldwide. He was a legend in the Park for his ability to "instrument anything." His low-cost method of monitoring Yellowstone's total geothermal output that is presented in Chapter I of this volume and the satellite telemetry monitoring of Norris Geyser Basin presented in the following chapter, will be standards for many years to come. Irving received many awards and honors in his lifetime. None meant more to him than "Honorary Yellowstone Park Ranger"—complete with felt hat—that was awarded to him for his longtime contributions leading to better protection of the Park and its resources.

Contents

Abstract 513
Acknowledgments 513
Introduction 513
Precipitation 515
Observed Changes in Thermal Activity 524
    Echinus Geyser 524
    Steamboat Geyser 524
    Basin-Wide Thermal Event 525
    Diurnal Changes in Discharge 527
Water Chemistry 529
    Chloride and Sulfate Flux from Norris Geyser Basin 529
Summary and Conclusions 532
References Cited 532

Figures

1–2. Photographs of:
    1. Weir 514
    2. Interior of stilling well box 515
3–12. Plots of:
    3. Discharge of Tantalus Creek versus time from 1998 to 2003 516
    4. Instantaneous discharge measurements at Tantalus Creek weir 525
    5. Discharge of Tantalus Creek 526
    6. Discharge at Tantalus Creek weir and temperature in Echinus Geyser pool 527
    7. Discharge of Tantalus Creek showing effect of eruptions of Steamboat Geyser 528
    8. Discharge and water-temperature data during a thermal event 529
    9. Discharge and water temperature of Tantalus Creek for various dates 530
    10. Discharge versus chloride and sulfate concentrations for water samples at Tantalus Creek weir 531
    11. Discharge versus chloride and sulfate fluxes for water samples at Tantalus Creek weir 531
    12. Discharge versus chloride-sulfate ratio for water samples at Tantalus Creek weir 532

Monitoring Changes in Geothermal Activity at Norris Geyser Basin by Satellite Telemetry, Yellowstone National Park, Wyoming

By Irving Friedman[1]

Abstract

Instrumentation on a weir on Tantalus Creek, which captures 98 percent of the surface discharge of Norris Geyser Basin, Yellowstone National Park (the Park), records discharge and water temperature every 10 minutes and telemeters recorded data every hour via GOES satellite. Plots of discharge from June 1998 through mid-November 2003 record frequent—and often large—changes in discharge.

Data recorded during five eruptions of Steamboat Geyser (May 2000, April 2002, September 2002, April 2003, and October 2003) allow calculation of the time and duration of the eruptions, as well as amounts of water released by each eruption.

Water discharge at the weir also recorded the eruptions of Echinus Geyser, one of the major attractions in Norris Geyser Basin. Prior to late September 1998, Echinus erupted regularly approximately every 50 minutes. During the winter of 1998, and probably coincident with a major increase in thermal activity in the Ragged Hills area about a kilometer west of Echinus, Echinus ceased to erupt.

A basin-wide thermal event that began in April 2002 was recorded. During this event—which was not directly witnessed—the discharge from the basin increased in minutes from 5 ft^3 per second (cfs) to more than 10 cfs, while water temperature at the weir increased from 25°C to 70°C. In order to account for this temperature increase, the increased discharge from the basin would have to have been close to the boiling point. The discharge and temperature returned to normal in a day or two.

Chloride and sulfate concentrations in water samples collected from 1988 to late 2002 show that these concentrations are independent of stream discharge

This study proves the utility of satellite telemetry of hydrothermal and geochemical data from remote areas.

[1]U. S. Geological Survey.

Acknowledgments

This research could not have been carried out without the aid received from Rick Hutchinson, park geologist, who died in an avalanche in March 1997 while providing assistance to another investigator. Rick not only made the installation of the weir at Tantalus Creek possible but was instrumental in its construction, including backpacking concrete and other heavy construction materials to the site.

I wish to acknowledge the help of Park personnel attached to the firefighting group ("Fire Cache"), who took this project under its wing, provided access to the satellite platform, and also backpacked the heavy electronic equipment to the site. These include Phil Perkins, Pet Overstreet, Ashley Sipes, and Jim Kitchen. Thanks are also due to park personnel Steven Miller and Guida Veronda. Recently, the installation by Henry Heasler, park geologist, of a temperature recorder in the outflow from Steamboat Geyser has made it possible to accurately time the eruptions of this geyser. Heasler has also been responsible for the installation of a rain gage in the Norris Geyser Basin.

Daniel Norton, my collaborator in many projects within the Park, was of great help in getting this project started.

Introduction

White and others (1988) stated in their monograph that Norris Geyser Basin (NGB) is the most diverse thermal area in Yellowstone National Park (the Park). Not only does it have a greater variety of thermal features than anywhere else in the Park, but these thermal features also change rapidly with time (days to years), and the thermal waters display a wide variety of chemical compositions.

In 1988, we began to monitor the total amount of thermal water leaving Norris Geyser Basin in order to determine whether the changes in activity of the thermal features are a result of variations in thermal input to the basin or whether the changes are due to variations in the redistribution

Figure 1. *A,* Photograph of weir looking upstream. *B,* Photograph of weir looking downstream. A, The gray plastic stilling well box can be seen at the right of the weir plate. B, Confluence of Tantalus Creek and Gibbon River is just out of sight beyond the upper left side of the photograph.

Figure 2. Photograph of the interior of the stilling well box showing the float gage. A, The bottle at the left is a float that is connected to the precision wire-wound potentiometer contained in the bottle to the right. B, The shaft of the potentiometer. C, is sealed by an O-ring where it passes through the bottle cap. This seals the interior of the bottle from the atmosphere. However, over time, a small amount of water enters the bottle. This leakage is captured by silica-gel desiccant contained in a cloth bag inside the bottle. The stilling well box is covered to prevent snow buildup on the equipment.

of thermal energy among various parts of the Norris system due to changes in conduits feeding various springs within the basin. This monitoring was carried out by measuring the discharge of Tantalus Creek, which receives 98 percent of the surface water leaving the basin (a small amount bypasses Tantalus Creek and flows directly into the Gibbon River). In 1988,[1] a dam and weir were constructed on the creek at a site 100 m from the point at which Tantalus Creek discharges into the Gibbon River (fig. 1). The discharge was measured by determining the height of the water behind a 36-inch-wide Cipoletti weir using a float gage (fig. 2) and referring to standard discharge tables that relate discharge to the height of the water in the weir. The discharge was recorded every hour, but, later, the recording interval was shortened to 10 minutes.

Initially, data was telemetered by radio to Norris Museum and was accessed via modem. The telemetry equipment operated intermittently and was replaced in August 1998 by an on-site "Onset StowAway" data logger that stored readings taken every 10 minutes and had a memory of 270 days of data. Because the site was visited infrequently and because equipment failure—usually the failure of the wire-wound potentiometer that responded to changes in water level—was not detected until the next visit, we added a data-collection platform that telemetered data via GOES satellite to a receiver in Menlo Park, Calif., and then by modem to Denver, Colo., where daily inspections of the data assured that long periods of lost data did not occur.

The data are plotted as discharge in cubic feet per second (cfs) versus time. Figure 3 shows plots for every 2 months beginning in August 1998. Vertical lines in each plot separate days.

In addition to instrumental data, occasional measurements of discharge were made manually by reading a staff gage that measured the height of water behind the weir. These data are plotted in figure 4. The discharge from NGB exhibits great variability, for example, discharge was sustained at 6 cfs for several months in early 1989, and again for a short period in 1991, interspersed with flows as low as 1.5 cfs.

Precipitation

To access the effect of precipitation on the discharge of Tantalus Creek, precipitation at the two nearest weather-reporting stations (Mammoth, 32 km to the north, and Canyon, 24 km to the east) are plotted on the discharge record (fig. 3). The majority of the large, sudden increases in discharge last for a day or so and correlate with significant increases in precipitation recorded at one or both of the weather stations.

[1]The device that measured stream discharge at the Tantalus Creek weir failed in mid-January 2004. The equipment was replaced in July 2004 by an automatically operated station maintained by the U.S. Geological Survey Water Resources Division (Tantalus Creek, station no. 06036940). The station collects data on stream discharge, water temperature and precipitation every 15 minutes and transmits the data in real time via GOES satellite. Plots and tabular data can be viewed and retrieved on the internet at: http://waterdata.usgs.gov/mt/nwis/uv/?site_no=06036940&PARAmeter_cd=00060,00065,00010.

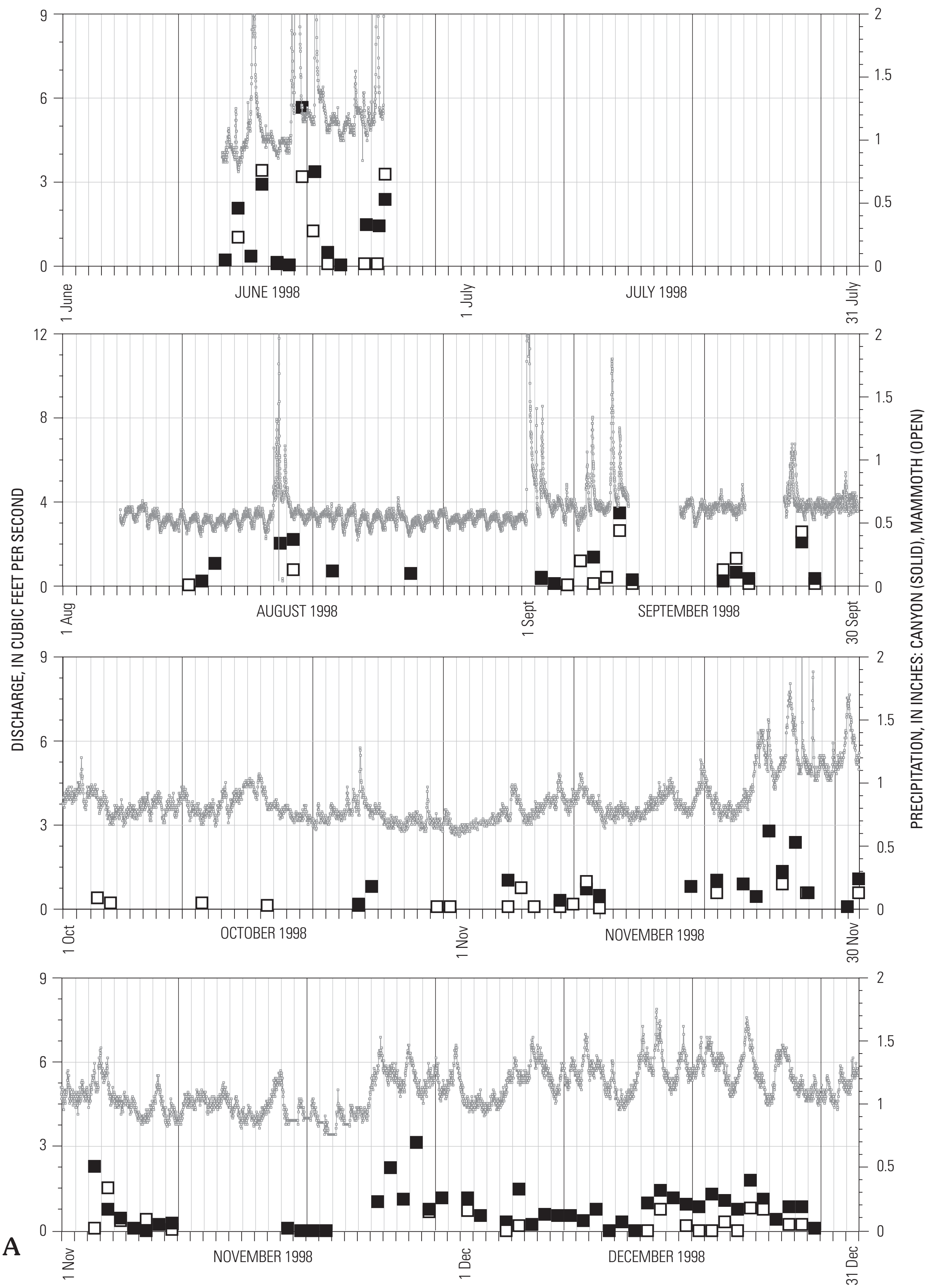
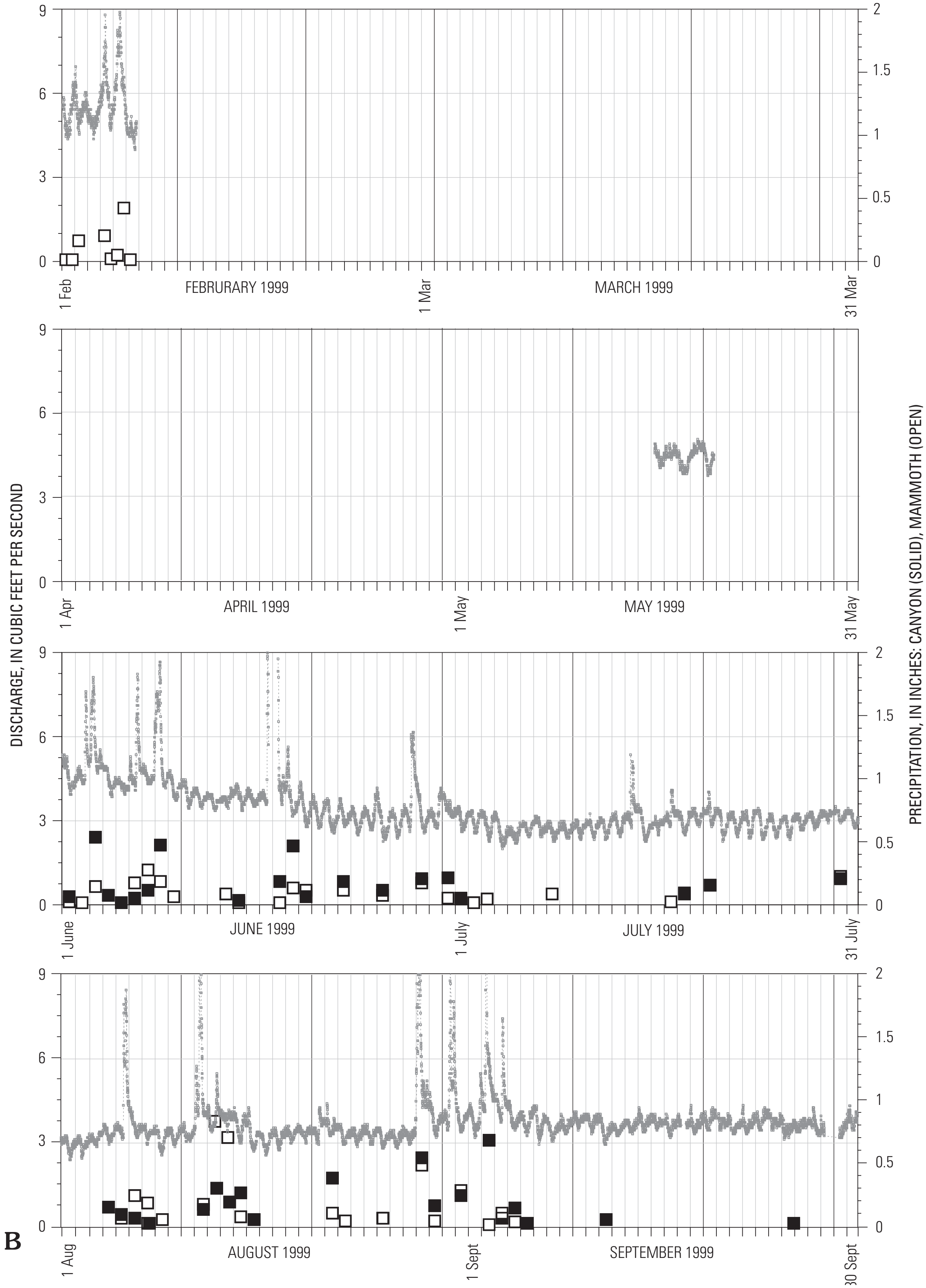
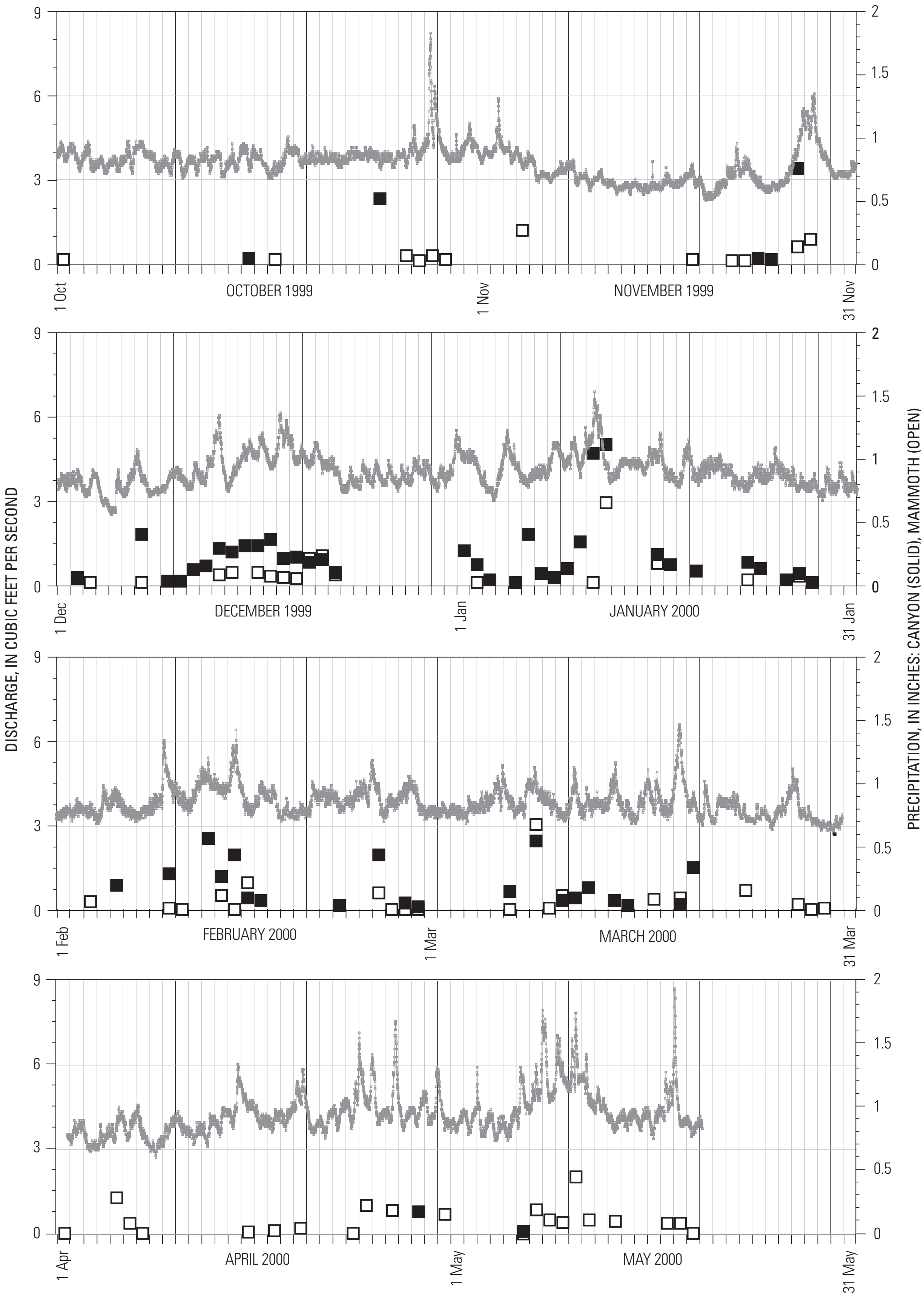


Figure 3 (above and succeeding pages). Plots of discharge of Tantalus Creek versus time from 1998 to 2003. Precipitation recorded at nearby weather stations (Canyon and Mammoth) are also plotted. Precipitation data for

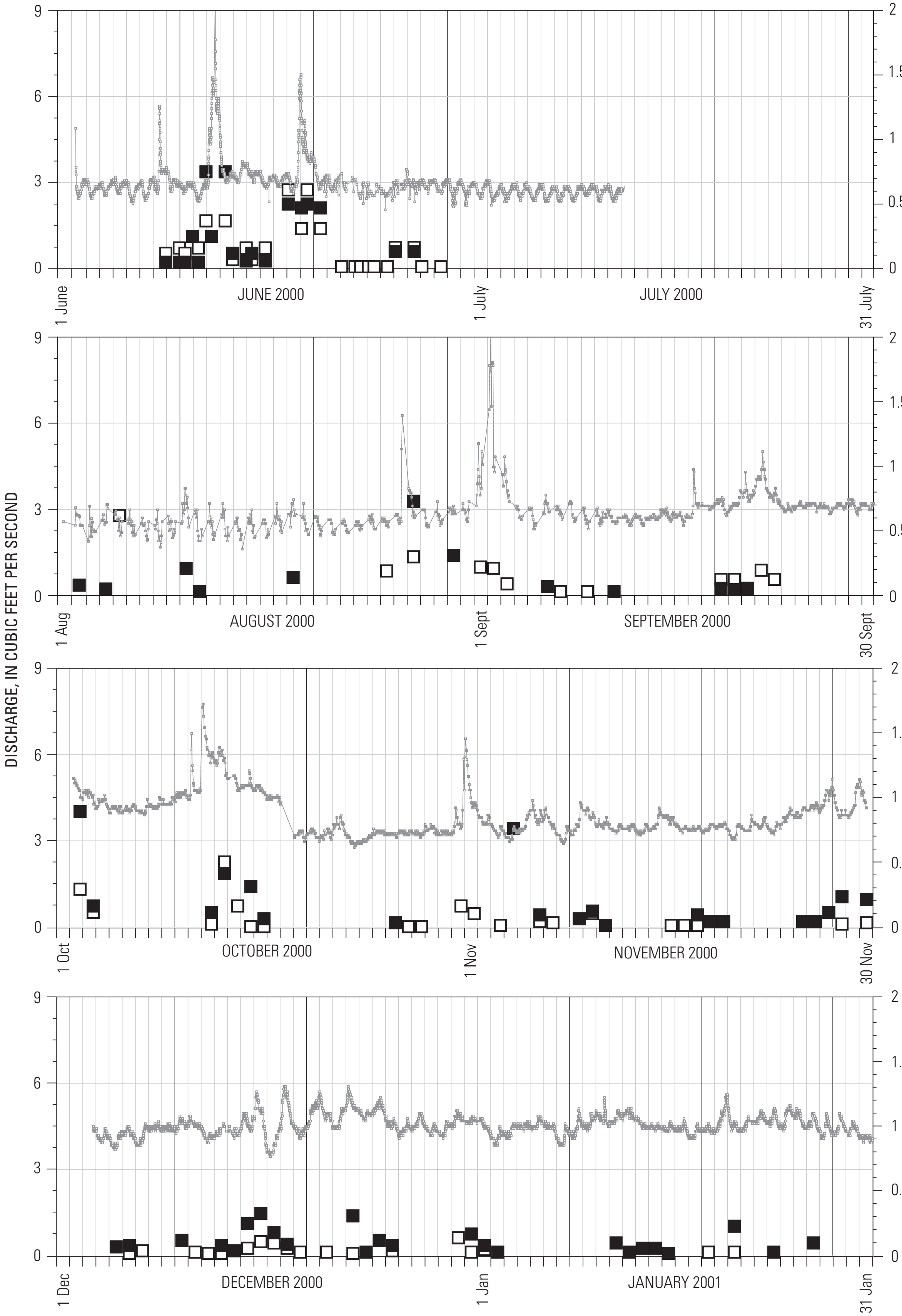


Canyon from October 2001 to December 2002 are not available. Precipitation in Norris Geyser Basin, recorded by a rain gage installed in mid-June 2003, is also shown.

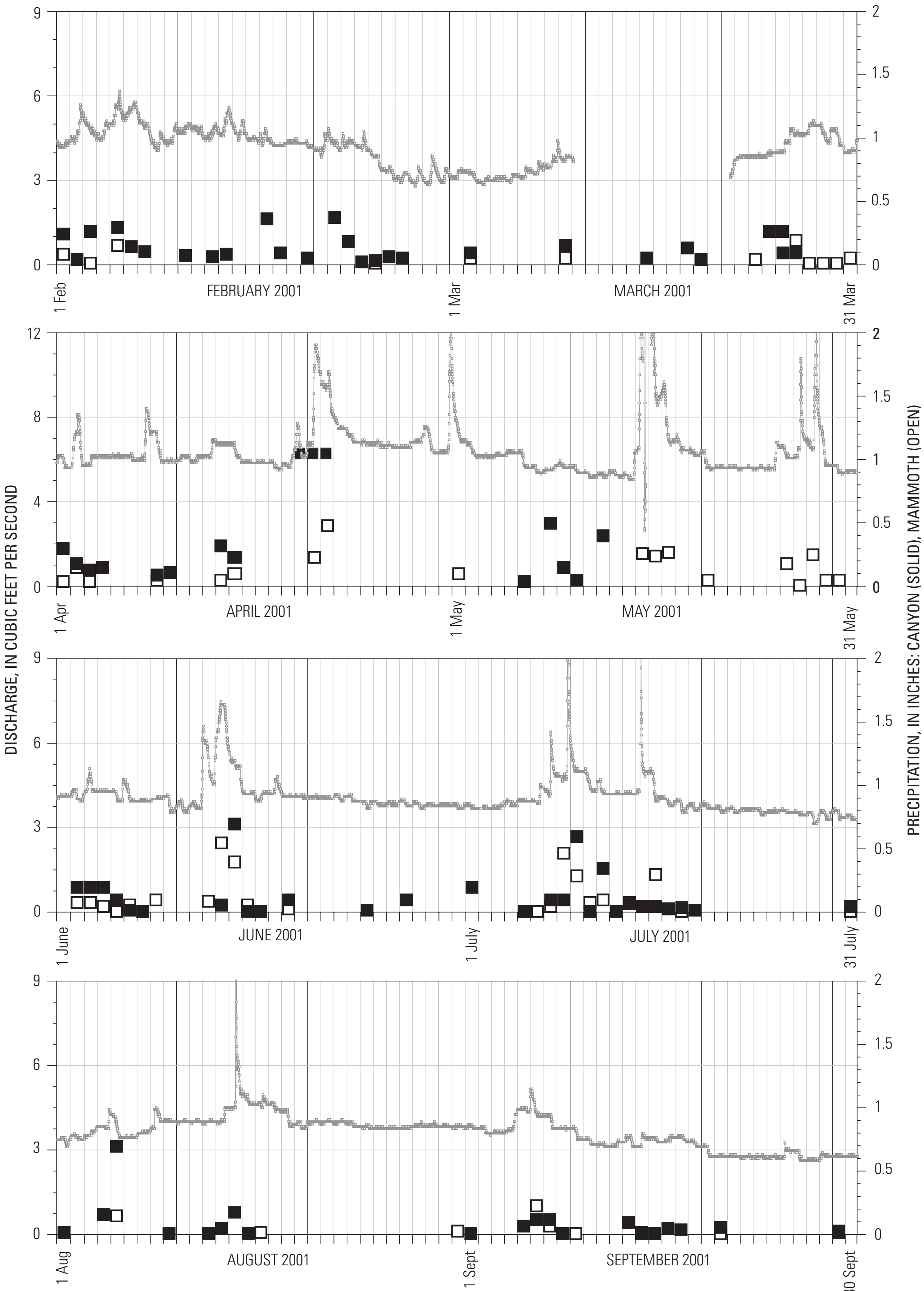


DISCHARGE, IN CUBIC FEET PER SECOND
PRECIPITATION, IN INCHES: CANYON (SOLID), MAMMOTH (OPEN)
1 Oct
OCTOBER 1999
1 Nov
NOVEMBER 1999
31 Nov
1 Dec
DECEMBER 1999
1 Jan
JANUARY 2000
31 Jan
1 Feb
FEBRUARY 2000
1 Mar
MARCH 2000
31 Mar
1 Apr
APRIL 2000
1 May
MAY 2000
31 May

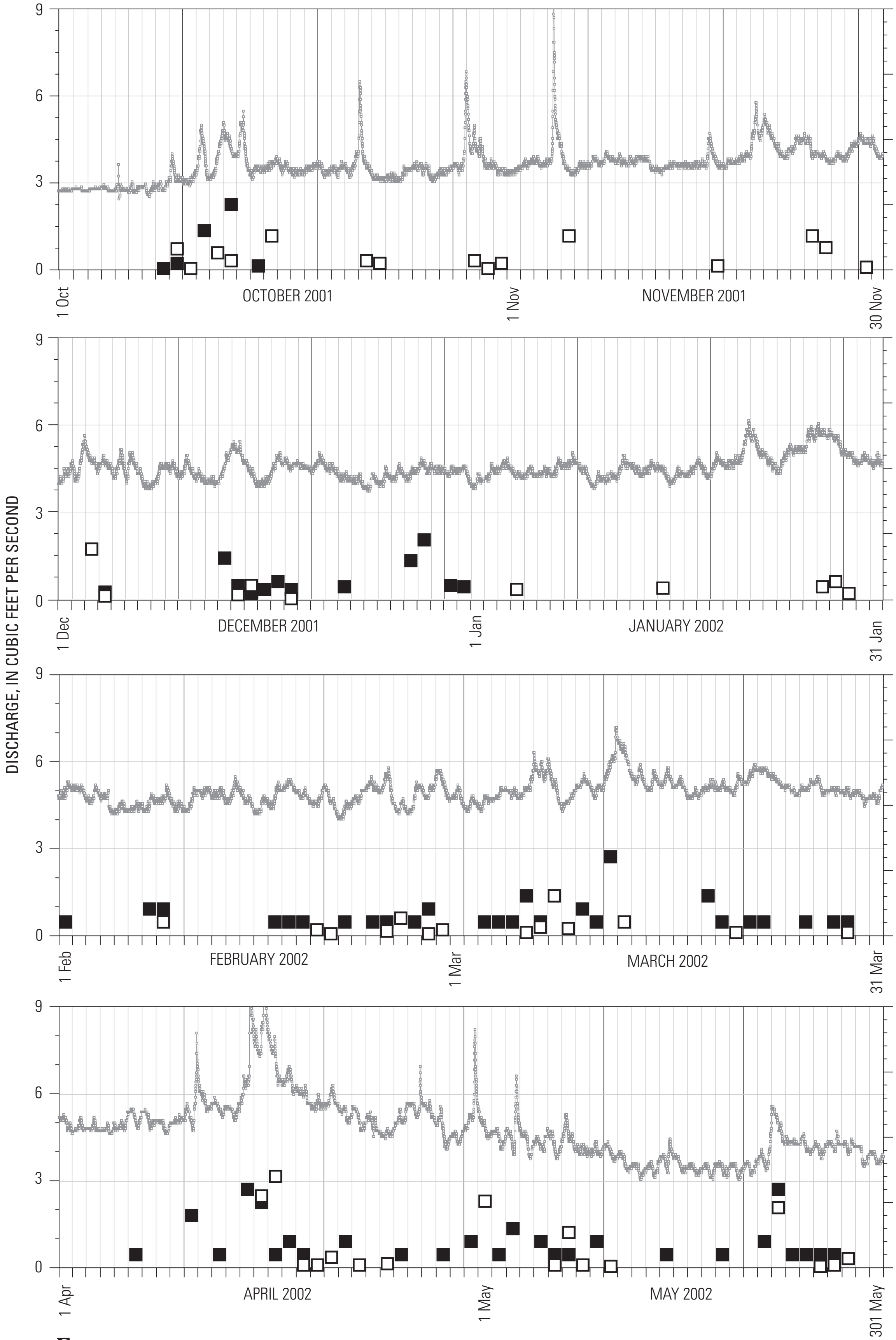
C


DISCHARGE, IN CUBIC FEET PER SECOND
PRECIPITATION, IN INCHES: CANYON (SOLID), MAMMOTH (OPEN)
1 June
JUNE 2000
1 July
JULY 2000
31 July
1 Aug
AUGUST 2000
1 Sept
SEPTEMBER 2000
30 Sept
1 Oct
OCTOBER 2000
1 Nov
NOVEMBER 2000
30 Nov
1 Dec
DECEMBER 2000
1 Jan
JANUARY 2001
31 Jan

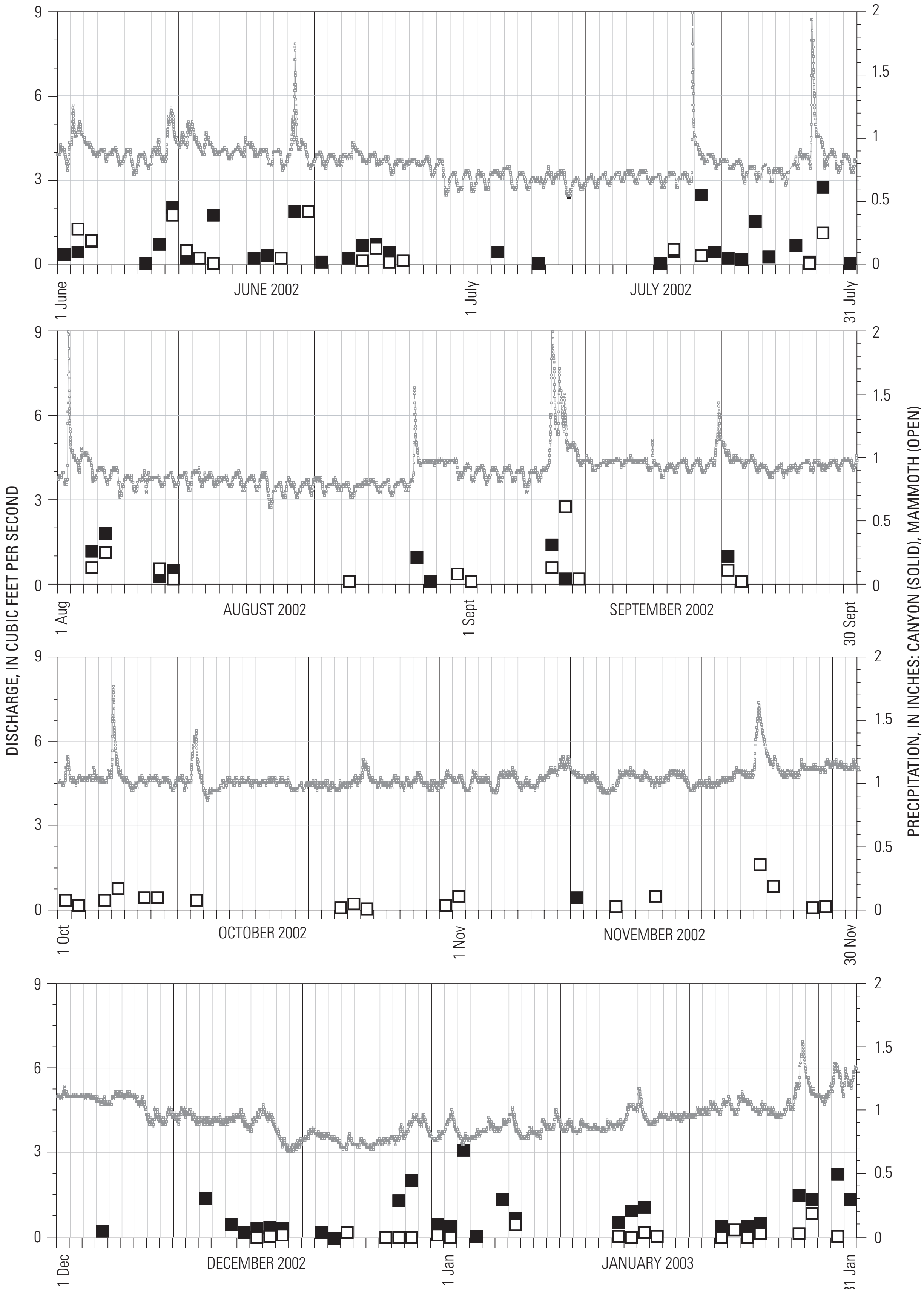
D


DISCHARGE, IN CUBIC FEET PER SECOND
PRECIPITATION, IN INCHES: CANYON (SOLID), MAMMOTH (OPEN)
1 Feb
FEBRUARY 2001
1 Mar
MARCH 2001
31 Mar
1 Apr
APRIL 2001
1 May
MAY 2001
31 May
1 June
JUNE 2001
1 July
JULY 2001
31 July
1 Aug
AUGUST 2001
1 Sept
SEPTEMBER 2001
30 Sept

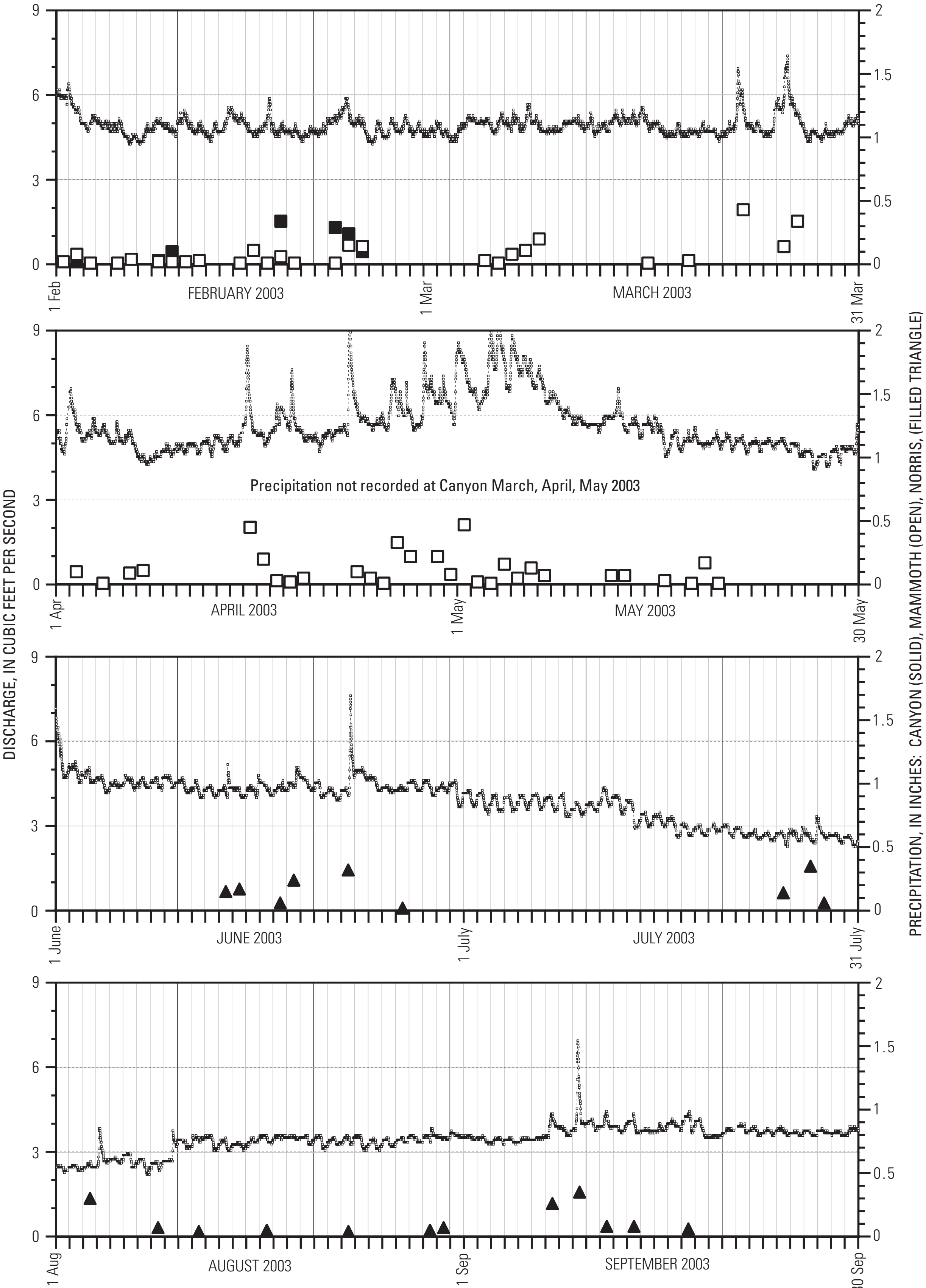
E


DISCHARGE, IN CUBIC FEET PER SECOND
PRECIPITATION, IN INCHES: CANYON (SOLID), MAMMOTH (OPEN)
1 Oct
OCTOBER 2001
1 Nov
NOVEMBER 2001
30 Nov
1 Dec
DECEMBER 2001
1 Jan
JANUARY 2002
31 Jan
1 Feb
FEBRUARY 2002
1 Mar
MARCH 2002
31 Mar
1 Apr
APRIL 2002
1 May
MAY 2002
301 May
0
3
6
9
0
0.5
1
1.5
2

F

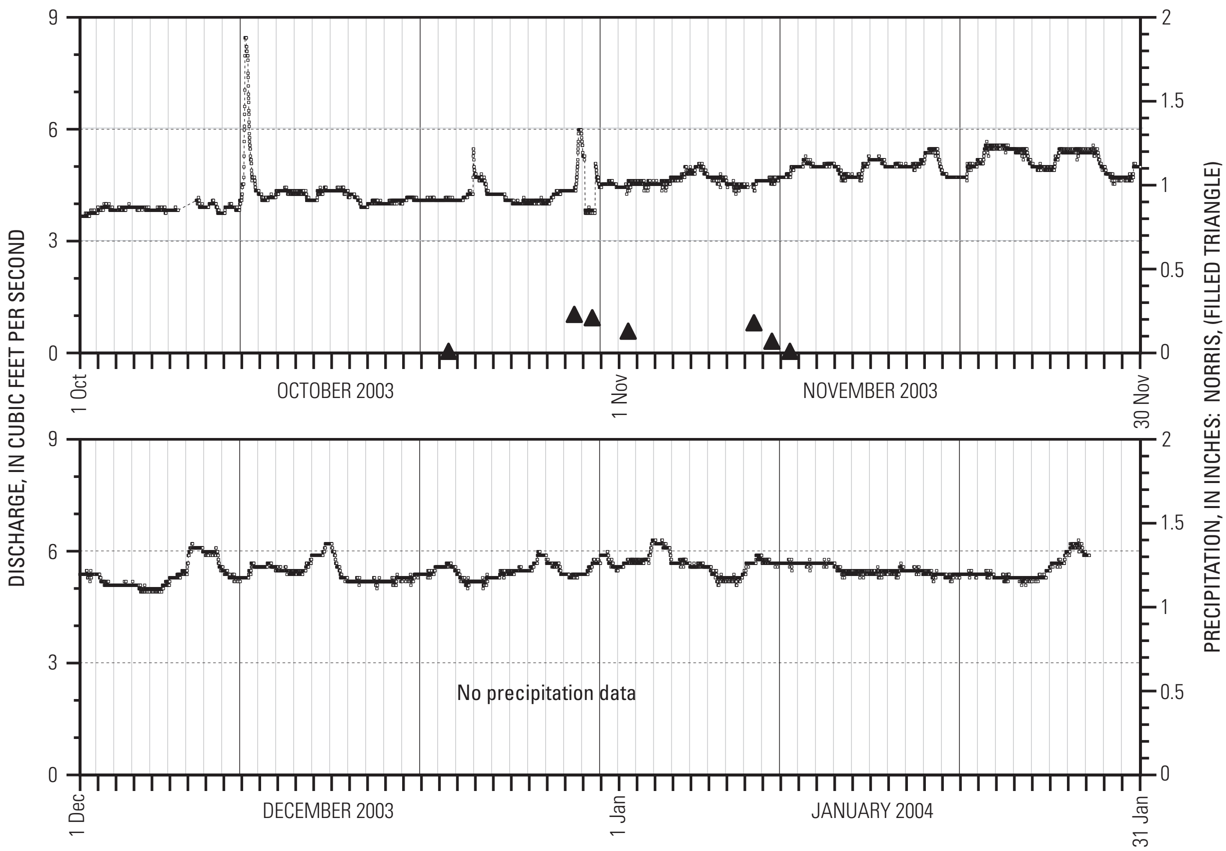

DISCHARGE, IN CUBIC FEET PER SECOND
PRECIPITATION, IN INCHES: CANYON (SOLID), MAMMOTH (OPEN)
9
6
3
0
2
1.5
1
0.5
1 June
JUNE 2002
1 July
JULY 2002
31 July
1 Aug
AUGUST 2002
1 Sept
SEPTEMBER 2002
30 Sept
1 Oct
OCTOBER 2002
1 Nov
NOVEMBER 2002
30 Nov
1 Dec
DECEMBER 2002
1 Jan
JANUARY 2003
31 Jan

G



DISCHARGE, IN CUBIC FEET PER SECOND
PRECIPITATION, IN INCHES: CANYON (SOLID), MAMMOTH (OPEN), NORRIS, (FILLED TRIANGLE)
1 Feb
FEBRUARY 2003
1 Mar
MARCH 2003
31 Mar
Precipitation not recorded at Canyon March, April, May 2003
1 Apr
APRIL 2003
1 May
MAY 2003
30 May
1 June
JUNE 2003
1 July
JULY 2003
31 July
1 Aug
AUGUST 2003
1 Sep
SEPTEMBER 2003
30 Sep

H



I

Observed Changes in Thermal Activity

Echinus Geyser

During the winter of 1998–1999 thermal activity greatly increased in an area about 2 km northeast of the "Hundred Springs Plain" in Norris Geyser Basin. This area, informally known as the "Ragged Hills," has now become a major contributor of thermal activity. Apparently coincident with this change of focus of activity in the NGB, the nature of the eruptions of Echinus Geyser changed. For many years, these eruptions occurred every 50–60 minutes and resulted in discharge, for 5 to 20 minutes, to heights of 10 to 20 m (fig. 5*A*). Since the outbreak of activity in the Ragged Hills area, Echinus rarely erupts, and the eruptions are much less intense than was previously the case. This change in Echinus is shown in detailed plots of the discharge of Tantalus Creek (fig. 5), where the Echinus eruptions are clearly displayed in data taken in the fall of 1998 (fig. 5*A*). Similar plots of data acquired in the late winter and spring of 1999—and in subsequent years—show very small eruptions at 2- to 5-hour intervals and no eruptions for some days (figs. 5*B*, 5*C*, 5*D*, 5*E*). It is interesting to note that a temperature recorder, placed in the Echinus pool (fig. 6), shows periodic (~hourly), short-term (few minutes) increases in water temperature in the pool, indicating that Echinus was still erupting small amounts of water every hour or so (its previous period). However, these eruptions were too small to result in a significant increase in the outflow of Tantalus Creek.

Coincident with the activity at Ragged Hills, the average flow of Tantalus Creek increased in late November 1998 from 3 to 4 cfs to approximately 4 to 5 cfs. It remained high for several months. Subsequently, Tantalus Creek exhibited periods of increased flow (for example, winter 1999 through early spring 2000). Except for these periods of high discharge, the discharge of Tantalus has returned to a flow of approximately 3 cfs. However, Echinus has not returned to its former (pre-Ragged Hills) eruptive pattern. Apparently, thermal water that previously fed Echinus has now been shunted to the Ragged Hills thermal area.

Steamboat Geyser

A description of the history of Steamboat Geyser is given in the classic publication on the Norris Geyser Basin by White and others (1988).

During the early morning of May 2, 2000, two tourists sleeping in their camper parked in the visitors center parking lot, less than 1 km from Steamboat, were awakened by noise and violent ground shaking. As they drove away, fearing that an

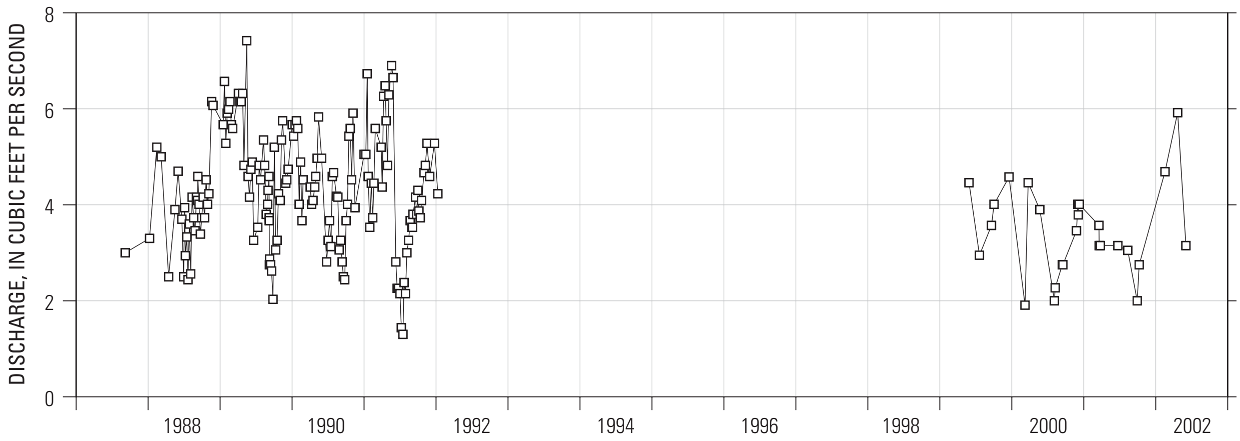


Figure 4. Plot of instantaneous discharge measurements made from a staff gage at the Tantalus Creek weir.

earthquake was occurring, they saw a large plume of steam and water from the vicinity of Steamboat and reported the eruption. Because the eruption occurred early in the morning and shortly after the opening of the park to tourists, only one other person, a park employee on his way to work, reported seeing the eruption.

The eruption was captured by the monitoring equipment in place at Tantalus Creek, as can be seen in figure 7*A*, which shows discharge data for May 1 and 2. The record for May 1 shows that the somewhat irregular eruptions of Echinus Geyser was followed in the early morning of May 2 by the eruption of Steamboat Geyser. The first arrival of the water phase of Steamboat occurred at approximately 5:20 a.m. local time. The water phase lasted 40 to 60 minutes, reaching a peak discharge rate of 1.4 ft^3/s (10.5 gal/s). The total amount of water discharged during the eruption can be calculated from the area under the curve in figure 7*A* from the assumed base flow shown on the figure to the peak of the curve and is approximately 7,600 ft^3 (57,000 gal). The water phase of the eruption was followed by the eruption of steam and a little water. In addition to the water that was measured, a large, but unknown, amount of steam escaped into the atmosphere.

In 2001 and 2002 Steamboat erupted again. Tantalus Creek discharge data for the three eruptions (May 2, 2000, April 26, 2002, and Sept. 13, 2002—figs. 7*A*, 7*B*, and 7*C*, respectively) show that the three eruptions resemble each other very closely, both in maximum water discharge and eruption duration. The total water erupted for each event is: May 2, 2000, event—7,600 ft^3; April 26, 2002, event—4,600 ft^3; Sept. 13, 2002, event—8,700 ft^3.

Two eruptions occurred during March 2003—the data are plotted in figures 7*D* and 7*E*. These two closely spaced eruptions, which occurred during March 22–23 and during March 26, lasted far longer than those that occurred in 2000 and 2002. The first of these erupted approximately 62,000 ft^3 of water, and the second 36,000 ft^3.

A temperature recorder, located in the Steamboat Geyser outflow channel, close to the geyser, recorded the first pulse of water from the eruption of April 27, 2003, at 02:53 mountain standard time (m.s.t.). The first indication of this event at the Tantalus Creek weir occurred at 04:20 (m.s.t.), which indicates a travel time of 1 hour 27 minutes.

The times recorded for the eruption of October 22, 2003, were 19:25 (m.s.t.) for the eruption and 21:00 (m.s.t.) for the first increase at the weir. The travel time of 1 hour 35 minutes agrees with the travel time calculated for the previous eruption.

Basin-Wide Thermal Event

For the past 75 years, widespread disturbances (thermal events) have been observed in Norris Geyser Basin (White and others, 1988, p. 61 and table 8). During these thermal events, increased discharge was observed to have occurred simultaneously at a large number of the thermal features in the geyser basin. These events lasted for a day or so, and the increased basin-wide activity slowly declined for several days. Thermal events were said to usually occur in the summer or early fall. The fact that they never have been observed during the winter or early spring may be because of the lack of observers during these parts of the year. During the thermal events of 1988, 1989, 1990, 1991, and 2003, the discharge of Tantalus Creek did not increase. These thermal events appear to be caused by a short-term redirection of thermal water rather than an overall increase in thermal water input to the geyser basin.

With the introduction of a water-temperature sensor to the Tantalus Creek weir station, which telemeters via GOES satellite stream discharge of the entire Norris Geyser Basin, we were able to detect and measure the results of a very large thermal event that occurred on April 14, 2002 (fig. 8). The event was initiated very suddenly when the discharge of water from Norris Geyser Basin doubled within 30 minutes. The water temperature increased from 25°C (77°F) to a maximum of 70°C (158°F). The discharge and temperature decreased to pre-eruption levels during the next 4 to 6 days. The seismic network maintained by the University of Utah did not record any seismic signal associated with this thermal event.

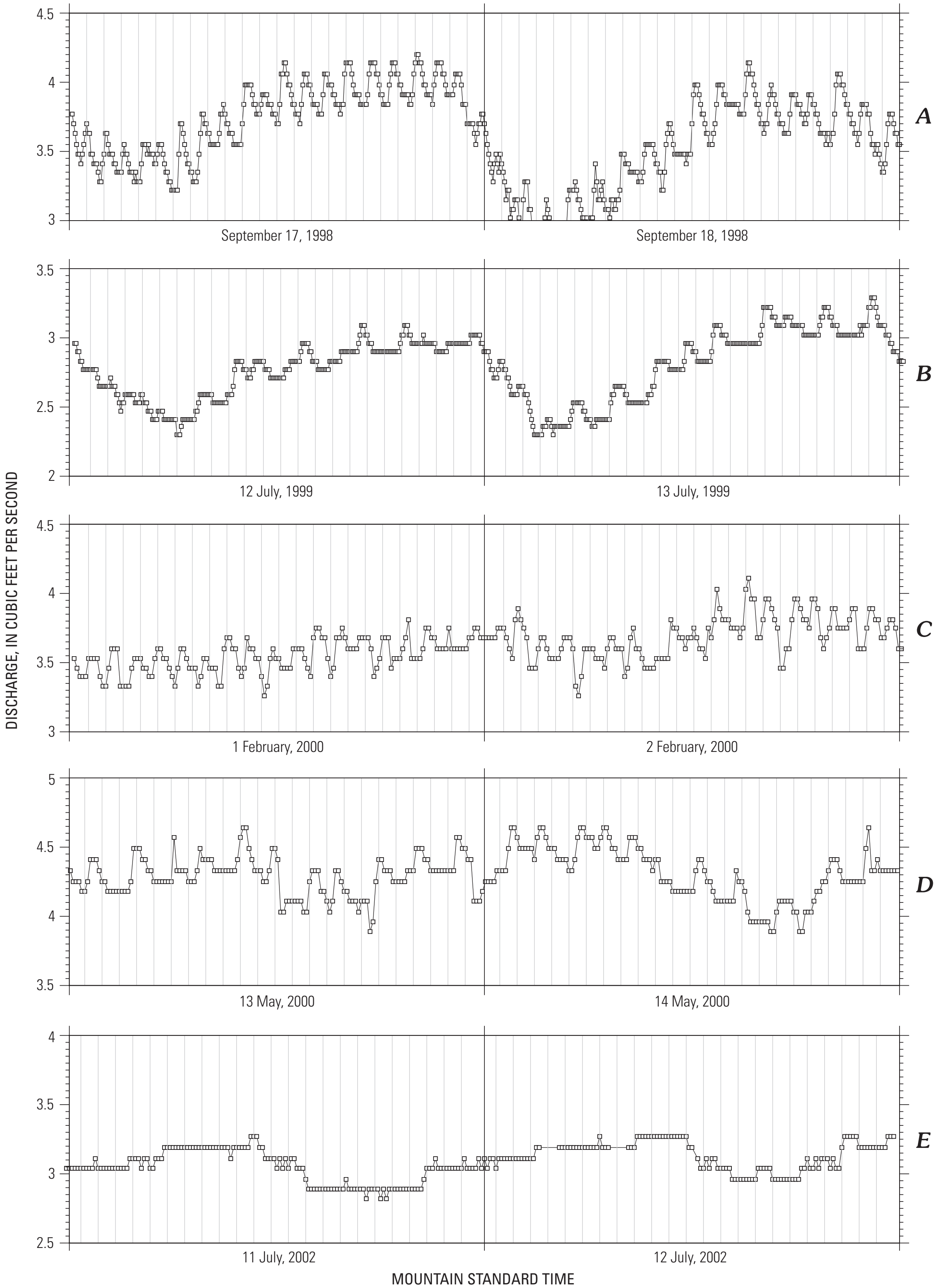


Figure 5. Plots of discharge of Tantalus Creek. *A*, Plot of the data collected September 17–18, 1998, showing the approximately hourly increase in discharge due to the eruption of Echinus Geyser before the increased thermal activity at Ragged Hills. *B*, *C*, *D*, and *E* are plots of data after the increase in activity at Ragged Hills and illustrate the decline in eruptive activity of Echinus Geyser.

The thermal event began with the sudden (within 30 minutes) increase in discharge from 6.5 cfs to 14–15 cfs (A, fig. 8). Simultaneously, the water temperature at Tantalus weir increased from 23° to 42°C. During the next 30 minutes (B, fig. 8), the discharge decreased to 9 cfs and the water temperature increased to 48°C. The temperature remained relatively stable for about 8 hours, while the discharge slowly decreased from 9 to 8 cfs (C, fig. 8). For the next 12 hours, water temperature increased to 70°C and the discharge varied from 7 to 9.3 cfs. The temperature maximum (70°C) (D, fig. 8) occurred an hour before the peak discharge of 9.3 cfs (E, fig. 8). The water temperature and discharge slowly declined for the next several days and reached steady values of 4.5 cfs and 40°C by April 29, 5 days after the beginning of the event.

The complexity of the discharge-temperature events indicates that, during the thermal event, water of different temperatures—and probably from different sources—erupted at different times.

Diurnal Changes in Discharge

A pronounced diurnal variation in discharge from NGB has been observed. This effect occurs during periods when precipitation inflow is absent. During the summer, discharge *decreases* during the daytime and *increases* at night. The onset of the decrease seems to coincide with sunrise and the decrease with sunset (fig. 9*A*). The diurnal variation in discharge is approximately 10 percent of the peak flow. When temperature data became available in early 2002, the water temperature was observed to increase during the day and decrease at night, as might be expected due to solar heating of the bed of shallow Tantalus Creek.

The diurnal oscillation in discharge is easily seen in the discharge data. For example, refer to the August 1998 and April 1999 records (fig. 3).

Two records of winter discharge (figs. 9*B* and 9*C*) also show a diurnal variation but are out of phase with the summer and spring records (figs. 9*A* and 9*D*). The reasons for these

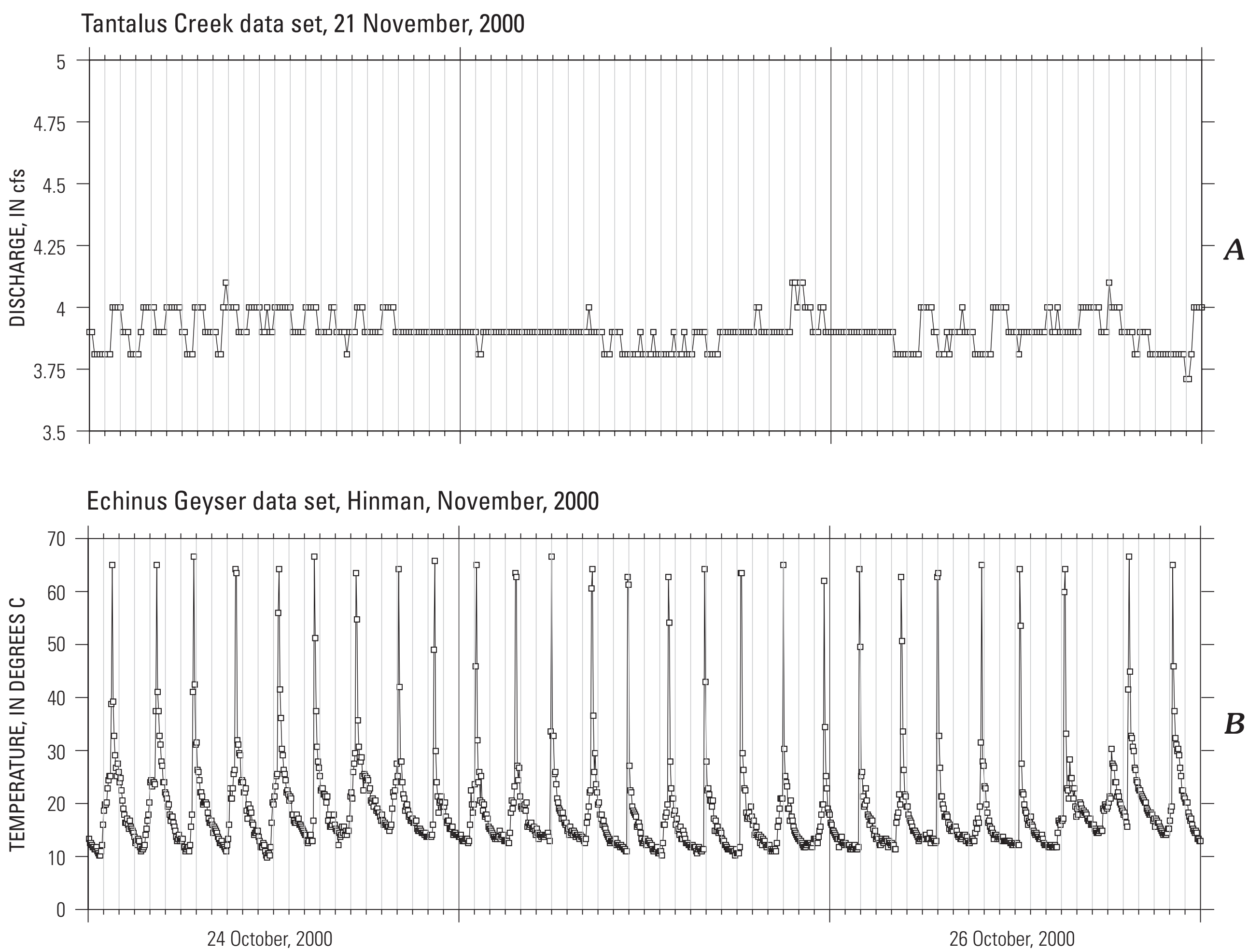
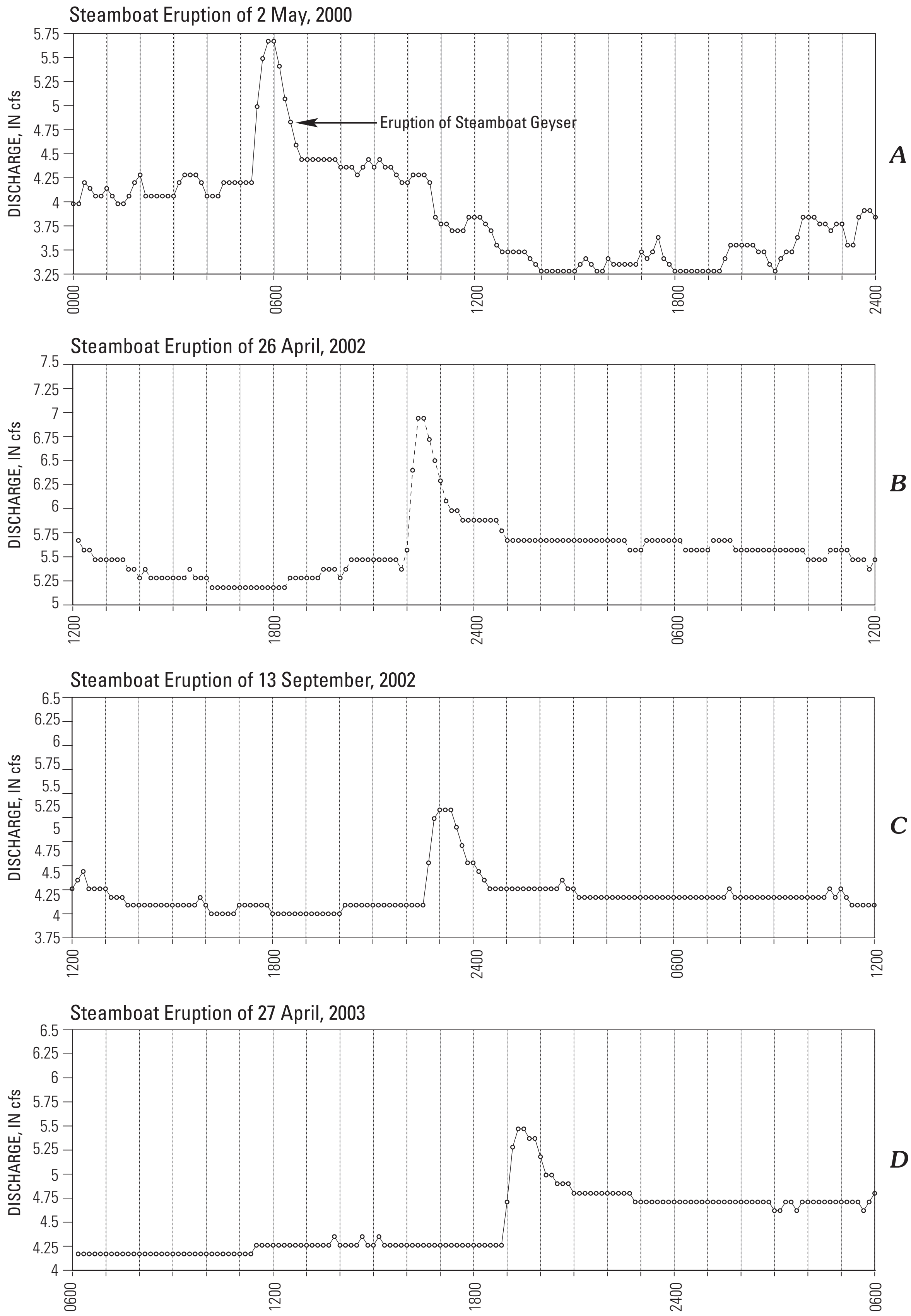


Figure 6. *A*, Plot of discharge at the Tantalus Creek weir for October 24–26 showing the absence of discharge due to eruptions of Echinus Geyser. *B*, Plot of temperature recorded in the Echinus Geyser pool that surrounds the orifice of Echinus Geyser. The temperature record clearly shows that hot water periodically (once every 2.5 hours) entered the pool. This indicated that Echinus erupted, but that it did not emit enough water to (1) produce a subaerial water jet, and (2) show as increased discharge of Tantalus Creek.



All times and dates = Mountain Standard 10 minute measurement interval

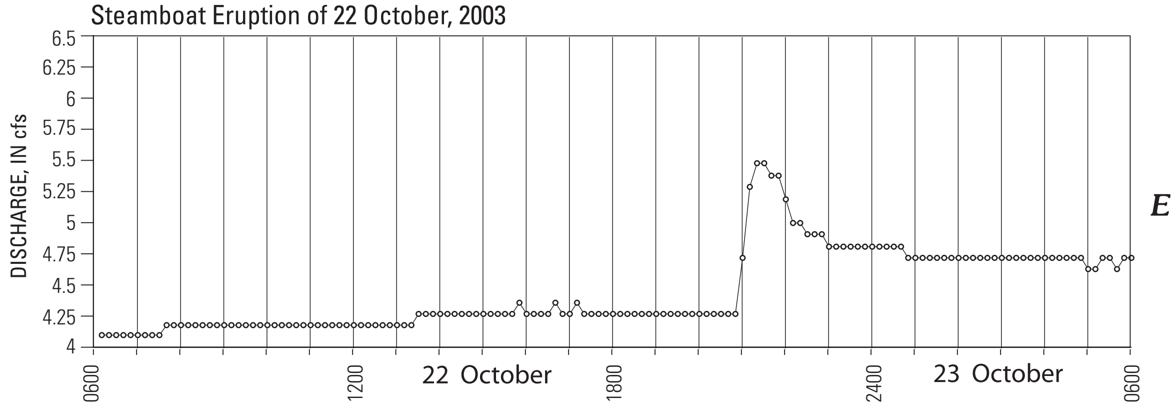


Figure 7 (above and facing page). Plots of the discharge of Tantalus Creek showing the effect of eruptions of Steamboat Geyser. *A*, Eruption of May 2, 2000. *B*, Eruption of April 26, 2002. *C*, Eruption of September 13, 2002. *D*, Eruption of April 27, 2003. *E*, Eruption of October 22, 2003.

oscillations in discharge are not apparent. The decreased flow during the day in summer might be related to increased evapotranspiration during the day. The increased flow during the day in winter might be due to increased snowmelt. However, almost all of NGB is free of snow in winter due to the warmth of the ground—therefore, snowmelt cannot explain the increase in discharge from NGB during the day in winter.

Water Chemistry

To measure chloride and sulfate fluxes exiting Norris Geyser Basin, water samples were periodically collected. These samples were analyzed by the water quality laboratory of the Water Resources Division, USGS, Denver, Colo.

Chloride and Sulfate Flux from Norris Geyser Basin

Samples for chemical analysis were collected weekly during 1989–1991. Since then, samples have been collected intermittently. All samples were filtered through a 5-µm filter during collection. The chloride concentration varies from 350 to 550 ppm; sulfate varies from 100 to 180 ppm. Although the concentration of chloride does not appear to be a function of discharge (fig. 10), the concentration of sulfate increases as discharge decreases below 2 cfs. However, both chloride and sulfate *fluxes* are linear functions of discharge (fig. 11). A similar variation of chloride flux with discharge has been observed for Mammoth Hot Springs as well as springs in the Boundary Creek drainage in the southwestern portion of the Park

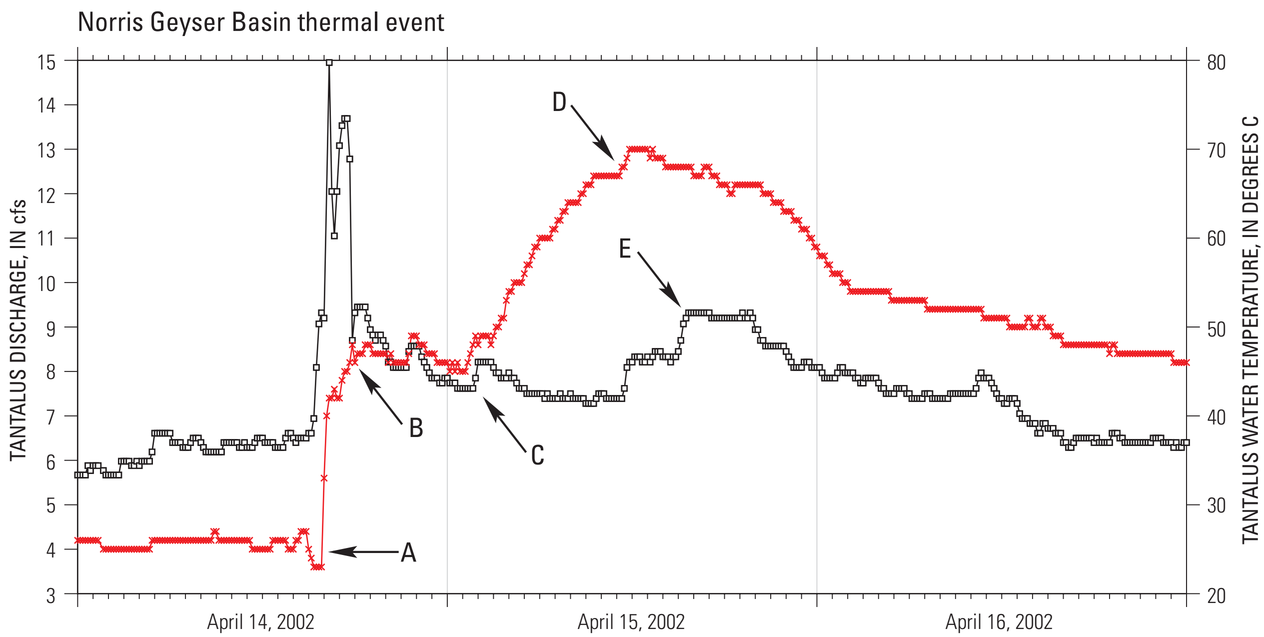


Figure 8. Plots of discharge and water-temperature data acquired during a thermal event. The temperature record is shown in red and the discharge in black.

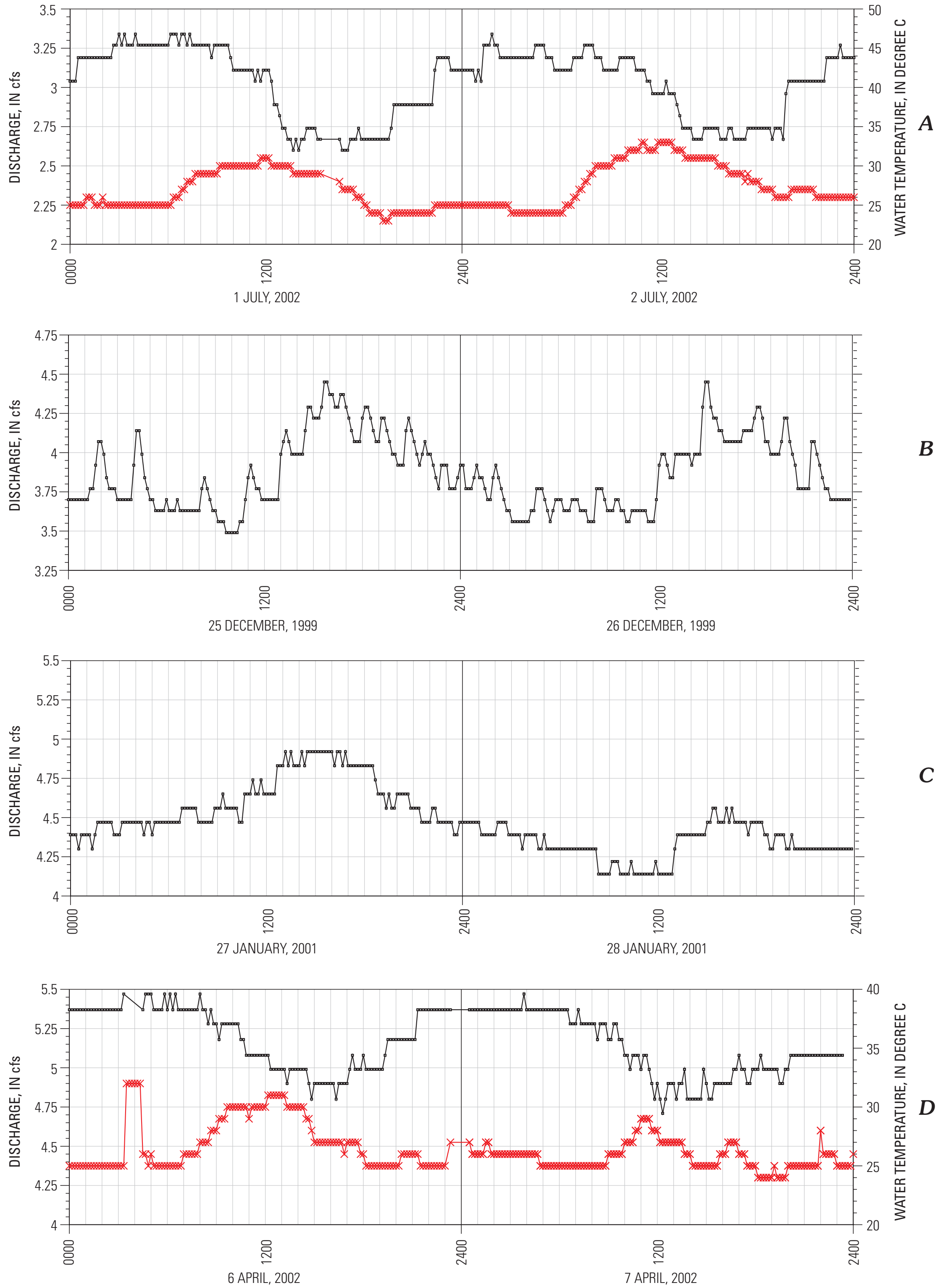


Figure 9. *A*, Plot of 2-day discharge and water temperature of Tantalus Creek for July 1–2, 2002, illustrating diurnal variation in these variables. *B*, Plot of discharge for December 25–26, 1999. *C*, Plot of data for January 27–28, 2001. *D*, Plot of data for April 6–7, 2002. The variation in discharge for the two winter plots (*B*, *C*) are not in phase with the summer data (*A*, *D*). The temperature record is shown in red and the discharge in black.

(Friedman and Norton, 1990; Friedman and Norton, this volume). The chloride versus sulfate flux did not appear to be a function of the discharge (fig. 12).

Most (94 percent) of the chloride exiting the Park is derived from the magma underneath the Park (Norton and Friedman, 1985). Sulfate is believed to be formed largely by the oxidation of reduced sulfur, present either as hydrogen sulfide or elemental sulfur, which are also products of magma. Oxidation occurs when oxygenated water from the surface interacts with the reduced sulfur species—it is unclear whether bacteria are involved with this process (Truesdell and others, 1978; Schoen and Rye, 1970).

In Norris Geyser Basin, the ratio of chloride to sulfur (Cl/S) varies from about 8 to 14 (a chloride to sulfate ratio of 2.5 to 4.5) and is not related to discharge (fig. 11).

Fournier and others (1997) observed that chloride concentration increased at Cistern Spring for several months preceding a thermal disturbance. Immediately following the onset of disturbances, decreased chloride and *increased* sulfate was found. In another example quoted—a neutral-chloride spring at Opal Terrace—the sulfate was observed to *decrease* from 133 ppm to 99 ppm in the 4 days following a disturbance.

Our sampling, although not as detailed as that of Fournier and others (1997), covered a longer time period and integrated the thermal activity of the whole basin. During the distur-

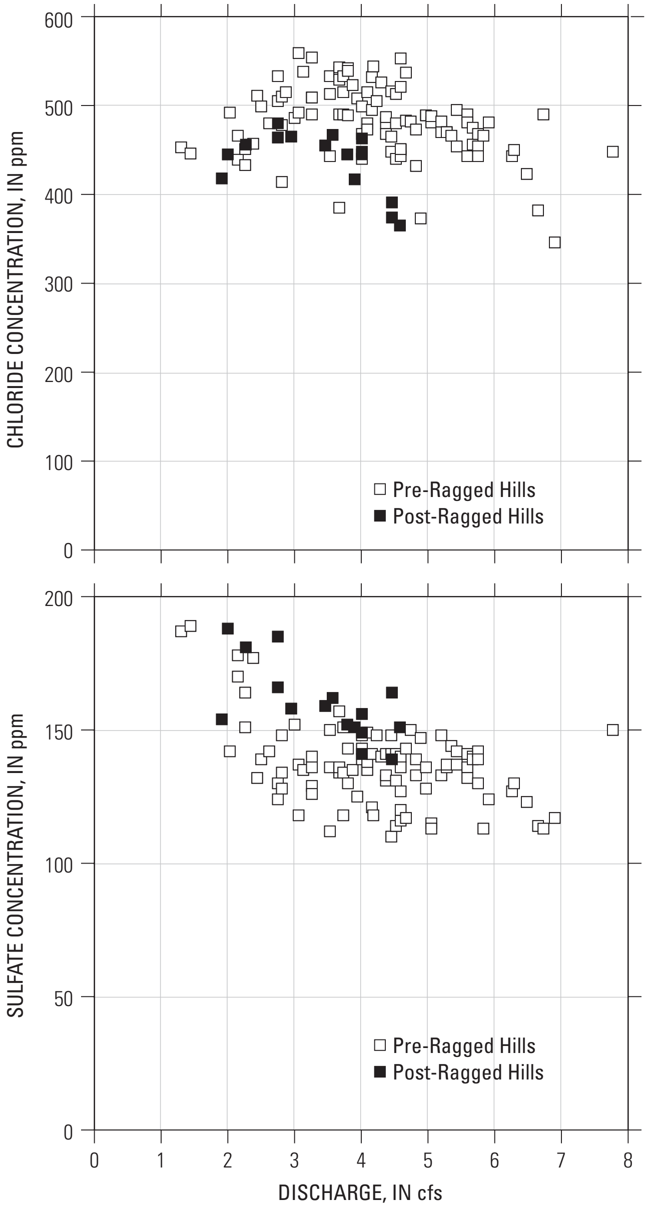


Figure 10. Plots of discharge versus chloride and sulfate concentrations, in parts per million, of water samples collected during 1988–2002 at the Tantalus Creek weir.

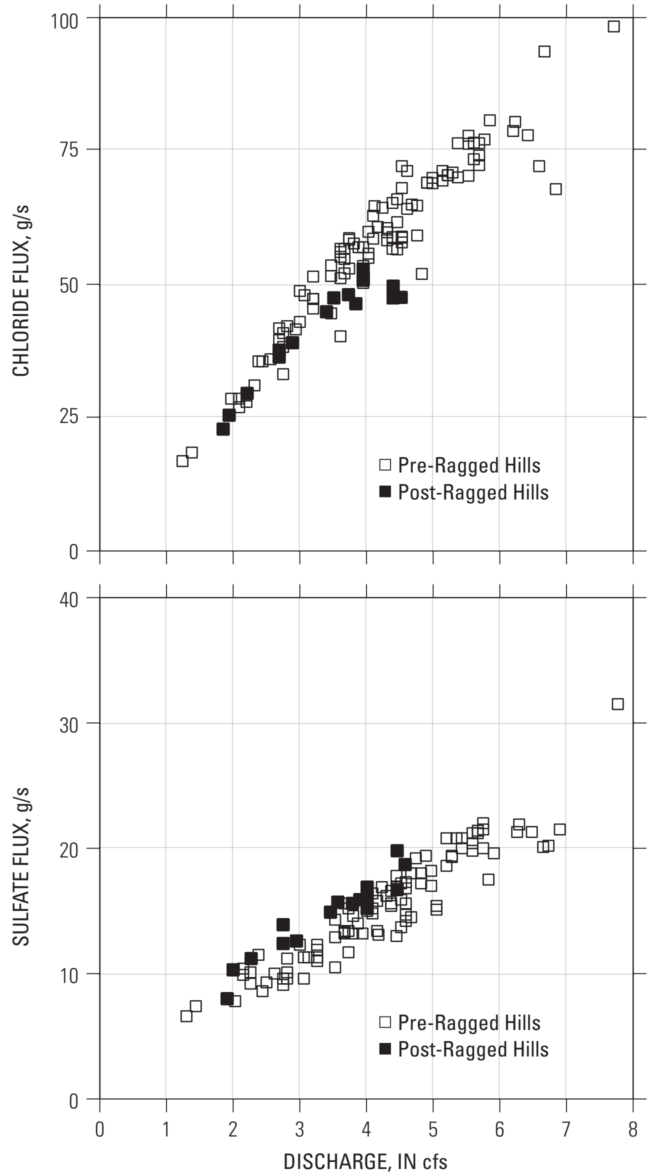


Figure 11. Plots of discharge versus chloride and sulfate fluxes, in grams per second, for water samples collected during 1988–2002 at the Tantalus Creek weir.

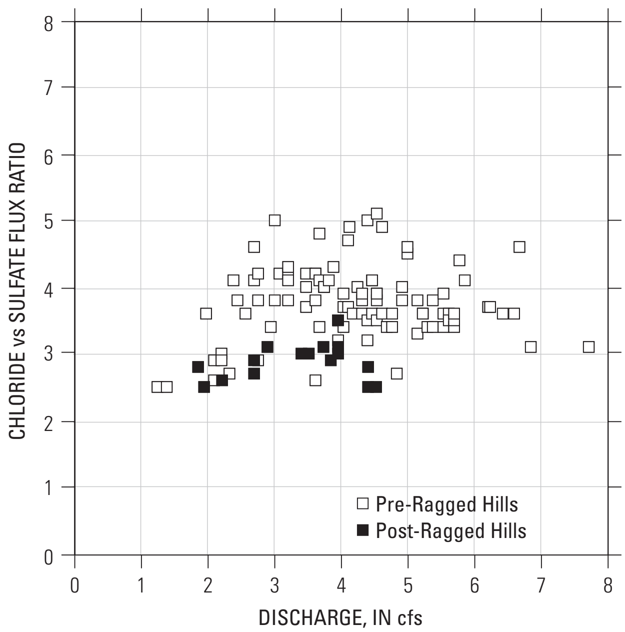


Figure 12. Plot of discharge versus chloride-sulfate ratio for water samples collected during 1988–2002 at the Tantalus Creek weir.

bances of 1988, 1989, 1990, and 1991, both discharge and chloride flux decreased and regained their former values during a period of several months. The changes in both discharge and chloride flux during the 1988, 1989, and 1991 disturbances were as large as a factor of 3, whereas the changes during the 1990 event were much smaller. The changes in sulfate flux were in the same direction as the changes in chloride flux. The ratio of chloride to sulfate flux varied from approximately 2 to 4. With the exception of the data for 1991, the ratio was independent of the discharge rate. In 1991, for discharge rates below 4 cfs, the ratio increased with discharge. At higher discharges, the changes are more random but show a tendency to decrease with increasing discharge. A factor of 4 change in chloride flux over a time interval of a month or so occurred several times in our 4-year data set

Summary and Conclusions

The data presented here illustrate the usefulness of satellite-telemetered data of thermal features that are acquired at closely spaced time intervals.

1. Although some of the variation in discharge from NGB can be related to the effect of precipitation within the basin, examples are given that relate changes in discharge to the eruption of specific thermal features such as Steamboat and Echinus Geysers. Other basin-wide changes are due to changes in thermal-water input from deep sources.
2. An important finding is the large month-to-month change in both chloride and sulfate fluxes. A change by a factor of 4 in chloride flux over a time interval of a month or so occurred several times in our 4-year data set. These measurements confirm qualitative observations made over the years of the extreme variability of thermal activity at NGB. This variability is not restricted to individual thermal features but includes the entire geyser basin
3. A daily variation in discharge occurs with a amplitude of 10 percent. Maximum discharge occurs during the night in summer and during the afternoon in winter. The mechanisms for these diurnal variations in discharge are poorly understood.

References Cited

Fournier, R.O., Janik, C.J., and Weltman, U., 1997, Chemical and isotopic changes in thermal waters during an annual hydrothermal disturbance at Norris Geyser Basin, Yellowstone National Park: Eos, Transactions, American Geophysical Union, v. 78, no. 46, (Suppl.), p. 808.

Friedman, I., and Norton, D.R., 1990, Anomalous chloride flux discharges from Yellowstone National Park: Journal of Volcanology and Geothermal Research, v. 42, p. 225–234.

Norton, D.R., and Friedman, I., 1985, Chloride flux out of Yellowstone National Park: Journal of Volcanology and Geothermal Research, v. 26, p. 231–250.

Schoen, R., and Rye, R.O., 1970, Sulfur isotope distribution in solfataras, Yellowstone National Park: Science, v. 170, p. 1,082–1,084.

Truesdell, A.H., Rye, R.O., Whelan, J.F., and Thompson, J.M., 1978, Sulfate chemical and isotopic patterns in thermal waters of Yellowstone Park, Wyoming, *in* Zartman, R.E., ed., Short papers of the Fourth International Conference, Geochronology, Cosmochronology, Isotope Geology: U.S. Geological Survey Open-File Report 78-701, p. 435–436.

White, D.S., Hutchinson, R.A., and Keith, T.E.C., 1988, The geology and remarkable thermal activity of Norris Geyser Basin, Yellowstone National Park, Wyoming: U.S. Geological Survey Professional Paper 1456, 84 p.