

MEASUREMENTS OF THERMAL-WATER DISCHARGE OUTSIDE

LASSEN VOLCANIC NATIONAL PARK, CALIFORNIA, 1983-94

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CONVERSION FACTORS

Conversion factors for terms used in this report are listed below:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
meter (m)	3.281	feet (ft)
kilometer (km)	0.6214	miles (mi)
square kilometers (km ²)	0.3861	square miles (mi ²)
kilogram (kg)	2.205	pound (lb)
milligram per liter (mg/L)	6.243×10^{-5}	pounds per cubic foot (lb/ft ³)
liter per second (L/s)	0.03532	cubic feet per second (ft ³ /s)
milliwatt per square meter (W/m ²)	0.02389	heat-flow units (hfu) (1 hfu = 1 μ cal/cm ² /s)

For conversion of degrees Celsius ($^{\circ}$ C) to degrees Fahrenheit ($^{\circ}$ F), use the formula:

$$^{\circ}\text{F} = 1.8^{\circ}\text{C} + 32.$$

ABSTRACT

Thermal water derived from the hydrothermal system beneath Lassen Volcanic National Park, northern California, discharges by spring flow and ground-water seepage into streams draining the Lassen region. High concentrations of conservative constituents (chloride and boron) in the thermal water make it possible to determine the amount of thermal water in surface streams from measurements of chemical flux. Such measurements indicate that the total discharge of thermal water from the Lassen hydrothermal system is ≤ 46 L/s. Most (22 L/s) of this discharge occurs along Mill Creek in the vicinity Morgan and Growler Hot Springs, where repeated measurements have a relative standard deviation 15 percent, and indicate some correlation between thermal-water discharge and streamflow. Additional outflow of Lassen thermal water occurs at Domingo Springs and in Mill Creek downstream from Highway 36, and possibly in the North Fork Feather River and the Pit River. Arsenic and antimony are also present in high concentrations in the Lassen thermal waters, but are not transported conservatively in the streams. Significant, but variable, losses of arsenic and antimony contributed by thermal water inputs occur within 1-4 km of the hot springs due to oxidation in the stream water and subsequent adsorption on streambed sediments.

INTRODUCTION

Background

Lassen Volcanic National Park (LVNP), located in northeastern California, encompasses a 428 km region of Cenozoic volcanic rocks and surficial hydrothermal activity (figs. 1 and 2). The volcanic history of this region, including the most recent eruptive activity (1914-1917), is summarized by Clynne and Muffler (1989). Thermal fluid derived from the Lassen hydrothermal system discharges in the southern part of the Park and in the Lassen Known Geothermal Resources Area (KGRA) south of the Park (fig. 2). All but one of the thermal areas inside LVNP are steam-heated, that is, they have developed above zones of steam upflow. Such areas include fumaroles and acid-sulphate hot springs and pools. Hot-spring water from Bumpass Hell (table 1) is typical of thermal water from such areas. The exception is the Drakesbad thermal area where hot springs discharge higher pH, higher chloride water, suggesting that this area is conductively heated. Neutral pH, high-chloride thermal water has been detected in springs within the Lassen KGRA and in a well drilled at Terminal Geyser near the southern edge of the Park (table 1 and fig. 2).

Conceptual models of the Lassen hydrothermal system (Muffler and others, 1982; Sorey and Ingebritsen, 1984; and Ingebritsen and Sorey, 1985, 1988) involve a boiling region beneath the southeastern flank of Lassen Peak. Steam rises through a vapor-dominated zone to discharge at relatively high elevations inside the Park, and liquid flows laterally to the south toward the hot-spring areas at lower elevations in the KGRA. High-chloride hot springs occur at Morgan Hot Springs and Growler Hot Springs, approximately 4 km south of the Park boundary along the drainages of Mill Creek and Canyon Creek, respectively (fig. 2). Chloride concentrations at Domingo Springs (fig. 2) are approximately ten times higher than in other cold springs in the KGRA, suggesting the presence of a thermal component in Domingo Springs even though the temperature of the spring waters is not considered anomalous. Thermal water produced from the Walker "O" No. 1 well, drilled to a depth of 1,220 m at the Terminal Geyser thermal area just inside the Park boundary (fig. 3 and Beall, 1981), is chemically similar to the hot-spring waters in the KGRA (table 1). These observations, along with geothermometer calculations for hot-spring waters and fumarolic gases, electrical resistivity surveys, and temperatures measured in the well at Terminal Geyser, indicate that there are at least two zones of lateral outflow of hot water away from a boiling region beneath the southeastern flank of Lassen Peak (Ingebritsen and Sorey, 1985). One zone trends southward toward Morgan and Growler Hot Springs and the other trends southeastward toward Terminal Geyser and Domingo Springs.

Ratios of Br/Cl for thermal waters in the Lassen KGRA (near 0.0033) are essentially the same as for sea water (Mason, 1958). Thompson (1985) suggested that this results from a small (5 percent) component of sea water derived from Late Cretaceous marine sedimentary rocks that may underlie the Lassen volcanic rocks. A similar relation has been hypothesized for geothermal waters in parts of the Cascade Range in Oregon (Mariner and others, 1988, 1990). Alternative sources of the anomalous concentrations of Cl, B, and As in the Lassen KGRA waters include dissolution of evaporitic minerals within the sedimentary rocks and components of magmatic volatiles derived from shallow intrusions.

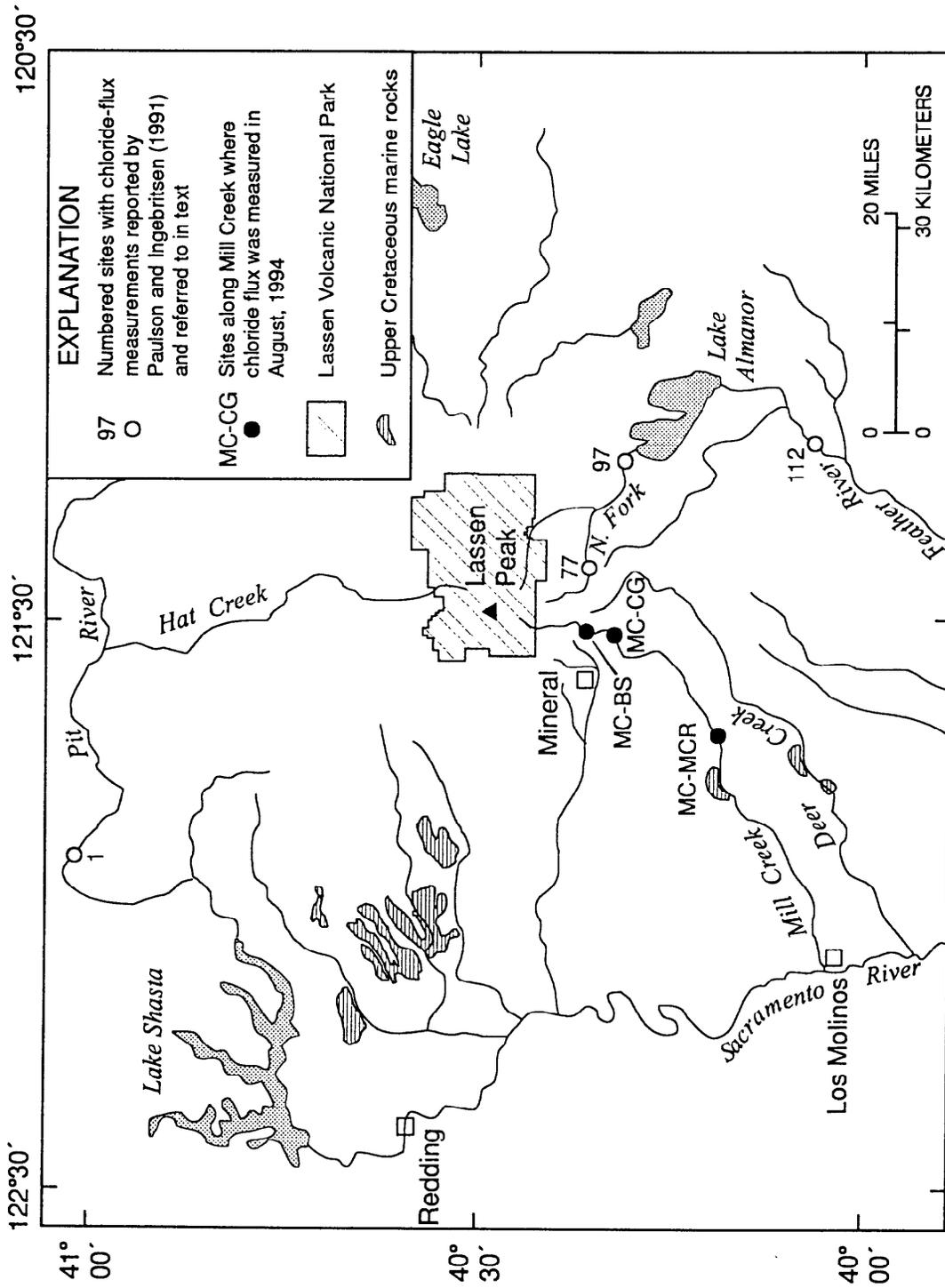
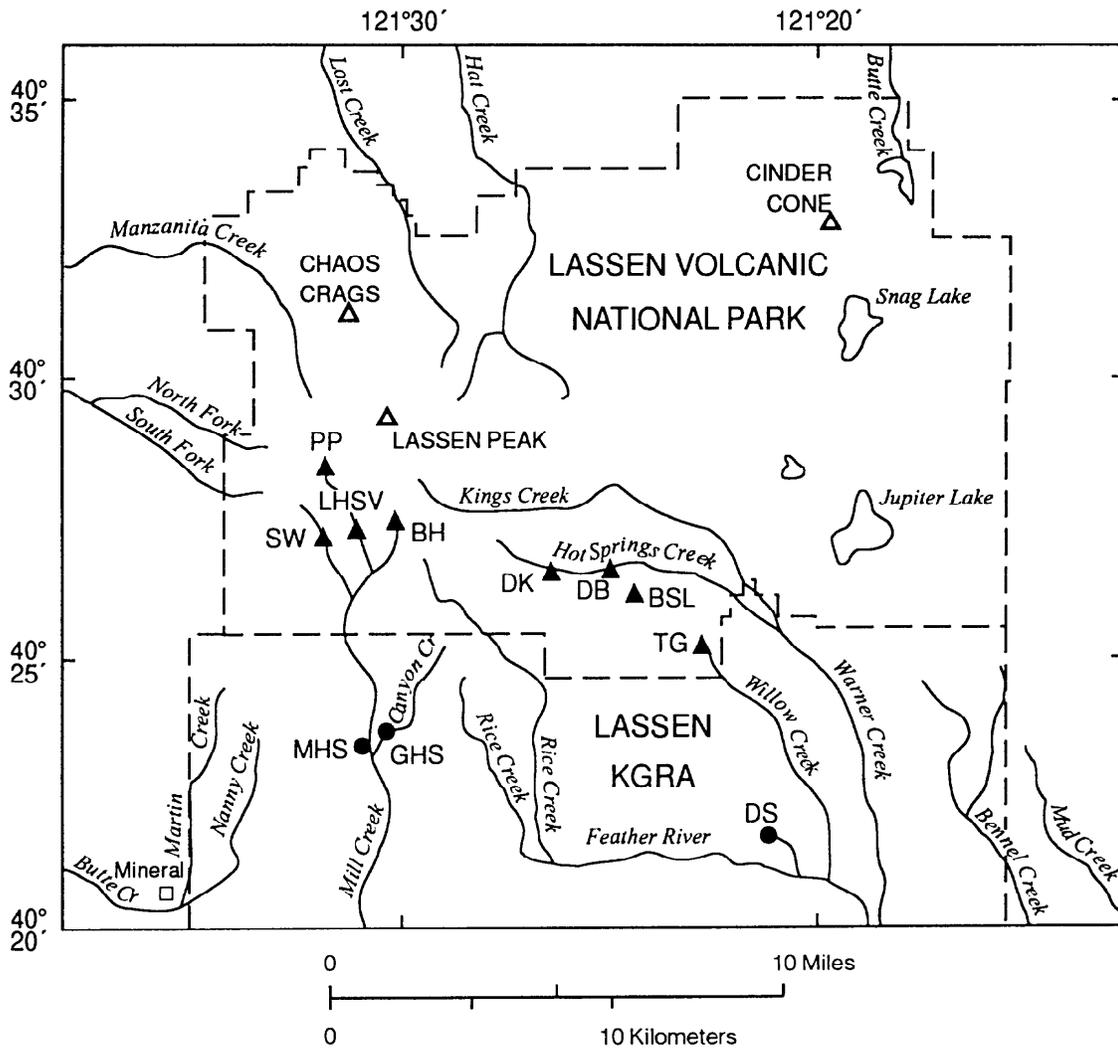


Figure 1. Map of the Lassen region in northeastern California showing Lassen Volcanic National Park, principal streams, and sites referred to in text where chloride flux has been determined.



EXPLANATION

- △ Area of recent eruptive activity
- ▲ Principal steam-heated thermal area

BH	Bumpass Hell	PP	Pilot Pinnacle
BSL	Boiling Springs Lake	SW	Sulphur Works
DK	Devils Kitchen	TG	Terminal Geyser
LHSV	Little Hot Springs Valley	DB	Drakesbad (conductively heated)
- Area of neutral-pH thermal springs

DS	Domingo Springs	MHS	Morgan Hot Springs
GHS	Growler Hot Springs		

Figure 2. Map of Lassen Volcanic National Park and Lassen Known Geothermal Resources Area (KGRA) showing areas of thermal-fluid discharge.

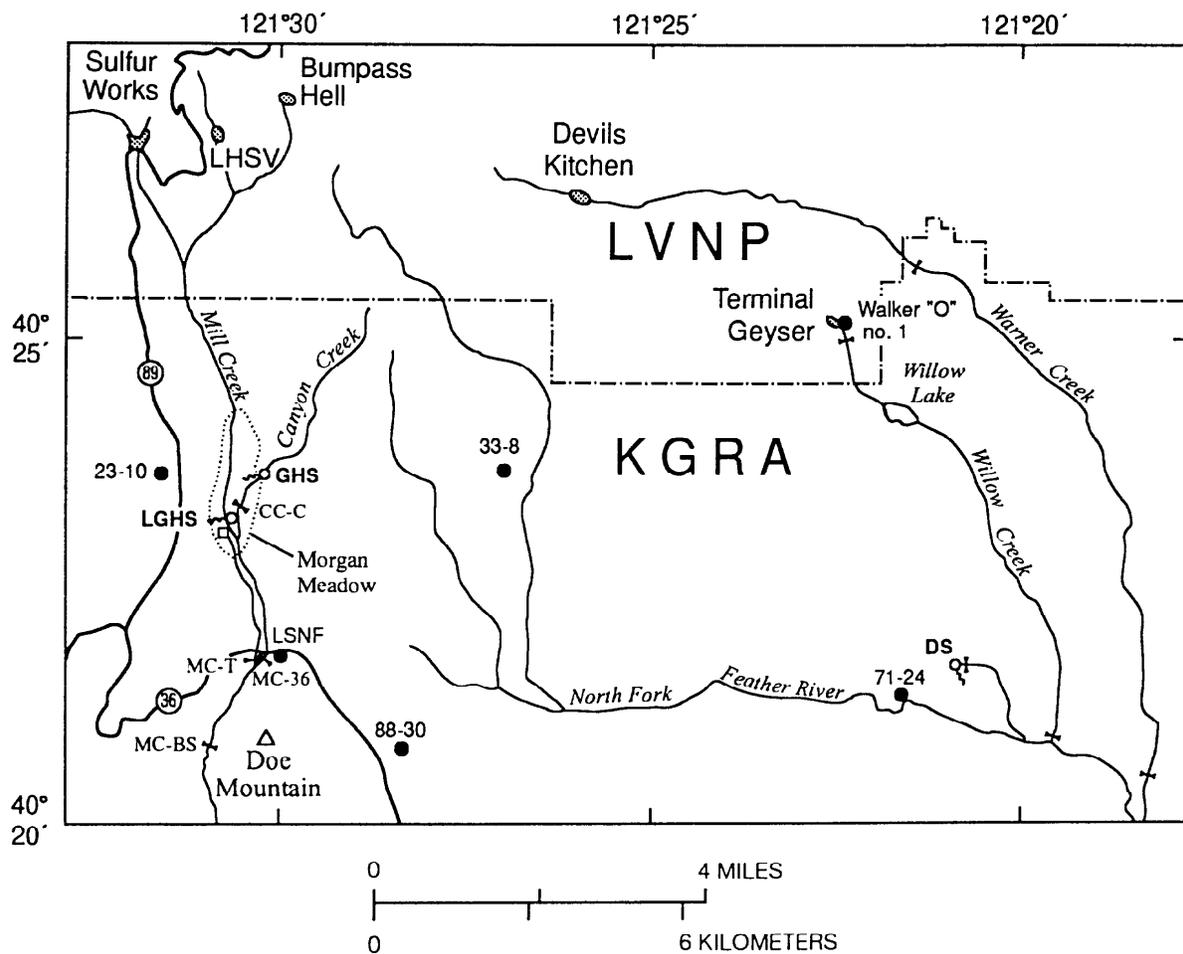
Table 1. Typical concentrations of selected ions in thermal waters from Lassen Volcanic National Park (LVNP) and Lassen Known Geothermal Resources Area (KGRA)

[Data from Thompson (1985); T, temperature; SO₄, sulfate; Cl, chloride; B, boron; As, arsenic; °C, degrees Celsius; mg/L, milligrams per liter; *, no data]

Location	T	pH	SO ₄	Cl	B	As
	(°C)		(mg/L)	(mg/L)	(mg/L)	(mg/L)
<u>Inside LVNP:</u>						
Bumpass Hell	93	2.0	458	<1	1	*
Drakesbad	65	6.5	140	3	1	*
Terminal Geyser Well	² 86	*	81	2,180	62	9.9
<u>In Lassen KGRA:</u>						
Morgan Hot Springs ¹	94	7.2	110	2,250	67	10.4
Growler Hot Springs ¹	94	8.0	90	2,430	71	12.7

¹ Samples collected in 1982 from Little Growler Hot Spring at Morgan Hot Springs and the main vent at Growler Hot Springs.

² Temperature of sample collected at wellhead. Subsurface temperature of production zone = 176°C (Beall, 1981).



EXPLANATION

- | | | | |
|---------|--|------|---------------------------|
| ● 23-10 | Test well with designation | DS | Domingo Springs |
| ♁ GHS | Principal hot spring with designation | GHS | Growler hot spring |
| □ | Seward swimming pool | LGHS | Little Growler hot spring |
| MC-36 | Stream gaging and sampling site with designation | | |
| ♁ | Steam-heated thermal area | | |

Figure 3. Map showing selected thermal areas in Lassen Volcanic National Park (LVNP), test wells referred to in text, and sites for stream gaging and fluid sampling in the Lassen Known Geothermal Resources Area (KGRA).

Periodic monitoring of the rate and composition of thermal-fluid discharge in the Lassen KGRA began in 1983, in order to (1) provide values needed to model the hydrothermal system and (2) assess the variability in these parameters under natural (pre-geothermal development) conditions. Sorey and Ingebritsen (1984) and Sorey (1986) describe the monitoring data collected over the 1983-85 period. Measurements of chloride flux at approximately 116 sites in streams draining the larger Lassen region (as depicted in fig. 1) during the 1989-90 period were reported by Paulson and Ingebritsen (1990). Temperature gradients measured in shallow (<200 m) test holes drilled by the U.S. Geological Survey (USGS) in the Lassen KGRA (Mase and others, 1980) also provide limited indications of subsurface flow of thermal water, as do temperature measurements in one deeper (670 m) test hole drilled by Unocal Corporation just south of the Park boundary.

Purpose and Scope

This report describes rates of thermal-water discharge in Mill Creek, Canyon Creek, and Domingo Springs between 1983-94, based on measurements of chloride and boron flux. A companion report, WRIR 94-4180-A (Sorey and Colvard, 1994), describes measurements of heat loss and steam upflow at the thermal areas inside LVNP over a similar period. Taken together, these reports provide information needed to develop a revised model of the Lassen hydrothermal system and for assessing the degree of variability in thermal-fluid discharge from the system. Monitoring data for the Lassen KGRA also provide evidence of loss of arsenic and antimony between the hot springs and downstream gaging sites on Mill Creek and Canyon Creek, and mechanisms responsible for these losses are discussed in this report. The information presented on arsenic and antimony loss can be compared with similar types of information obtained at other areas where waters with high arsenic and antimony concentrations discharge into streams.

Acknowledgments

The authors are indebted to Michael Friebel and Lee Price of the U.S. Geological Survey for their assistance in our field investigations and to Michael Bodell of Unocal Corporation for providing information on test holes drilled by Unocal. Permission for access to sites along Mill Creek and Canyon Creek north of Highway 36 was granted by Elizabeth Seward and her family.

MEASUREMENT TECHNIQUES

Chemical Flux

In the Lassen KGRA, thermal fluid discharges from numerous springs and seeps within and adjacent to the streambeds of Mill Creek and Canyon Creek upstream from Highway 36 (fig. 3). The flow of most of these vents cannot be measured directly; indirect measurements of the thermal-water input to these streams are obtained by determining the increase in chemical flux in the streams as they flow through the hot-spring areas. Thermal water at Morgan and Growler Hot Springs has relatively high concentrations of conservative ions such as chloride and boron (table 1), so that thermal-water discharge to streams can be determined at dilution factors of as much as 500 to 1.

The following formula relates the discharge of thermal water entering a stream between two measuring sections to measurements of chemical flux.

$$Q_T = [Q_S(Cl_S/Cl_T + B_S/B_T)/2]_{ds} - [Q_S(Cl_S/Cl_T + B_S/B_T)/2]_{us}, \quad (1)$$

where Q_T = thermal-water discharge with Cl and B concentrations Cl_T and B_T ,
 Q_S = streamflow with Cl and B concentrations Cl_S and B_S ,
subscripts "us" and "ds" refer to upstream and downstream sampling sites.

Chloride and boron fluxes are averaged to reduce the effect of analytical error in each species. Although boron concentrations in the stream samples were uniformly lower than corresponding chloride concentrations, results for duplicate samples run at different laboratories indicate that laboratory accuracy was generally comparable for both constituents.

Values of chemical flux upstream from each thermal area were determined three times for Mill Creek and seven times for Canyon Creek during the 1983-87 period. In each case, upstream fluxes of Cl and B were less than 7 percent of the corresponding fluxes at the downstream sampling sites. For these sample sets, Cl values ranged from 0.2-0.4 mg/L for the Mill Creek upstream samples and 0.4-12 mg/L for the Canyon Creek upstream samples. In the results that follow, the fluxes at the upstream sections were assumed negligible and the following simplified equation was used.

$$Q_T = [Q_S(Cl_S/Cl_T + B_S/B_T)/2]_{ds} \quad (2)$$

The values of Cl_T and B_T used in equation 2 (2,400 and 85 mg/L, respectively) are rounded averages of approximately 30 analyses of different samples of Growler hot spring, the main vent on the stream bank at Growler Hot Springs, and Little Growler hot spring, a boiling vent upstream from the bridge over Mill Creek at Morgan Hot Springs (fig. 3 and table 2). The relative standard deviations are less than 10 percent of the average values for both elements, so the composition of the thermal-water input is reasonably well-constrained over the sampling period. Our Cl_T value is within 10 percent of the data of Thompson (1985), based on samples collected in 1982, although B_T is approximately 20 percent higher than those data (table 1).

Table 2. Concentrations of chloride, boron, arsenic, and antimony in Growler Hot Spring at Growler Hot Springs and Little Growler Hot Spring at Morgan Hot Springs

[Laboratory abbreviations: CL, U.S. Geological Survey Central Laboratory in Arvada, Colorado; MP, U.S. Geological Survey laboratories in Menlo Park, California; UU, the Earth Science Laboratory at the University of Utah Research Institute in Salt Lake City, Utah. Cl, chloride; B, boron; As, arsenic; Sb, antimony; mg/L, milligrams per liter; *, no data]

Spring Name	Date	Lab	Cl (mg/L)	B (mg/L)	As (mg/L)	Sb (mg/L)
Growler Hot Spring (Main vent at Growler Hot Springs)	840815	CL	2600	89	9.0	*
	841101	CL	2700	91	12.0	*
	850730	CL	2400	88	11.0	*
	851029	CL	3000	79	12.0	*
	860521	CL	2400	86	12.0	*
	860826	CL	2600	86	12.0	*
	870730	CL	¹ 750	91	12.0	*
	870922	CL	2200	89	13.0	2.10
	871020	CL	2300	81	¹ 25.0	1.80
	880510	CL	2300	88	12.0	¹ 0.44
	880630	CL	2200	81	11.0	2.30
	880726	CL	2200	83	9.1	¹ 0.10
	890525	UU	2490	81	11.0	¹ 0.49
	890628	UU	2472	89	11.1	¹ 0.35
	890816	UU	2280	90	10.5	*
	900801	UU	2450	104	¹ 3.8	*
	910813	MP,UU ²	2460	91	*	*
920810	MP,UU ²	2460	90	*	*	
930824	MP	2410	87	*	*	
940720	MP	2440	91	*	*	
Little Growler Hot Spring (Morgan Hot Springs)	840815	CL	2600	79	8.4	*
	841101	CL	2600	86	11.0	*
	850730	CL	2300	87	9.8	*
	851029	CL	2700	74	10.0	*
	870922	CL	2300	86	11.0	2.70
	880510	CL	2300	86	11.0	¹ 0.56
	880630	CL	2200	81	9.3	2.50
	880726	CL	2200	83	12.0	1.40
	890525	UU	2415	81	10.2	1.25
	890628	UU	2420	87	9.9	1.51
	890816	UU	2400	89	9.6	1.11
	900801	UU	2370	100	¹ 3.6	*
	910813	MP	2390	*	*	*
920810	MP,UU ²	2250	89	*	*	
930824	MP	2275	81	*	*	
940720	MP	2400	90	*	*	

*Table 2. Concentrations of chloride, boron, arsenic, and antimony in Growler Hot Spring at Growler Hot Springs and Little Growler Hot Spring at Morgan Hot Springs
--continued*

Spring	Date	Lab	Cl	B	As	Sb
Name			(mg/L)	(mg/L)	(mg/L)	(mg/L)
Average of both springs			2415	87	10.8	1.9
Standard deviation			171	5.7	1.2	0.57

¹ Value assumed incorrect and not used in computations.

² Chloride determined at USGS laboratory in Menlo Park, California (MP); boron determined at University of Utah Research Institute in Salt Lake City, Utah (UU).

In contrast to chloride and boron, some of the arsenic and antimony contributed by thermal water input to the streams appears to be lost by adsorption and precipitation on streambed sediments. Measured fluxes of As and Sb at sampling sites below the hot-spring areas were compared with fluxes expected on the basis of Q_T values calculated from equation 2 to quantify the loss of As and Sb within the stream systems. Values of As and Sb concentrations in hot-spring water (As_T and Sb_T) required to make such comparisons were taken from average values listed in table 2 (rounded to $As_T = 11$ mg/L and $Sb_T = 2$ mg/L). Relative standard deviations of 11 percent and 30 percent, respectively, are somewhat larger than those for Cl_T and B_T , reflecting in part larger analytical uncertainty in the arsenic and antimony concentrations.

Three main sites were used for periodic gaging and sampling in Mill Creek and Canyon Creek: MC-36 on Mill Creek just below Highway 36, MC-T on a tributary of Mill Creek just below Highway 36, and CC-C on Canyon Creek at the culvert above Morgan Meadow. These sites are shown in figure 3, along with other sites monitored less frequently. Stream velocity and depth were measured at all sites, and depth-integrated samples were obtained at equal width increments.

Similar measurements were made for the composite flow of Domingo Springs at a culvert approximately 10 m downstream from the spring vents (site DS in fig. 3). Values of chemical flux at this site were converted to equivalent thermal-water discharge using the same values of Cl_T and B_T as for Morgan and Growler Hot Springs because concentrations of Cl and B in water from the well at Terminal Geyser (assumed to tap a zone of thermal-water outflow that moves downstream to Domingo Springs) are only slightly lower than the values in the hot-spring water and the ratio of Cl/B in the two waters is identical (table 1).

Laboratory Techniques and Accuracy

Analytical results used in this study were obtained from three different laboratories: the USGS Central Laboratory in Arvada, Colorado (CL), the Earth Science Laboratory at the University of Utah Research Institute in Salt Lake City, Utah (UU), and research laboratories operated by the USGS in Menlo Park, California (MP). Results for samples collected between 1983-88 were obtained primarily from the USGS Central Laboratory; samples collected after 1988 were run either in the UURI or MP laboratories. Techniques used by each laboratory are listed below.

CL: Chloride - Colorimetric titration
Boron - ICP spectroscopy
Arsenic - Hydride AAS
Antimony - Hydride AAS

UU: Chloride - Colorimetric titration
Boron - ICP spectroscopy
Arsenic - ICP spectroscopy and hydride AAS
Antimony - ICP spectroscopy and hydride AAS

MP: Chloride - Colorimetric (mercuric thiocyanate)
Boron - ICP spectroscopy
Arsenic - Hydride AAS

Duplicate samples of stream water and hot-spring water were collected during site visits in 1988-90 for analysis in different laboratories. In general, comparable results were obtained for Cl and B concentrations from each laboratory. In cases where a calculated Cl or B flux appeared anomalous, the Cl/B ratio in the sample was compared with the average Cl_T/B_T value of 28. For the few analyses where this ratio differed by >10 percent, either the Cl_S or B_S value was assumed to be in error (based on the measured streamflow) and that value was omitted from subsequent calculations.

THERMAL-WATER DISCHARGE

Mill Creek and Canyon Creek

Flux Data

Results from periodic monitoring of chemical flux and streamflow at sites MC-36, MC-T, and CC-C are presented in tables 3-5 and figures 4-6. Thermal-water discharge was calculated for each site from chemical-flux data using equation 2, rounding the results to two significant digits for each measurement set. Two or more sets of measurements were made at most sites each year prior to 1991; after 1990 the sites were visited only once each year. More detailed information (fig. 7) on streamflow and precipitation variations is available for sites at Mineral and Mill Creek at Los Molinos. Although the Los Molinos site is near the Sacramento River (fig. 1), its hydrograph is assumed to reflect the types of changes in streamflow occurring near our thermal-water monitoring sites over the 1983-94 period.

Variations in Q_T at the three chemical-flux monitoring sites are relatively large (RSD = 14 - 44 percent of the mean values). Part of this variance is due to laboratory inaccuracies, sampling error, and errors in stream gaging. Estimates of the variability introduced from such uncertainties are given in the next section of the report. Linear regression between streamflow and thermal-water discharge yields correlation coefficients of 0.30 to 0.60 for the three sites (fig. 8), indicating that 9-36 percent of the variation in Q_T can be explained by a linear relation with Q_S . A significant improvement in correlation using $\ln Q_S$ and $\ln Q_T$ was obtained only for site CC-C ($r = 0.63$ compared with $r = 0.30$). These correlations suggest that rates and locations of thermal-water inputs to Mill Creek and Canyon Creek vary with streamflow, presumably because of the effect of stream stage on ground-water levels. The systematic seasonal pattern of streamflow variation for Mill Creek and Canyon Creek would then explain the apparent seasonal trends in Q_T observed for some years.

Changes in the measured thermal-water discharge at our gaging sites can also occur when water is diverted out of the creeks below the thermal areas for pasture irrigation. Such diversions result in a decrease in the chemical flux at the downstream gaging sites. Water was being diverted for irrigation during site visits in the summer of 1988 and 1989, and might have occurred during other years without being noted. In contrast, additions of nonthermal water from tributary channels during the spring runoff period lowers the concentrations of Cl and B in the main stream, but does not affect the chemical flux.

Variability in thermal-water discharge is greatest for site MC-T, where the RSD is 44 percent of the mean value over the 1983-94 period (table 4). The Mill Creek tributary that flows under Highway 36 includes stream water that is diverted from Mill Creek above Morgan Hot Springs for irrigation and also water from hot springs that discharge in the vicinity of the Seward swimming pool. Fluctuations in Q_T values at the MC-T site are due in part to periodic filling and draining of the swimming pool, which is fed by several hot springs. There may also be periods during the spring and early summer when salts deposited in the shallow soil by evaporation of hot-spring waters are redissolved in surficial runoff, ending up in this tributary and in Mill Creek itself.

Table 3. Streamflow, chemical concentration, chemical flux, and thermal-water discharge for site MC-36 on Mill Creek at Highway 36

[Laboratory abbreviations: CL, U.S. Geological Survey Central Laboratory in Arvada, Colorado; MP, U.S. Geological Survey laboratories in Menlo Park, California; UU, the University of Utah Research Institute in Salt Lake City, Utah. Q_s, streamflow; Q_T, thermal water discharge; Cl, chloride; B, boron; As, arsenic; Sb, antimony; L/s, liters per second; mg/L, milligrams per liter; mg/s, milligrams per second; *, no data]

Date	Q _s (L/s)	Lab	Cl (mg/L)	B (mg/L)	As (mg/L)	Sb (mg/L)	Cl flux (mg/s)	B flux (mg/s)	As flux (mg/s)	Sb flux (mg/s)	Q _T ¹ (L/s)
830804	4840	MP	7.5	² 0.15	0.021	0.002	36300	*	102	9.7	15
831020	1150	MP	34	² 0.80	0.098	0.003	39100	*	113	3.4	16
840621	4870	CL,MP ³	8.5	0.30	0.025	0.005	41400	1460	122	24.4	17
840815	1170	CL,MP ³	31	1.00	0.082	0.004	36300	1170	95.9	4.7	14
841101	1030	CL	40	1.30	0.120	*	41200	1340	124	*	16
850730	793	CL	46	1.65	0.180	*	36500	1310	143	*	15
851029	1030	CL	45	1.50	0.160	*	46400	1550	165	*	19
860320	3400	CL	18	0.65	0.050	*	61200	2210	170	*	26
860423	5440	CL	7.7	0.28	0.002	*	41900	1520	10.9	*	18
860521	6830	CL	7.4	0.26	0.023	*	50500	1780	157	*	21
860625	3710	CL	12	0.46	0.037	*	44500	1710	137	*	19
860723	1560	CL	29	1.00	0.083	*	45200	1560	129	*	19
860826	1070	CL	42	1.55	0.105	*	44900	1660	112	*	19
860930	1380	CL	30	1.10	0.100	*	41400	1520	138	*	18
861030	1690	CL	30	1.20	0.067	*	50700	2030	113	*	22
861210	1010	CL	46	*	0.110	*	46500	*	111	*	19
870326	1470	CL	31	1.10	0.097	*	45600	1620	143	*	19
870427	5470	CL	10	0.33	0.029	*	54700	1810	159	*	22
870527	2730	CL	14	0.56	0.038	*	38200	1530	104	*	17
870722	926	CL	44	1.70	0.130	*	40700	1570	120	*	18
870818	668	CL	55	2.00	0.195	*	36700	1340	130	*	16
870922	583	CL	² 8	1.90	0.090	0.017	*	1110	52.5	9.9	13
871022	620	CL	53	1.90	0.185	0.021	32900	1180	115	13.0	14
880120	1040	CL	43	1.60	0.140	0.017	44700	1660	146	17.7	19
880218	1220	CL	35	1.20	0.110	0.015	42700	1460	134	18.3	18
880315	1690	CL	27	1.00	0.077	0.008	45600	1690	130	13.5	19
880426	2290	CL	18	0.71	0.072	0.002	41200	1630	165	4.6	18
880510	2240	CL	20	0.79	0.079	0.005	44800	1770	177	11.2	20
880629	2060	CL	20	0.76	0.078	0.004	41200	1570	161	8.2	18
880727	898	CL	46	1.60	0.220	0.007	41300	1440	198	6.3	17
880819	776	CL	² 33	2.00	0.17	<0.01	*	1550	132	*	18
880929	663	CL	66	2.20	0.20	<0.01	43800	1460	133	*	18
881028	722	CL	58	1.94	0.14	0.02	41900	1400	101	14.4	17
890214	852	UU	48	1.64	0.125	0.025	40900	1400	107	21.3	17
890329	3060	UU	² 43	² 0.75	0.048	<0.01	*	*	147	*	*
890427	3140	UU	17	0.56	0.04	0.012	53400	1760	126	37.7	21
890524	3170	UU	14	0.38	<0.01	<0.01	44400	1210	*	*	16
890627	3030	UU	² 20	0.40	0.024	<0.01	*	1210	72.9	*	14

Table 3. Streamflow, chemical concentration, chemical flux, and thermal-water discharge for site MC-36 on Mill Creek at Highway 36--continued

Date	Q _s (L/s)	Lab	Cl (mg/L)	B (mg/L)	As (mg/L)	Sb (mg/L)	Cl flux (mg/s)	B flux (mg/s)	As flux (mg/s)	Sb flux (mg/s)	Q _T ¹ (L/s)
890720	1250	UU	34	1.11	0.067	<0.01	42500	1390	83.8	*	17
890817	985	MP,UU ⁴	44	1.61	0.144	<0.01	43300	1590	142	*	18
891020	833	UU	49	1.57	0.15	<0.01	40800	1310	125	*	16
900416	3540	UU	13	0.41	0.052	<0.01	46000	1450	184	*	18
900518	1820	UU	25	0.73	0.028	0.014	45500	1330	51.0	25.5	17
900620	2113	UU	24	0.75	*	*	50700	1590	*	*	20
900730	813	MP,UU ⁴	48	1.68	0.098	<0.02	39000	1370	79.7	*	16
901023	725	MP	52	1.80	*	*	37700	1310	*	*	16
910812	680	MP,UU ⁴	54	1.76	*	*	36700	1200	*	*	15
920810	648	MP,UU ⁴	62	2.43	*	*	40200	1580	*	*	18
930824	1215	MP	30	1.06	*	*	36500	1290	*	*	15
940720	886	MP	50	1.90	*	*	44300	1680	*	*	19
Average											17.7
Standard deviation											2.4

¹ $Q_T = Q_s [(Cl/2400) + (B/85)]/2$, where Q_s is streamflow.

² Value assumed incorrect and not used in computations.

³ Antimony determined at MP laboratory; all other values determined at CL laboratory.

⁴ Chloride determined at MP laboratory; boron, arsenic, and antimony determined at UU laboratory.

Table 4. Streamflow, chemical concentration, chemical flux, and thermal-water discharge for site MC-T on the Mill Creek tributary crossing Highway 36

[Laboratory abbreviations: CL, U.S. Geological Survey Central Laboratory in Arvada, Colorado; MP, U.S. Geological Survey laboratories in Menlo Park, California; UU, the Earth Science Laboratory at the University of Utah Research Institute in Salt Lake City, Utah. Q_s , streamflow; Q_T , thermal water discharge; Cl, chloride; B, boron; As, arsenic; Sb, antimony; L/s, liters per second; mg/L, milligrams per liter; mg/s, milligrams per second; *, no data]

Date	Q_s (L/s)	Lab	Cl (mg/L)	B (mg/L)	As (mg/L)	Sb (mg/L)	Cl flux (mg/s)	B flux (mg/s)	As flux (mg/s)	Sb flux (mg/s)	Q_T^1 (L/s)
830804	85	MP	98	² 2.00	*	*	8330	*	*	*	3.5
831020	43	MP	163	² 0.41	*	*	7010	*	*	*	2.9
840621	179	CL	40	1.60	0.062	*	7160	286	11.1	*	3.2
840815	113	CL	76	2.60	0.082	*	8590	294	9.3	*	3.5
841101	67	CL	160	4.20	0.210	*	10700	281	14.1	*	3.9
850730	74	CL	115	3.60	0.180	*	8510	266	13.3	*	3.3
851029	28	CL	320	11.00	0.430	*	8960	308	12.0	*	3.7
860320	263	CL	58	2.00	0.140	*	15300	526	36.8	*	6.3
860423	382	CL	45	1.70	0.014	*	17200	649	5.4	*	7.4
860521	94	CL	39	1.60	0.100	*	3670	150	9.4	*	1.6
860625	189	CL	73	2.70	0.170	*	13800	510	32.1	*	5.9
860723	54	CL	110	3.50	0.100	*	5940	189	5.4	*	2.3
860826	57	CL	120	3.80	0.083	*	6840	217	4.7	*	2.7
860930	69	CL	200	6.20	0.120	*	13800	428	8.3	*	5.4
861030	56	CL	300	10.00	0.170	*	16800	560	9.5	*	6.8
861210	42	CL	330	11.00	0.160	*	13900	462	6.7	*	5.6
870326	93	CL	120	4.30	*	*	11200	400	*	*	4.7
870427	82	CL	155	5.35	0.335	*	12700	439	27.5	*	5.2
870527	61	CL	175	6.55	0.165	*	10700	400	10.1	*	4.6
870722	68	CL	98	3.30	0.074	*	6660	224	5.0	*	2.7
870818	53	CL	55	2.00	0.195	*	2920	106	10.3	*	1.2
870922	43	CL	*	4.30	*	0.012	*	185	*	0.52	2.2
871022	18	CL	270	9.60	0.170	0.022	4860	173	3.1	0.40	2.0
880120	59	CL	220	7.90	0.180	0.021	13000	466	10.6	1.24	5.4
880218	62	CL	210	*	0.570	0.026	13000	*	35.3	1.61	5.4
880315	96	CL	140	5.30	0.330	0.020	13400	509	31.7	1.92	5.8
880426	79	CL	180	6.70	0.440	0.019	14200	529	34.7	1.50	6.1
880510	65	CL	210	7.40	0.160	0.015	13700	481	10.4	0.97	5.7
880629	45	CL	140	4.80	0.280	0.013	6300	216	12.6	0.59	2.6
880727	85	CL	120	4.00	0.230	0.009	10200	340	15.6	0.77	4.1
880819	58	CL	126	5.00	0.13	<0.01	7310	290	7.5	*	3.2
880929	38	CL	188	5.73	0.12	<0.01	7140	218	4.6	*	2.8
881028	7	CL	280	8.40	0.05	0.17	2000	60	0.4	1.2	0.8
890214	60	UU	271	9.62	0.235	0.030	16260	577	14.1	1.8	6.8
890329	275	UU	52	² 2.54	0.216	0.30	14300	*	59.4	8.3	6.0
890427	118	UU	106	3.93	0.212	0.032	12500	464	25.0	3.8	5.3
890524	180	UU	80	2.89	0.142	<0.01	14400	520	25.6	*	6.1

Table 4. Streamflow, chemical concentration, chemical flux, and thermal-water discharge for site MC-T on the Mill Creek tributary crossing Highway 36--continued

Date	Q _s (L/s)	Lab	Cl (mg/L)	B (mg/L)	As (mg/L)	Sb (mg/L)	Cl flux (mg/s)	B flux (mg/s)	As flux (mg/s)	Sb flux (mg/s)	Q _T ¹ (L/s)
890720	39	UU	123	4.58	0.050	<0.01	4800	179	2.0	*	2.1
890817	35	UU	185	6.30	0.240	<0.01	6500	220	8.4	*	2.6
891020	15	UU	396	12.40	0.22	<0.01	5940	186	3.3	*	2.3
900416	44	UU	218	7.60	0.475	0.012	9590	334	20.9	0.5	4.0
900518	13	UU	318	10.10	0.125	<0.01	4130	131	1.6	*	1.6
900620	44	UU	185	6.90	*	*	8140	304	*	*	3.5
900730	39	UU	163	5.90	0.181	<0.02	6360	230	7.1	*	2.7
901023	21	UU	388	13.90	*	*	8150	290	*	*	3.4
910812	43	UU	137	5.03	*	*	5890	215	*	*	2.5
920810	23	MP	175	6.66	*	*	4030	153	*	*	1.7
930824	27	MP	170	5.82	*	*	4590	157	*	*	1.9
940720	26	MP	165	6.30	*	*	4290	164	*	*	1.9
Average											3.8
Standard deviation											1.7

¹ Q_T = Q_s[(Cl/2400) + (B/85)]/2, where Q_s is streamflow.

² Value assumed incorrect and not used in computations.

Table 5. Streamflow, chemical concentration, chemical flux, and thermal-water discharge for site CC-C on Canyon Creek at the culvert above Morgan Meadow and on Canyon Creek near the confluence with Mill Creek

[Laboratory abbreviations: CL, U.S. Geological Survey Central Laboratory in Arvada, Colorado; MP, U.S. Geological Survey laboratories in Menlo Park, California; UU, the Earth Science Laboratory at the University of Utah Research Institute in Salt Lake City, Utah. Q_s , streamflow; Q_T , thermal water discharge; Cl, chloride; B, boron; As, arsenic; Sb, antimony; L/s, liters per second; mg/L, milligrams per liter; mg/s, milligrams per second; *, no data or incorrect value reported]

Date	Q_s (L/s)	Lab	Cl (mg/L)	B (mg/L)	As (mg/L)	Sb (mg/L)	Cl flux (mg/s)	B flux (mg/s)	As flux (mg/s)	Sb flux (mg/s)	Q_T ¹ (L/s)
² 830804	292	MP	24	0.6	0.079	0.005	7000	175	23.1	1.46	2.5
² 831020	57	MP	164	3.4	0.42	0.015	9350	194	23.9	0.86	3.1
² 840621	402	CL,MP ³	15	0.56	0.066	0.006	6030	225	26.5	2.41	2.6
840815	37	CL,MP ³	170	5.6	0.53	0.021	6290	207	19.6	0.78	2.5
850730	29	CL	220	6.9	0.44	*	6380	200	12.8	*	2.5
851029	69	CL	67	2.3	0.24	*	4620	159	16.6	*	1.9
860521	920	CL	6.3	0.2	0.024	*	5800	184	22.1	*	2.3
860826	19	CL	170	6.1	0.48	*	3230	116	9.1	*	1.4
870722	48	CL	120	4.5	0.39	*	5760	216	18.7	*	2.5
870922	16	CL	200	7.7	0.56	0.094	3200	123	9.0	1.50	1.4
871022	17	CL	170	8.3	⁴ 1.20	0.097	2890	141	20.4	1.65	1.4
880510	326	CL	17	0.7	0.079	0.007	5540	228	25.8	2.28	2.5
880630	52	CL	96	3.1	0.37	0.012	4990	161	19.2	0.62	2.0
880727	40	CL	140	4.8	0.73	0.015	5600	192	29.2	0.60	2.3
880820	28	UU	180	6.9	0.66	<0.01	5040	193	18.5	*	2.2
881027	11	UU	250	8.5	0.61	0.07	2750	94	6.7	0.77	1.1
890525	362	UU	17	0.5	0.065	<0.01	6150	181	23.5	*	2.3
890816	23	UU	182	6.2	0.45	0.011	4190	143	10.4	0.25	1.7
900517	109	UU	48	1.5	0.145	<0.01	5230	164	15.8	*	2.1
900801	28	MP,UU ⁵	190	⁴ 0.05	0.288	<0.02	5320	*	8.1	*	2.2
901023	18	UU	211	7.72	*	*	3800	139	*	*	1.6
910813	18	UU	250	8.95	*	*	4500	161	*	*	1.9
920810	24	MP,UU ⁵	252	9.51	*	*	6050	228	*	*	2.6
930824	37	MP	100	3.73	*	*	3700	138	*	*	1.6
940720	26	MP	218	7.6	*	*	5670	198	*	*	2.3
Average											2.1
Standard deviation											0.48

¹ $Q_T = Q_s [(Cl/2400) + (B/85)]/2$, where Q_s is streamflow.

² Data for Canyon Creek near confluence with Mill Creek.

³ Chloride and bromide determined at CL laboratory, arsenic and antimony determined at MP laboratory.

⁴ Value assumed incorrect and not used in computations or plots.

⁵ Chloride determined at MP laboratory; other values determined at UU laboratory.

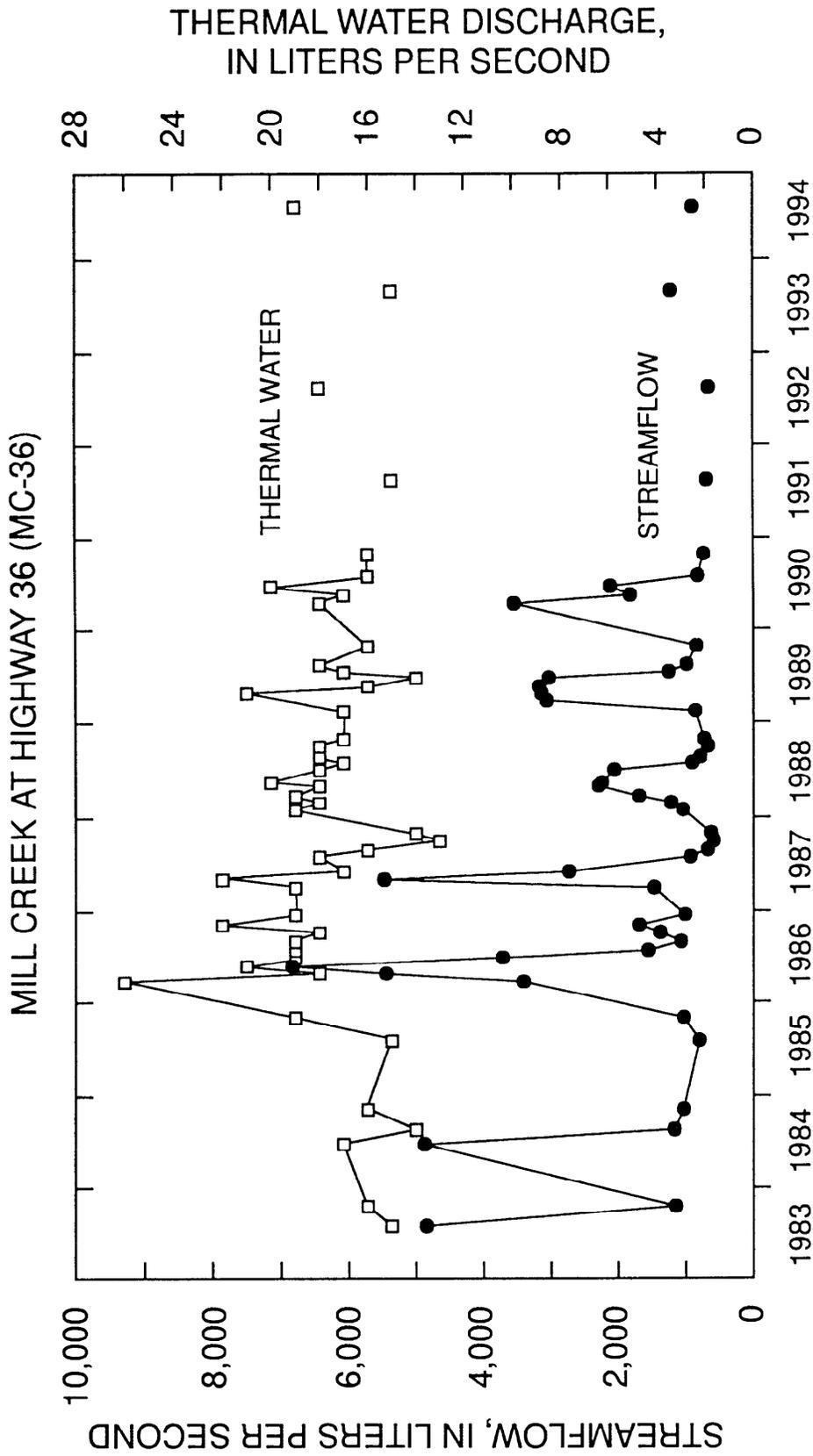


Figure 4. Measured streamflow and calculated thermal-water discharge for site MC-36 on Mill Creek below Highway 36.

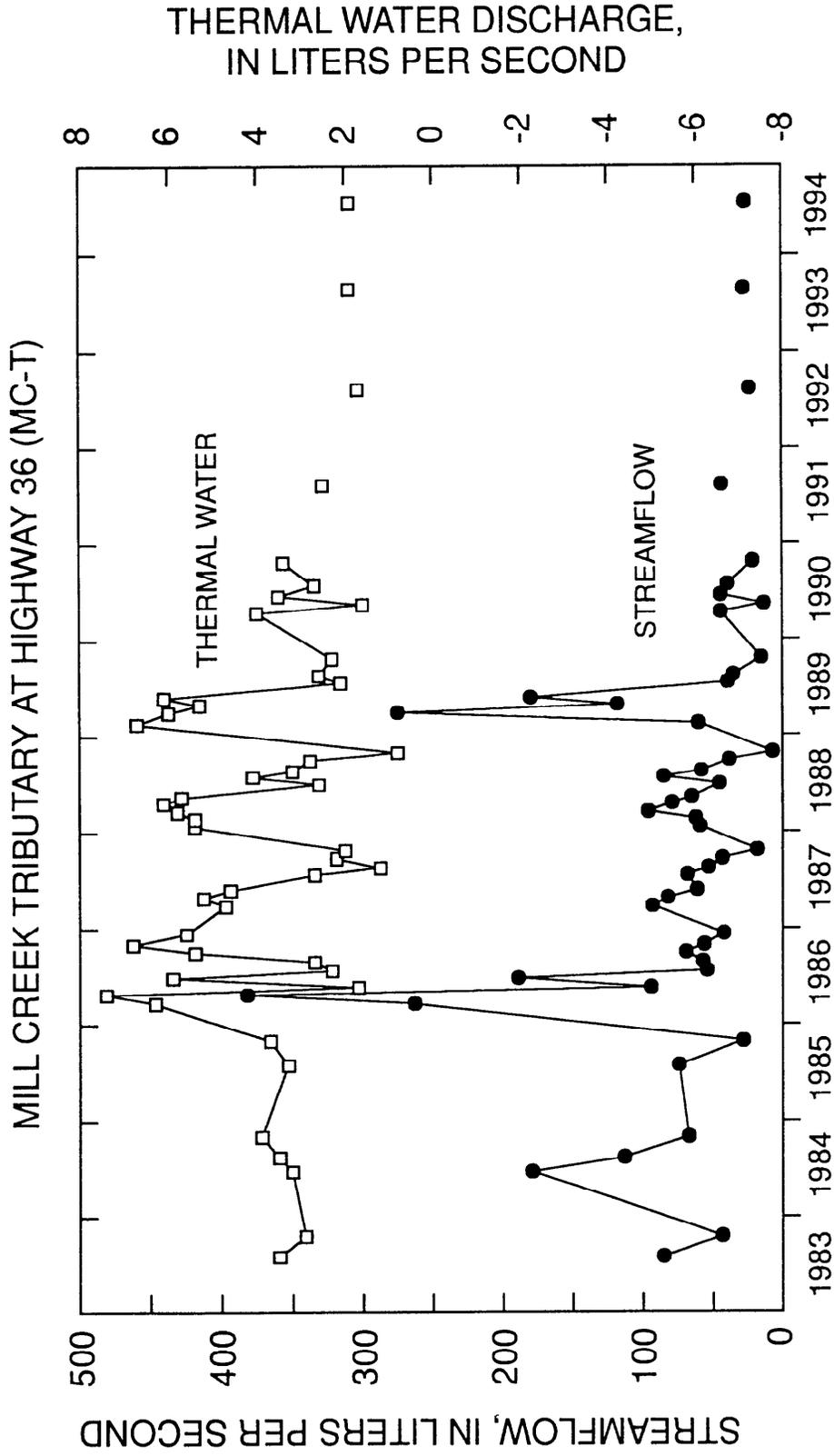


Figure 5. Measured streamflow and calculated thermal-water discharge for site MC-T on the Mill Creek tributary crossing Highway 36.

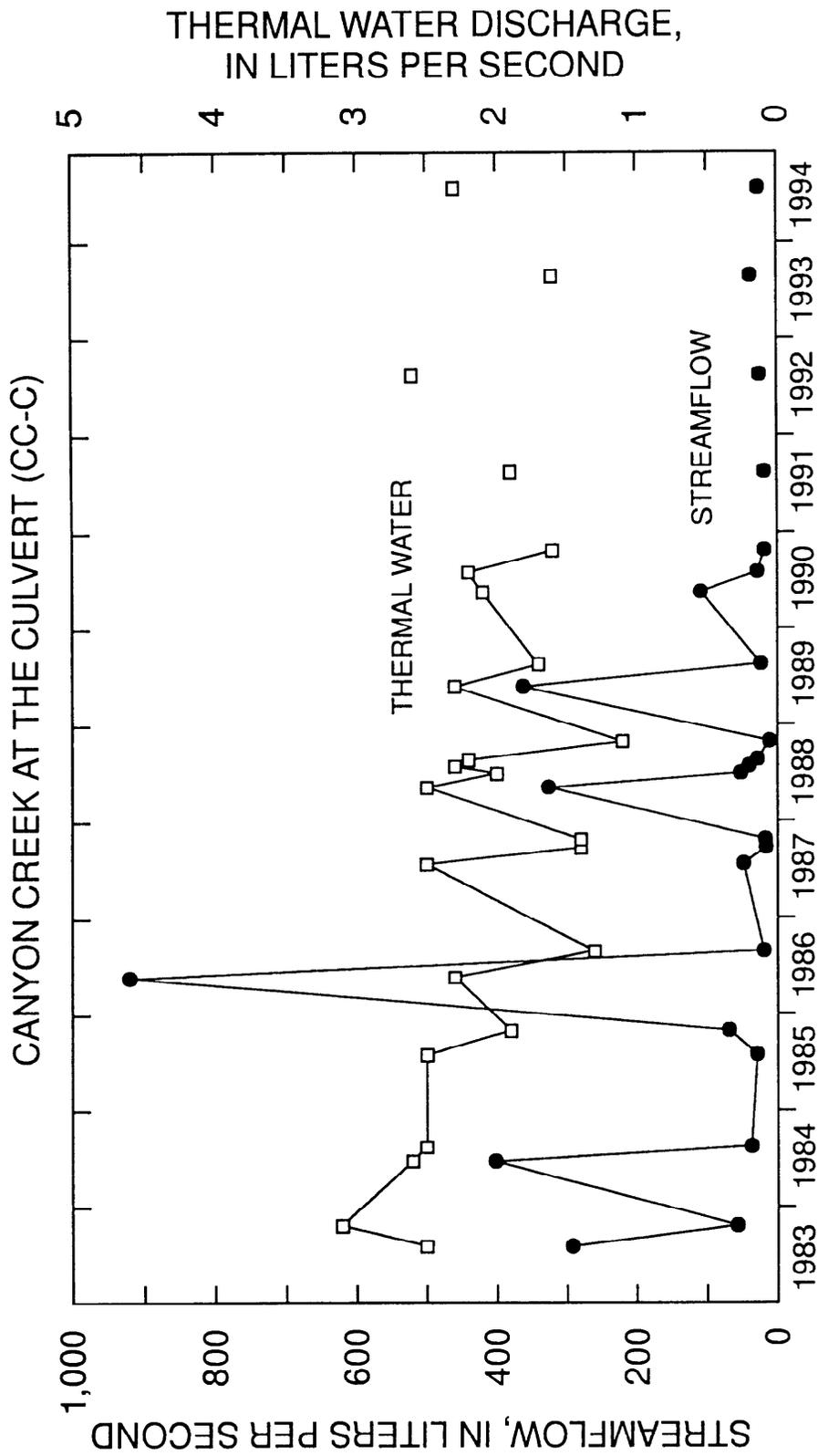


Figure 6. Measured streamflow and calculated thermal-water discharge for site CC-C on Canyon Creek at the culvert above Morgan Meadow.

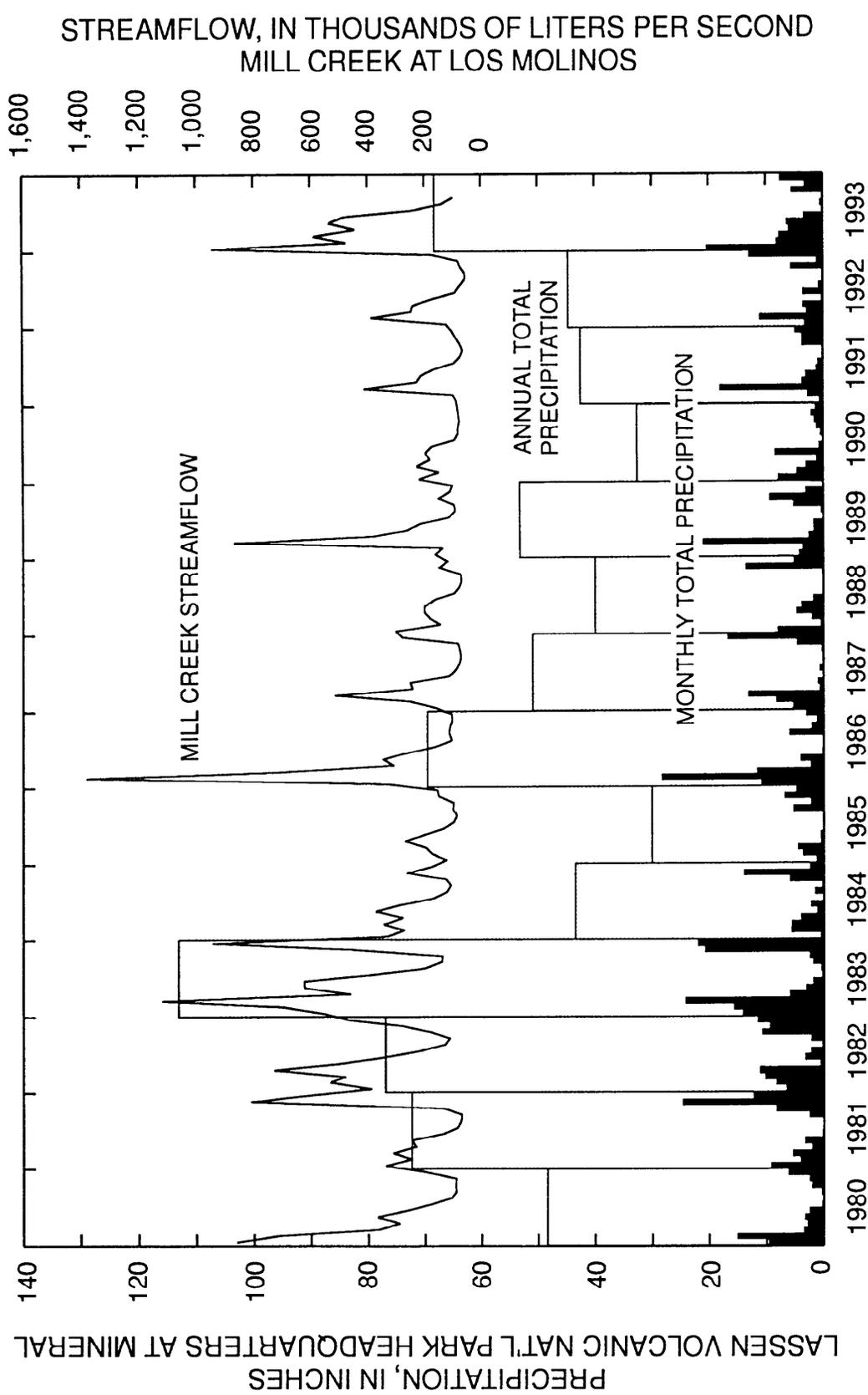


Figure 7. Streamflow for Mill Creek at Los Molinos and monthly precipitation at National Park headquarters in Mineral, California. Site locations shown in figure 1.

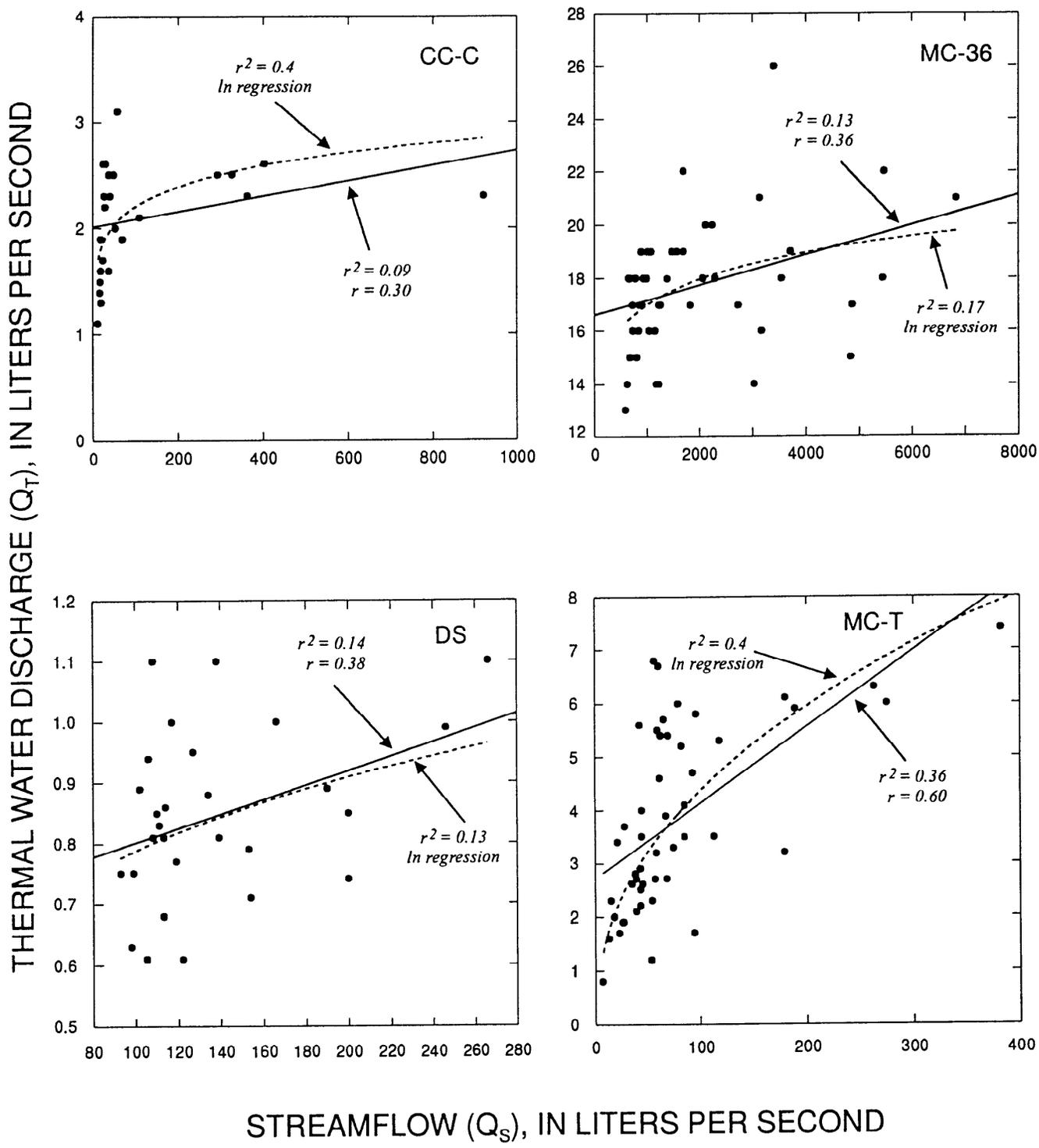


Figure 8. Streamflow plotted against thermal-water discharge for sites MC-36, MC-T, CC-C, and DS, and correlation coefficients (r) for linear regression.

Average values of Q_T for sites MC-36, MC-T, and CC-C over the 1983-94 period are 18 ± 0.6 , 3.9 ± 0.7 , and 2.1 ± 0.5 L/s, respectively. The thermal-water component at CC-C is included in MC-36, so that the thermal-water discharge to Mill Creek from Morgan and Growler Hot Springs totals approximately 22 L/s. The corresponding RSD value for this total, which expresses the observed variability in our Q_T measurements, is approximately 15 percent.

The possibility that inputs of thermal water occur in Mill Creek downstream from Highway 36 was evaluated using measurements of chemical flux at three additional sites: MC-BS, MC-CG, and MC-MCR (figs. 1 and 3). In these site designations, BS stands for Brokenshire Picnic Area, CG stands for the campground at the town of Mill Creek, and MCR stands for Mill Creek Rim. These sites are located at distances of 2.6, 5.2, and ~30 km downstream from Highway 36. Chemical flux was measured at the MC-BS site on fourteen visits over the 1989-94 period. The average value of Q_T at MC-BS is 20 L/s, compared with an average value of 19.5 L/s for the sum of Q_T at MC-36 and MC-T over the same period. This indicates that no significant input of thermal water occurs in this reach of Mill Creek.

One set of chemical flux measurements was obtained in August 1994 at MC-BS and the two sites further downstream along Mill Creek. Values of Q_T calculated from these measurements (assuming the Cl_T and B_T values as for other sites in this study) are 18, 23, and 19 L/s at sites MC-BS, MC-CG, and MC-MCR, respectively. Although streamflow increased by a factor of about 3 between MC-BS and MC-MCR due to inflow of cold water from numerous tributaries, ratios of Cl/B were ~28 at each of the three sites. These data suggest that there could be an input of ~5 L/s of thermal water between MC-BS and MC-CG. The apparent decline in Q_T between MC-CG and MD-MCR could be due to a combination of (1) errors in streamflow measurements and (2) loss of stream water containing a thermal component by seepage into the stream bed. Additional flux measurements are needed to check these results.

Measurement Accuracy

Comparison of analyses from different laboratories for duplicate samples collected between 1988 and 1991 (table 6) provides measures of variability in flux determinations attributable to laboratory error. Chloride and boron concentrations for the stream sites during this period ranged from 12 to 390 mg/L and from 0.4 to 14 mg/L, respectively. Differences in Cl and B concentrations reported by the USGS Central Laboratory (CL) and the University of Utah laboratory (UU) for samples collected in 1988, expressed as a percentage of the CL value, range from 0 to 8 percent for chloride and 0 to 7 percent for boron. For chloride concentrations reported by the University of Utah and Menlo Park (MP) laboratories over the 1989-91 period, the differences are 0-16 and 4-12 percent, respectively, of the MP values. In these comparisons, results from neither laboratory were consistently higher or lower than those from the other laboratory. These comparisons indicate that the degree of variability in measured flux values resulting from laboratory error is less than ± 10 percent. The corresponding variability in values of Q_T computed by averaging chloride and boron fluxes should be less than that for the individual flux values.

Additional sources of error in the calculated thermal-water discharge values are associated with streamflow measurements, the use of integrated samples to represent the average chemical concentrations, and the assumption that the "upstream" chemical fluxes were always negligibly

Table 6. Comparison of analytical results from three different laboratories on samples collected at monitoring sites in the Lassen Known Geothermal Resources Area

[Laboratory abbreviations: CL, U.S. Geological Survey Central Laboratory in Arvada, Colorado; UURI, the Earth Science Laboratory at the University of Utah Research Institute in Salt Lake City, Utah; MP, U.S. Geological Survey research laboratories in Menlo Park, California. Arsenic and antimony standards were prepared in Menlo Park; standard values determined gravimetrically. L/s, liters per second; *, no data]

Site	Date	Flow (L/s)	Chloride			Boron			Chloride/Boron			Antimony		Arsenic			
			CL (mg/L)	UURI (mg/L)	MP (mg/L)	CL (mg/L)	UURI (mg/L)	MP (mg/L)	CL (mg/L)	UURI (mg/L)	MP (mg/L)	CL (mg/L)	UURI (mg/L)	CL (mg/L)	UURI (mg/L)	MP (mg/L)	
MC-36	880120	1040	43	46	*	1.6	1.78	*	26.9	25.8	*	0.017	<0.002	0.140	0.12	*	
	880218	1220	35	38	*	1.2	1.57	*	29.2	24.2	*	0.015	<0.002	0.110	*	*	
	880315	1690	27	29	*	1.0	1.04	*	27.0	27.9	*	0.008	0.009	0.077	0.09	*	
	880426	2290	18	21	*	0.71	0.79	*	25.3	26.6	*	0.002	<0.005	0.072	0.044	0.09	
	880510	2240	20	22	*	0.79	0.83	*	25.3	26.5	*	0.005	<0.07	0.079	0.06	0.088	
	880629	2060	20	24	*	0.76	0.67	*	28.9	35.8	*	0.004	<0.07	0.078	0.60	0.08	
	880727	898	46	51	*	1.6	1.61	*	28.8	31.7	*	0.007	<0.01	0.220	0.164	*	
	890817	985	*	51	44	*	1.61	1.61	*	*	31.7	*	*	<0.01	*	0.144	*
	891020	833	*	49	46	*	1.57	1.57	*	*	31.2	*	*	<0.01	*	0.15	*
	900416	3540	*	13	12	*	0.41	0.41	*	*	31.7	*	*	<0.01	*	0.052	*
	900518	1820	*	25	22	*	0.73	0.73	*	*	34.2	*	*	0.014	*	0.028	*
	900730	813	*	² 163	48	*	1.68	1.68	*	*	*	*	*	<0.02	*	0.098	*
	901023	725	*	60	52	*	1.98	1.98	1.80	*	25.7	28.8	*	*	*	*	*
	910812	680	*	54	54	*	1.76	1.76	*	*	30.7	*	*	*	*	*	*
MC-T	880120	59	220	223	*	*	7.90	8.39	27.8	26.6	*	0.021	0.002	0.180	*	*	
	880218	62	210	200	*	*	8.05	*	*	23.5	*	0.026	0.002	0.570	0.3	*	
	880315	96	140	143	*	*	5.30	5.51	26.4	26.0	*	0.02	0.007	0.330	0.3	*	
	880426	79	180	180	*	*	6.70	7.08	26.9	25.4	*	0.019	0.031	0.440	0.34	0.54	
	880510	65	210	196	*	*	7.40	7.99	28.4	24.5	*	0.015	<0.07	0.160	0.4	0.5	
	880629	45	140	142	*	*	4.80	5.37	29.2	26.4	*	0.013	<0.07	0.280	0.3	0.3	
	880727	85	120	117	*	*	4.00	4.27	30.0	27.4	*	0.009	<0.01	0.230	0.15	*	
	891020	15	*	396	390	*	12.4	*	31.5	*	*	*	<0.01	0.22	<0.01	*	

Table 6. Comparison of analytical results from three different laboratories on samples collected at monitoring sites in the Lassen Known Geothermal Resources Area--continued

Site	Date	Flow (L/s)	Chloride			Boron			Chloride/Boron			Antimony			Arsenic		
			CL (mg/L)	UURI (mg/L)	MP (mg/L)	CL (mg/L)	UURI (mg/L)	MP (mg/L)	CL (mg/L)	UURI (mg/L)	MP (mg/L)	CL (mg/L)	UURI (mg/L)	MP (mg/L)	CL (mg/L)	UURI (mg/L)	MP (mg/L)
	900416	44	*	218	220	*	7.60	*	28.7	*	*	0.012	*	0.475	0.012	*	
	900518	13	*	318	310	*	10.1	*	31.5	*	*	<0.01	*	0.125	<0.01	*	
	901023	21	*	388	390	*	13.9	12.4	*	27.9	31.5	*	*	*	*	*	
	910812	43	*	137	135	*	5.03	*	*	27.4	*	*	*	*	*	*	
CC-C	880510	326	17	20	*	0.69	0.69	*	24.6	29.0	*	0.007	*	0.079	0.07	0.091	
	880630	52	96	93	*	3.1	3.25	*	31.0	28.6	*	0.012	*	0.37	0.27	0.3	
	880727	40	140	144	*	4.8	5.19	*	29.2	27.7	*	0.015	<0.01	0.73	0.56	*	
	900517	109	*	48	46	*	1.46	*	*	32.9	*	<0.01	<0.01	0.145	*	*	
	900801	28	*	217	190	*	20.05	*	*	*	*	<0.02	*	0.288	*	*	
	901023	18	*	211	205	*	7.72	7.2	*	27.3	28.5	*	*	*	*	*	
	910813	18	*	250	252	*	8.95	*	*	27.9	*	*	*	*	*	*	
Average									28.2	28.7	29.6						
Standard deviation									2.0	3.4	1.7						
Growler hot spring	880510	*	2300	2450	*	88	95	*	26.1	25.8	*	0.44	0.21	12.0	10.5	12.8	
	880630	*	2200	2470	*	81	86	*	27.2	28.7	*	2.3	0.11	11.0	9.6	13.5	
	880726	*	2200	2470	*	83	91	*	26.5	27.1	*	0.1	<0.07	9.1	8.9	*	
Little Growler hot spring	880510	*	2300	2420	*	86	92	*	26.7	26.3	*	0.56	0.61	11.0	9.3	11.6	
	880630	*	2200	2410	*	81	84	*	27.2	28.7	*	2.5	0.44	9.3	9.4	10.8	
	880726	*	2200	2400	*	83	88	*	27.5	27.3	*	1.4	0.39	12.0	9.9	*	
Swimming pool spring	880510	*	2100	2190	*	79	85	*	26.6	25.8	*	0.065	<0.07	11.0	8.0	9.9	
	880630	*	2042	2240	*	74	79	*	27.6	28.4	*	1.1	<0.07	7.4	8.0	9.4	
	880726	*	2100	2240	*	76	83	*	27.6	27	*	0.094	<0.07	21.0	8.8	*	

Table 6. Comparison of analytical results from three different laboratories on samples collected at monitoring sites in the Lassen Known Geothermal Resources Area--continued

Site	Date	Flow (L/s)	Chloride			Boron			Chloride/Boron			Antimony			Arsenic					
			CL (mg/L)	UURI (mg/L)	MP (mg/L)	CL (mg/L)	UURI (mg/L)	MP (mg/L)	CL (mg/L)	UURI (mg/L)	MP (mg/L)	CL (mg/L)	UURI ¹ (mg/L)	MP (mg/L)	CL (mg/L)	UURI (mg/L)	MP (mg/L)			
Arsenic standards	1.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
	0.1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Antimony standards	10.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	1.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	0.1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	0.01	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

¹ Detection limit reported to be 0.07 mg/L using ICP analysis with concentration multiplied by ten by evaporation.

² Value assumed incorrect.

small. Stream-gaging conditions were rated as fair (± 8 percent) to good (± 5 percent). Each gaging site is at least 1 km downstream from the areas of hot-spring input, which should allow for adequate mixing of thermal and nonthermal water within the streams. The latter inference was not tested directly, however, by comparisons of samples from different points across each stream section.

Domingo Springs

At Domingo Springs (fig. 3), total spring flow and chemical flux have been monitored periodically since 1983. The data (fig. 9 and table 7) show that total spring flow, measured at a culvert under the road adjacent to the springs, varied from 93 L/s to 246 L/s. The corresponding values of Q_T ranged from 0.61 to 1.1 L/s. The correlation between Q_S and Q_T is at DS is comparable to that at the MC-36 site (fig. 8). Springflow temperature at DS varied from 7.5°C to 10.0°C over the entire period of record (table 7), but showed no clear correlation with spring flow or season.

Chloride concentrations measured at DS ranged from 9.5 to 22 mg/L, whereas Cl concentrations in other nonthermal springs and spring-fed creeks in the KGRA are ≤ 0.6 mg/L (Thompson, 1985; Paulson and Ingebritsen, 1991). Chemical-flux values (Cl and B) show slightly less variability than do Cl concentrations and spring flow, consistent with the elevated Cl and B in Domingo Springs being derived from a thermal-water component. Ratios of Cl/B in the spring water (averaging 34 ± 0.6 over the 1988-91 period) are similar to those found in Morgan and Growler Hot Springs. Assuming this thermal water to have the same chemical characteristics as Morgan and Growler Hot Springs, the calculated values of Q_T at Domingo Springs averaged 0.84 ± 0.14 L/s. The RSD of 17 percent is probably within the range of variability to be expected at this site due to errors in laboratory analyses and streamflow measurements.

Domingo Springs, which issue from the southern edge and near the basal part of the Kelly Mountain andesite flow (Clynne, 1984, 1990), is likely a point of discharge for thermal water flowing southeastward from the vicinity of Lassen Peak. The orientation of this outflow zone appears to be fault controlled, following traces of the Hot Springs Creek and Terminal Geyser faults as mapped by Clynne (1984, 1990). Regions of low electrical resistivity extend along this outflow zone as it passes beneath the Park boundary and are also delineated in the vicinity of Domingo Springs (Sorey and Ingebritsen, 1984; Christopherson and Pringle, 1981). Direct evidence of a hot-water aquifer along this outflow zone comes from temperature profiles and fluid chemistry data for the Walker "O" No. 1 well at Terminal Geyser (Sorey and Ingebritsen, 1984).

It is reasonable to expect that the total rate of thermal water flowing along this outflow zone is greater than the rate of discharge of thermal water at Domingo Springs (approximately 1 L/s). Evidence of additional areas of thermal-water discharge was sought during the summer of 1987 by comparing chemical flux at sites along Willow Creek and Warner Creek (fig. 3). Upstream sites along these creeks were near the Park boundary; downstream sites were located 8-12 km to the south. For each drainage, there was no discernable increase in chloride or boron flux between gaging sites. In 1990, chloride-flux measurements were made on the North Fork Feather River (fig. 1, sites #77 and #97) upstream and downstream from the point at which the

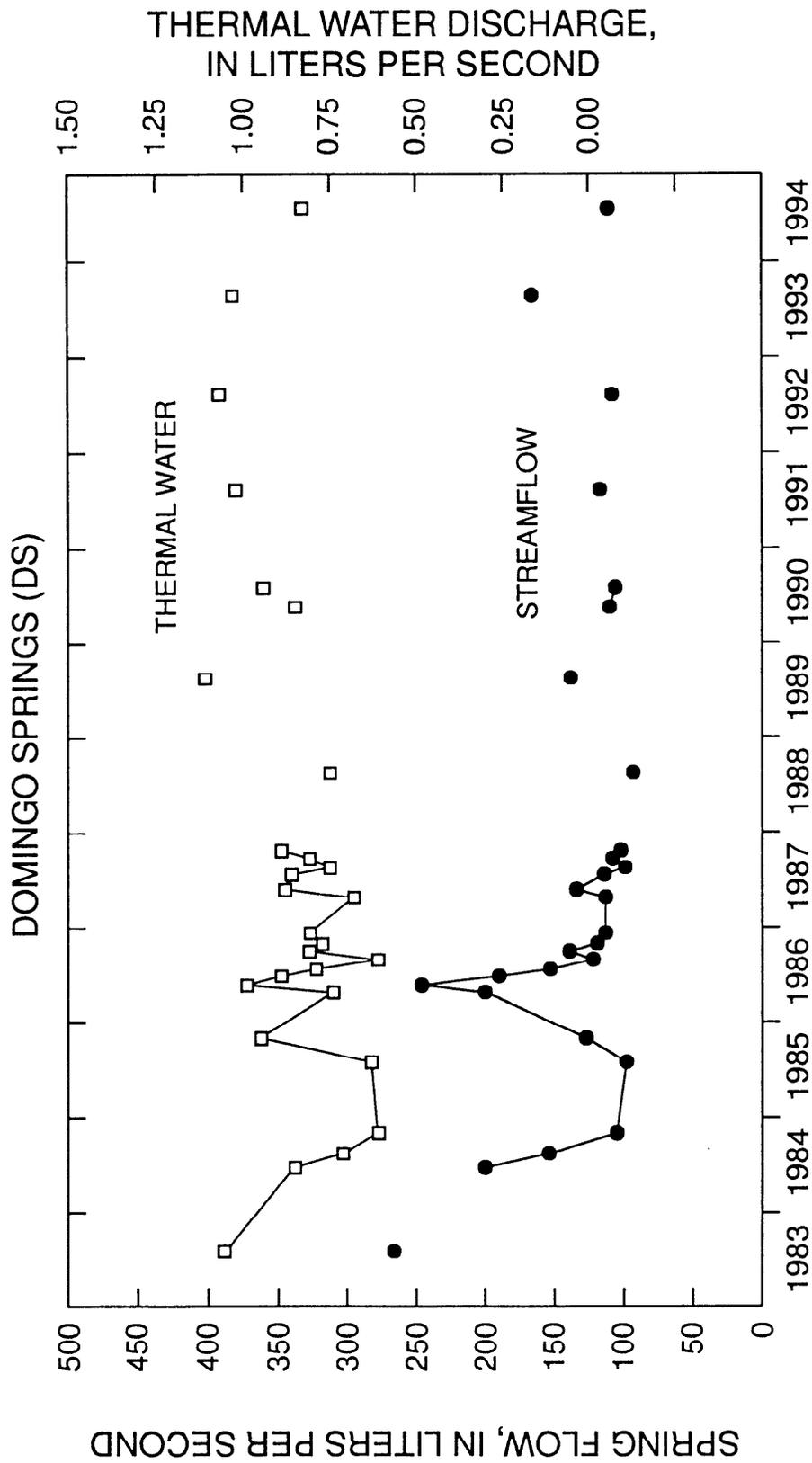


Figure 9. Measured spring flow and calculated thermal-water discharge for site DS at Domingo springs.

Table 7. Streamflow, chemical concentration, chemical flux, and thermal-water discharge for site DS at Domingo Springs

[Laboratory abbreviations: CL, U.S. Geological Survey Central Laboratory in Arvada, Colorado; MP, U.S. Geological Survey laboratories in Menlo Park, California; UU, the Earth Science Laboratory at the University of Utah Research Institute in Salt Lake City, Utah. Q_s, streamflow; Q_T, thermal water discharge; T, temperature; Cl, chloride; B, boron; As, arsenic; Sb, antimony; L/s, liters per second; °C, degrees Celsius; mg/L, milligrams per liter; mg/s, milligrams per second; *, no data]

Date	Q _s (L/s)	Lab	T (°C)	Cl (mg/L)	B (mg/L)	As (mg/L)	Sb (mg/L)	Cl flux (mg/s)	B flux (mg/s)	As flux (mg/s)	Sb flux (mg/s)	Q _T ¹ (L/s)
830804	266	MP	8.5	9.5	*	*	*	2530	*	*	*	1.1
840621	200	CL	8.0	11.0	0.33	0.025	*	2200	66.0	5.00	*	0.85
840815	154	CL	8.5	11.0	0.39	0.016	*	1690	60.1	2.46	*	0.71
841031	105	CL	7.5	15.0	0.46	0.031	*	1580	48.3	3.26	*	0.61
850730	98	CL	9.0	16.5	0.51	0.030	*	1620	50.0	2.94	*	0.63
851029	127	CL	8.5	19.0	0.60	0.042	*	2410	76.2	5.33	*	0.95
860423	200	CL	9.0	9.4	0.30	0.002	*	1880	60.0	*	*	0.74
860521	246	CL	8.0	10.0	0.33	0.024	*	2460	81.2	5.90	*	0.99
860625	190	CL	8.0	12.0	0.37	0.030	*	2280	70.3	5.70	*	0.89
860723	153	CL	9.0	13.0	0.42	0.034	*	1990	64.3	5.20	*	0.79
860829	122	CL	9.5	11.0	0.46	0.034	*	1340	56.1	4.15	*	0.61
860930	139	CL	9.0	14.0	0.49	0.036	*	1950	68.1	5.00	*	0.81
861030	119	CL	8.5	² <0.1	0.55	0.037	*	*	65.5	4.40	*	0.77
861210	113	CL	9.0	17.0	0.61	0.036	*	1920	68.9	4.07	*	0.81
870427	113	CL	10.0	² 27.0	0.51	0.042	*	*	57.6	4.75	*	0.68
870527	134	CL	10.0	16.0	0.55	0.025	*	2140	73.7	3.35	*	0.88
870722	114	CL	9.0	18.0	0.65	0.042	*	2050	74.1	4.79	*	0.86
870818	99	CL	10.0	18.0	0.65	0.044	*	1780	64.4	4.36	*	0.75
870922	108	CL	10.0	18.0	0.64	0.039	*	1940	69.1	4.21	*	0.81
871022	102	CL	9.0	21.0	² 0.99	0.045	*	2140	*	4.59	*	0.89
880819	93	CL	9.0	19.0	0.70	0.050	<0.01	1770	65.1	4.65	*	0.75
890818	138	UU	9.0	22.0	0.59	0.046	0.014	3040	81.4	6.35	1.9	1.1
900518	110	MP,UU ³	9.5	20.0	0.60	0.022	<0.01	2200	66.0	2.42	*	0.85
900731	106	UU	9.0	25.0	0.62	<0.01	0.03	2650	65.7	*	3.2	0.94

Table 7. Streamflow, chemical concentration, chemical flux, and thermal-water discharge for site DS at Domingo Springs--
continued

Date	Q _s (L/s)	Lab	T (°C)	Cl (mg/L)	B (mg/L)	As (mg/L)	Sb (mg/L)	Cl flux (mg/s)	B flux (mg/s)	As flux (mg/s)	Sb flux (mg/s)	Q _r ¹ (L/s)
910813	117	MP	9.0	21.0	*	*	*	2460	*	*	*	1.0
920811	108	MP,UJ ³	10.0	22.0	0.90	*	*	2380	97.2	*	*	1.1
930826	166	MP	8.5	15.0	0.52	*	*	2490	86.3	*	*	1.0
940721	111	MP	9.5	19.0	0.60	*	*	2110	66.6	*	*	0.83
Average												
Standard deviation												
											0.85	
											0.14	

¹ $Q_r = Q_s [(Cl/2400) + (B/85)]/2$, where Q_s is streamflow.

² Value assumed incorrect and not used in computations.

³ Chloride determined in MP laboratory; other values determined at UU laboratory.

drainage from Domingo Springs enters the river (Paulson and Ingebritsen, 1991). These data can be interpreted to show the addition of a Lassen-type thermal component (2400 mg/L chloride) at a rate of approximately 3 L/s, 1 L/s of which is presumed to be from Domingo Springs itself.

Other Sites

Paulson and Ingebritsen (1991) report the results of Cl and specific conductance measurements for stream samples from 116 sites in the Lassen region. Chloride-enriched samples from streams at lower elevations near the Sacramento River were assumed to be influenced by groundwater from Upper Cretaceous marine rocks which crop out at elevations as high as 760 m (fig. 1). Major streams north and south of LVNP are large enough that they could contain substantial thermal components without appearing obviously chloride-enriched. The chloride flux in the Pit River at site #1 (fig. 1) measured in September 1989 was equivalent to a Lassen-type thermal component (Cl = 2250 mg/L, as used by Paulson and Ingebritsen, 1991) of about 4 L/s. Chloride flux for the North Fork Feather River at site #112 south of Lake Almanor in October 1989 was equivalent to a thermal component of about 2 L/s. Paulson and Ingebritsen (1991) investigated the possibility that these late summer/fall instantaneous flux measurements were influenced by dams and diversions by (1) combining measured chloride concentrations with annual average streamflow (1985-1988) and (2) correcting the measured Cl concentration for a "background" contribution determined from the Na/Cl ratio. This yielded estimates of 6 L/s and 12 L/s as upper limits for the thermal components in the Pit River and the North Fork Feather River, respectively.

Other evidence suggests that some or all of the chloride flux in the Pit and North Fork Feather Rivers could be contributed by sources other than the Lassen hydrothermal system. In the case of the Pit River, both a chloride and a thermal anomaly have been identified by R. H. Mariner (U.S. Geological Survey, personal communication, 1995) in the springs which feed the Fall River which drains into the Pit River from the north upstream of site #1. The Fall River springs in turn are derived from groundwater that flows through volcanic rocks derived from the Medicine Lake Volcano to the northwest of the Lassen area. The North Fork Feather River at site #112 is at the edge of an area which has numerous soda springs, some of which are chloride-rich (up to 900 mg/L), but only one of which has a B/Cl ratio similar to that of the Lassen thermal water.

Geophysical Evidence of Additional Thermal-Water Outflow

Geophysical indications of subsurface outflow of thermal-water from the Lassen geothermal system include low-resistivity anomalies detected by audio-magnetotelluric (AMT) surveys and elevated temperature gradients in two test wells south of the Park. The pattern of low resistivity anomalies corresponds reasonably well with outflow zones that surface along Mill Creek and at Domingo Springs (Sorey and Ingebritsen, 1984; Christopherson and Pringle, 1981). Most of the dozen or so test holes drilled in the Lassen KGRA show low temperature gradients indicative of ground-water recharge or conductive gradients associated with regional heat flow values near 70 mW/m² (Mase and others, 1980). An anomalously high gradient was found in well LSNF, drilled by the USGS to a depth of 225 m at the northern base of Doe Mountain (figure 3). The gradient and bottom-hole temperature in this well were 90°C/km and 26°C, respectively. Mase and others (1980) estimated a conductive heat flow of 230 mW/m at this site, suggesting that there may be

a flow of thermal water at depths below 225 m, perhaps associated with the same outflow zone supplying thermal water to Morgan and Growler Hot Springs. It is plausible that the additional thermal-water flow suggested by the LSNF data actually discharges in Mill Creek, causing the increase in chloride flux detected at the MC-CG site 5 km further downstream.

Four relatively deep (600-900 m) temperature gradient holes were drilled by Unocal Corporation in 1984 at sites within the Lassen KGRA (figure 3). Anomalously high temperatures and gradients were encountered only in well 33-8, drilled to a depth of 680 m at a location 6 km south-southwest of the Devils Kitchen thermal area. Although the data from this well are still proprietary, they indicate that a high-temperature ($>200^{\circ}\text{C}$) anomaly exists at that location. Such an anomaly could result either from a zone of thermal-water outflow from the geothermal system in LVNP or a localized convection system heated by a relatively young granodiorite intrusion (J.M. Bodell, Unocal Corporation, oral comm., 1994). No fluid samples were obtained from this well. Although a low-resistivity anomaly was not detected in the vicinity of this well in the AMT survey data noted previously, there is a zone of low resistivity between the well and the Devils Kitchen thermal area (Sorey and Ingebritsen, 1984; Christopherson and Pringle, 1981). A detailed review of the thermal and lithologic data collected from well 33-8, if and when it is made public, might provide clues to the regional significance of the anomalous thermal conditions encountered at this site. It is possible, for example, that thermal-water outflow from this area, if any, is reflected in the permissible chloride flux at site #112 (fig. 1).

Total Thermal-Water Discharge

A maximum value for the total rate of thermal-water discharge from the Lassen geothermal system can be obtained by combining (1) the 23 L/s from sites along Mill Creek near Highway 36 and Domingo Springs (tables 3, 4, and 7) with (2) an additional thermal-water input of 5 L/s to Mill Creek between MC-BS and MC-CG, and (3) the maximum permissible components of Lassen thermal water in the North Fork Feather and Pit Rivers of 18 L/s. This yields a total of 46 L/s, only about 28 L/s of which can be clearly identified with the Lassen geothermal system. Thus, rate of discharge of thermal water Lassen is expressed here as ≤ 46 L/s. The temperature data for well 33-8 provides evidence an indication that there could be some outflow of thermal water from the Park which is as yet undetected in surface streams.

ARSENIC AND ANTIMONY LOSS

Arsenic and antimony are present in both Morgan and Growler Hot Springs at concentrations near 11 and 2 mg/L, respectively (tables 1 and 2). If As and Sb acted conservatively upon entering Mill Creek and Canyon Creek, measured fluxes of these elements should be related to rates of thermal-water input to these streams. This was found to be the case in Hot Creek, located within the Long Valley caldera in east-central California (Sorey and Clark, 1981; Eccles, 1976). For the Lassen streams, however, Sorey (1986) and Thompson and others (1987) presented data from samples collected in 1983-85 from Mill Creek and Canyon Creek that indicated arsenic losses of 10-50 percent and antimony losses exceeding 70 percent of values expected from the measured Cl and B fluxes and the concentrations of As and Sb in the hot springs. This limited data set suggests that part of the arsenic and antimony contributed to the Lassen streams by thermal-water inflow is removed by chemical and/or biological processes.

Because of the apparent differences in behavior of As and Sb in the Lassen and Long Valley streams, our study of thermal-water discharge from the Lassen hydrothermal system was broadened to provide more data on the degree of arsenic and antimony loss in streams and to investigate possible causes for such losses. In addition, arsenic concentrations at our monitoring sites on Mill Creek and Canyon Creek are of interest from a public health standpoint, since they exceed the current Environmental Protection Agency drinking-water standard of 0.05 mg/L, except during periods of very high streamflow (tables 3-5).

Laboratory Accuracy

Some of the variability in arsenic and antimony flux is due to laboratory error, which is commonly larger for these elements than for chloride and boron. The results for duplicate stream samples analyzed at different laboratories (table 6) show generally lower As concentrations determined at the CL and UU laboratories compared with the MP laboratory. Differences between laboratory results for As, expressed as a percentage of the value from the MP laboratory, averaged 14 percent for CL and 23 percent for UU. In general, the hydride-AAS technique used by the USGS and CL laboratories is more accurate (detection limit near 0.001 mg/L) than the ICP technique used at the University of Utah Research Institute laboratory (detection limit 0.05 mg/L after 10:1 sample concentration) at low arsenic concentrations. However, the accuracy of the hydride-AAS technique is also partly dependent on the type of reductant, its concentration, and the time used to chemically reduce the samples before spectrographic analysis. Thus, arsenic values determined in the Menlo Park laboratory (in 1988 and 1989) are considered the most accurate of the three sets because more time was used in the reduction step (Ann S. Maest, personal comm., 1988). We assume that the properties of the reductants used by the CL and the MP laboratories were the same. Arsenic and antimony analyses for samples collected in 1983 and 1984 were also run in Menlo Park using the hydride generation technique (Thompson and others, 1987).

Arsenic concentrations reported by the CL and UU laboratories for standards with 1.0 and 0.1 mg/L As(III) showed relatively little error, suggesting that errors in As determinations on the Lassen stream waters result from lower ratios of As(III)/As(V) (for hydride AAS analyses) or interference of other constituents (for ICP analyses) in the stream waters. Adequate reduction of dissolved arsenic prior to laboratory analysis is important for the stream samples, which were

found to contain over 90 percent As(V) when sampled. In contrast to the differences in stream-water As values reported by these laboratories, differences in hot-spring As values between the CL and MP laboratories on 9 duplicate samples collected in 1988 ranged from only 4 to 9 percent. This is consistent with the finding that the hot-spring waters contained over 90 percent As(III) when sampled. Arsenic values determined by ICP at the UU laboratory on these same hot-spring samples were 13-29 percent lower than the MP values.

Antimony concentrations in the Lassen streams are probably too low for accurate determination on a routine basis by the ICP technique used at the UU laboratory, even though satisfactory results were obtained on standard solutions covering the range in Sb concentrations found in the stream samples. We do not know if there are constituents in the stream samples that interfere with Sb determinations. Antimony values reported for stream samples by the CL laboratory appear internally consistent in that Sb concentrations vary inversely with streamflow. However, Cl/Sb ratios show more variability than do Cl/B or Cl/As ratios. This may reflect differences in antimony loss above the gaging sites and/or greater laboratory error in Sb determinations. Significant loss of antimony above the gaging sites is indicated by average values of Cl/Sb for sites MC-36, MC-T, and CC-C, which are 2-10 times higher than average values for the hot-spring samples.

Computed Values of As and Sb Loss

Values of apparent arsenic loss were computed in percent from

$$[1 - (Q_S \times As_S) / (Q_T \times As_T)] \times 100, \quad (3)$$

where $Q_S \times As_S$ represents the measured arsenic flux at a gaging site and $Q_T \times As_T$ represents the expected arsenic flux contributed by the thermal-water input calculated from measured Cl and B fluxes (equation 2). An equivalent expression for antimony loss is obtained by substituting Sb for As in equation 3. Values of arsenic and antimony loss for each gaging site were computed for values of As_T and Sb_T of 11 and 2 mg/L, respectively, based on the analytical data in table 2. The results in table 8 and figure 10, which are based on analyses from the CL and UURI laboratories, show apparent arsenic losses ranging from 0-63 percent for site MC-36, 10 to 96 percent for site MC-T, 5 to 67 percent for site CC-C, and 29 to 74 percent for site DS. Computations for antimony loss yield similar, but generally higher values (table 8) at each site.

The range and variability in apparent arsenic and antimony losses noted above may be due in part to errors in reported As and Sb concentrations, as discussed previously. A comparison of As loss values computed for As concentrations reported by the CL and MP laboratories for five sample sets collected over the 1988-89 period is shown in table 9. The As loss values for four sites are generally lower for the MP analyses and show a more consistent relation with streamflow, that is higher streamflow corresponding to lower As loss. However, the relatively small data set precludes an adequate assessment of the degree of variability in As loss values attributable to errors in As determinations.

Based on a set of four samples collected in 1983-84, Thompson and others (1987) noted that antimony load (and hence loss) in Mill Creek and Canyon Creek varied inversely with streamflow and suggested that antimony loss by adsorption on sediments might be less effective

Table 8. Calculated values of arsenic and antimony loss above gaging sites on Mill Creek, Mill Creek tributary, Canyon Creek, and Domingo Springs

[Values based on data reported in tables 3, 4, 5, and 7. Sampling dates for site DS below Domingo Springs are within 1-3 days of the date shown for the other sites. Site abbreviations: MC-36, Mill Creek at Highway 36; MC-T, Mill Creek tributary at the Highway 36 crossing; CC-C, Canyon Creek at the culvert above Morgan Meadow; DS, Domingo Springs. Q_T , thermal water discharge; As, arsenic; Sb, antimony; NV, site was not visited; L/s, liters per second; %, percent; *, no data or incorrect value of As or Sb concentration reported]

Date	MC-36				MC-T				CC-C				DS	
	Flow Rate (L/s)	Q_T (L/s)	As Loss ² (%)	Sb Loss ³ (%)	Flow Rate (L/s)	Q_T (L/s)	As Loss ² (%)	Sb Loss ³ (%)	Flow Rate (L/s)	Q_T (L/s)	As Loss ² (%)	Sb Loss ³ (%)	Flow Rate (L/s)	As Loss (%)
830804	4840	15	39	69	85	3.5	*	*	4292	2.5	16	72	266	*
831020	1150	16	37	90	43	2.9	*	*	457	3.1	30	86	NV	*
840621	4870	17	35	32	179	3.2	68	*	4402	2.6	7.3	55	200	46
840815	1170	14	39	84	113	3.5	76	*	437	2.5	29	86	154	68
841101	1030	16	32	*	67	3.9	67	*	NV	*	*	*	105	52
850730	793	15	15	*	74	3.3	64	*	29	2.6	56	*	98	58
851029	1030	19	20	*	28	3.7	70	*	69	1.9	22	*	127	49
860320	3400	26	40	*	263	6.3	47	*	NV	*	*	*	NV	*
860423	5440	18	*	*	382	7.4	93	*	NV	*	*	*	200	*
860521	6830	21	32	*	94	1.7	48	*	920	2.3	14	*	246	46
860625	3710	19	35	*	189	5.9	50	*	NV	*	*	*	190	69
860723	1560	19	37	*	54	2.3	79	*	NV	*	*	*	153	40
860826	1070	19	47	*	57	2.7	84	*	19	1.3	39	*	122	38
860930	1380	18	29	*	69	5.4	86	*	NV	*	*	*	139	43
861030	1690	23	54	*	56	6.8	87	*	NV	*	*	*	119	48
861210	1010	19	47	*	42	5.6	89	*	NV	*	*	*	113	54
870326	1470	19	32	*	93	4.7	*	*	NV	*	*	*	NV	*
870427	5470	22	34	*	82	5.2	52	*	NV	*	*	*	113	29
870527	2730	17	44	*	61	4.6	80	*	NV	*	*	*	134	65
870722	926	18	39	*	68	2.7	83	*	48	2.5	31	*	114	49
870818	668	15	24	*	53	1.2	22	*	NV	*	*	*	99	48
870922	583	13	63	64	43	2.2	*	88	16	1.4	41	48	108	52

Table 8. Calculated values of arsenic and antimony loss above gaging sites on Mill creek, Mill creek tributary, Canyon Creek, and Domingo Springs--continued

Date	MC-36			MC-T			CC-C			DS				
	Flow Rate (L/s)	Q _T ¹ (L/s)	As Loss ² (%)	Sb Loss ³ (%)	Flow Rate (L/s)	Q _T ¹ (L/s)	As Loss ² (%)	Sb Loss ³ (%)	Flow Rate (L/s)	Q _T ¹ (L/s)	As Loss ² (%)	Sb Loss ³ (%)	Flow Rate (L/s)	As Loss (%)
871022	620	14	25	56	18	2.0	86	91	17	1.5	*	44	102	53
880120	1040	19	31	56	59	5.5	82	89	NV	*	*	*	NV	*
880218	1220	17	30	50	62	5.4	41	85	NV	*	*	*	NV	*
880315	1690	20	39	67	96	5.8	50	84	NV	*	*	*	NV	*
880426	2290	18	17	88	79	6.0	48	88	NV	*	*	*	NV	*
880510	2240	20	19	73	65	5.7	83	92	326	2.5	5.4	56	NV	*
880629	2060	18	19	78	45	2.6	56	89	52	2.0	12	85	NV	*
880727	898	17	0	83	85	4.1	66	91	40	2.3	11	87	NV	*
880819	776	18	34	*	58	3.2	79	*	28	2.2	23	*	93	45
880929	663	18	32	*	38	2.8	85	*	NV	*	*	*	NV	*
881028	722	17	46	59	7	0.8	96	25	11	1.1	46	66	NV	*
890214	852	17	43	37	60	6.7	81	87	NV	*	*	*	NV	*
890329	3060	*	*	*	275	6.0	10	31	NV	*	*	*	NV	*
890427	3140	22	48	14	118	5.3	57	64	NV	*	*	*	NV	*
890524	3170	16	*	*	180	6.1	62	*	362	2.3	7	*	NV	*
890627	3030	14	53	*	NV	*	*	*	NV	*	*	*	NV	*
890720	1250	17	55	*	39	2.1	91	*	NV	*	*	*	NV	*
890817	985	18	29	*	35	2.6	71	*	23	1.7	44	93	138	48
891020	833	16	29	*	15	2.3	87	*	NV	*	*	*	NV	*
900416	3540	18	7	*	44	4.0	53	*	NV	*	*	*	NV	*
900518	1820	17	73	25	13	1.6	91	*	109	2.1	32	*	110	74
900620	2113	20	*	*	44	3.5	*	*	*	*	*	*	NV	*
900730	813	16	55	*	39	2.7	76	*	28	2.2	67	*	NV	*

¹ Thermal water discharge from tables 3-6.

² Computed from equation 3 with As = 11 mg/L.

³ Computed from equation 3, using Sb concentrations in place of As concentrations and Sb = 2.0 mg/L.

⁴ Data for site on Canyon Creek near confluence with Mill Creek.

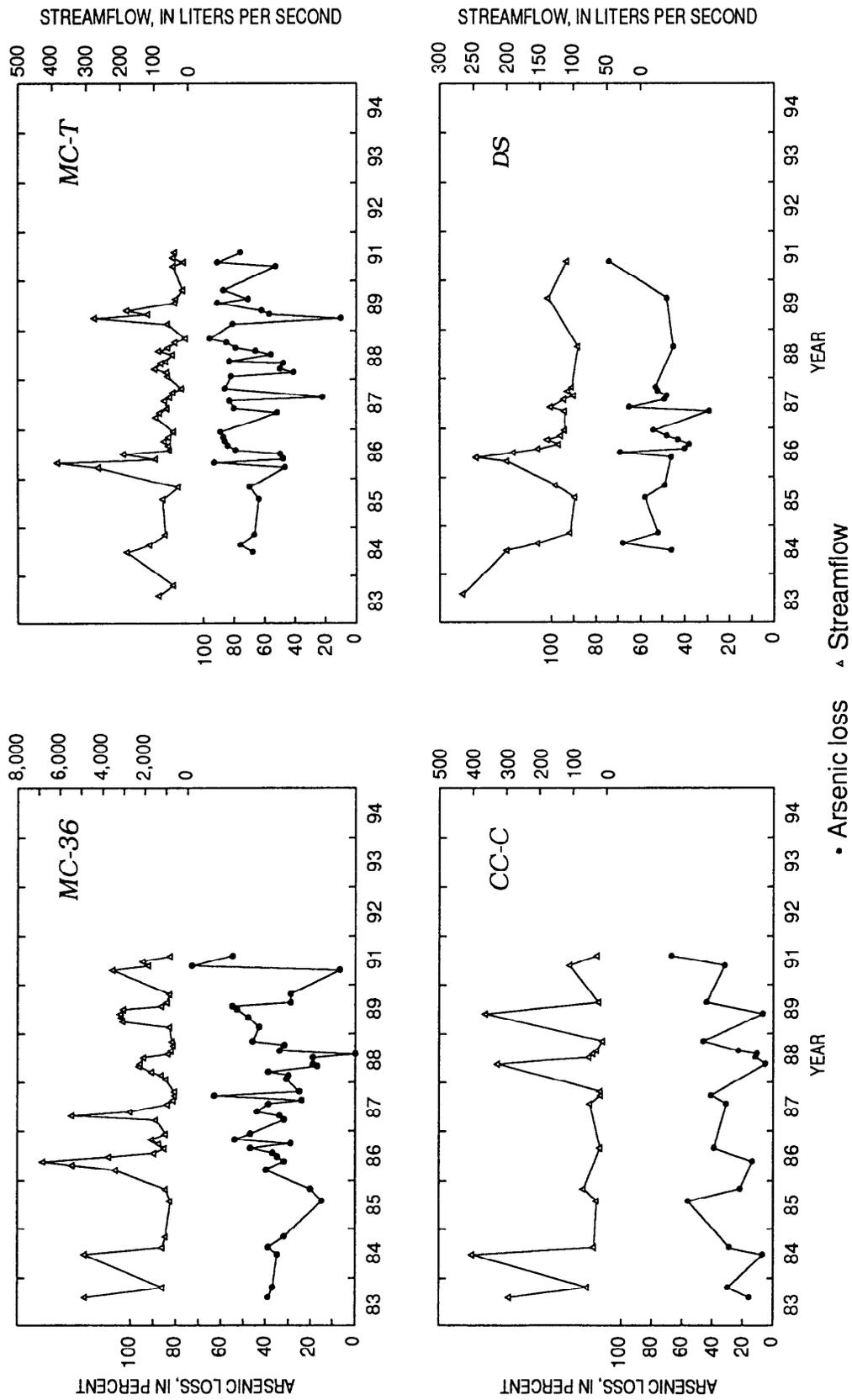


Figure 10. Calculated arsenic loss for sites MC-36 on Mill Creek at Highway 36, MC-T on the Mill Creek tributary crossing Highway 36, CC-C on Canyon Creek at the culvert above Morgan Meadow, and DS at Domingo Springs.

Table 9. Measured streamflow and calculated values of arsenic loss above gaging sites on Mill Creek, Mill Creek tributary, and Canyon Creek, based on arsenic concentrations reported by the Menlo Park laboratory and the USGS Central Laboratory

[Site abbreviations: MC-36, Mill Creek at Highway 36; MC-T, Mill Creek tributary at the Highway 36 crossing; CC-C, Canyon Creek at the culvert above Morgan Meadow; MC-BS, Mill Creek at Brokenshire campground. As, arsenic; L/s, liters per second; %, percent; *, no data]

Date	MC-36			MC-T			CC-C			MC-BS		
	Flow Rate (L/s)	As Loss ¹ (%)	As Loss ² (%)	Flow Rate (L/s)	As Loss ¹ (%)	As Loss ² (%)	Flow Rate (L/s)	As Loss ¹ (%)	As Loss ² (%)	Flow Rate (L/s)	As Loss ¹ (%)	As Loss ² (%)
880426	2290	3	17	79	37	47	*	*	*	*	*	*
880510	2240	9	19	65	48	83	326	0	5	*	*	*
880629	2060	16	19	45	53	56	52	29	12	*	*	*
880819	776	*	34	58	*	79	28	*	23	³ 834	51	*
890815	*	*	29	*	*	71	*	*	44	985	32	47

¹ Computed from equation 3 with As_T = 11 mg/L, using As_S value reported by Menlo Park laboratory.

² Computed from equation 3 with As_T = 11 mg/L, using As_S value reported by USGS Central Laboratory.

³ Calculated from sum of values listed for MC-36 and MC-T.

at high flow rates than at low flow rates. For the same set of samples, arsenic load in both streams was relatively constant. In general, the larger data set presented in this report shows too much scatter in As and Sb loss values to delineate a clear relation between streamflow and loss of As and Sb (fig. 10 and table 8). However, a clear inverse relation is observed between As loss and streamflow for Canyon Creek (fig. 11). For this stream, a correlation coefficient of 0.70 was obtained from linear regression between \ln (As loss) and \ln (Q_s). The more limited As-loss values based on arsenic analyses from the Menlo Park laboratory (table 9) also show a consistent trend of increasing arsenic loss with decreasing streamflow at CC-C, as well as at the other sites in this area. These considerations indicate that factors contributing to arsenic loss (and by inference antimony loss) are less effective at high flow rates when As concentrations are relatively low.

Chemical and Biological Processes

Arsenic contributed to Mill Creek and Canyon Creek by Morgan and Growler Hot Springs becomes oxidized from As(III) to As(V) as it flows from the springs to the gaging sites. A possible mechanism for removing arsenic from the stream water is adsorption of As(V) on iron, aluminum, and manganese coatings on streambed material, as delineated by Fuller and Davis (1989) for Whitewood Creek, South Dakota. Mill Creek and Canyon Creek drain areas of steam-heated thermal activity in LVNP and consequently contain both dissolved iron and iron-rich sediments (Sorey, 1986). In both these streams and in Whitewood Creek, arsenic concentrations are much lower than allowed by the solubilities of arsenic-bearing minerals in well-oxygenated, neutral pH environments (Ferguson and Gavis, 1972). Hence, precipitation of arsenic compounds in these streams is unlikely.

Samples of stream water and streambed material were collected at numerous sites along Mill Creek and Canyon Creek below the hot-spring areas by Chris Fuller and Ann Maest of the USGS in August, 1988 and August, 1989. Concentrations of As(III), As(V), and Cl were determined for each water sample; for each sediment sample, the arsenic and iron concentrations were determined from concentrated HNO_3 leachates for several size fractions (<60 μ , 60-120 μ and 210-500 μ). Unpublished results from three samples show that 90 percent of the arsenic is oxidized one kilometer downstream from the area of hot-spring input. In addition, increasing arsenic concentrations in sediment downstream from the hot-spring areas suggest that arsenic loss occurs by adsorption onto sediments (Chris Fuller, written comm., 1989). The Lassen stream data indicate that variations in arsenic loss above the primary gaging sites can be related to variations in streamflow and associated changes in dissolved arsenic concentrations due to dilution. Higher streamflow rates are accompanied by lower arsenic concentrations, which result in decreased As adsorption, and possibly some desorption of previously adsorbed arsenate due to a shift in sorption equilibrium. Results of laboratory experiments reported by (Fuller and Davis, 1989) suggests that arsenic loss by adsorption in the Lassen streams should also be pH dependent; higher loss being associated with lower pH. Values of pH measured in the field exhibited a relatively narrow range (7.5-8.5); no obvious correlation was observed between pH, streamflow, and arsenic loss. Other factors, such as site availability or accessibility, are thus more likely to be responsible for the observed variation in arsenic loss with decreasing streamflow.

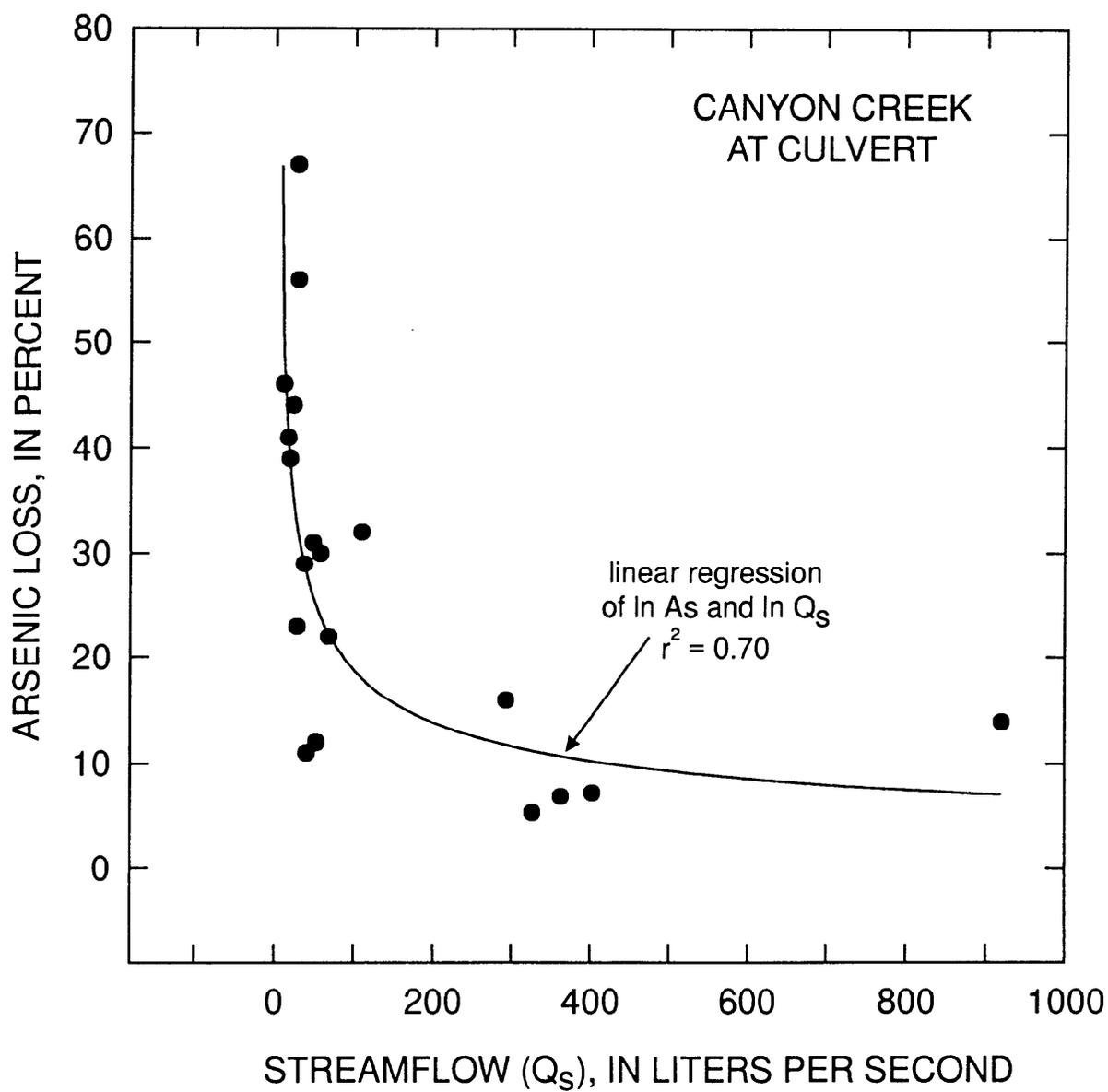


Figure 11. Calculated arsenic loss and measured streamflow for site CC-C on Canyon Creek at the culvert above Morgan Meadow, showing logarithmic relation fitted by linear regression.

Dissolved arsenic might also be consumed by algae, which are abundant near hot-spring vent areas in Morgan Meadow and also in the swimming pool in the meadow. However, the Cl/As data for stream samples collected in August 1988, which show arsenic loss in portions of these streams relatively devoid of algal growth, argue against such a biological process controlling the removal of dissolved arsenic. Upper limits for arsenate removal by algae, based on the Whitewood Creek studies (Fuller and Davis, 1989), are small compared with changes in dissolved arsenic measured and inferred for sections of the Lassen streams below the hot springs.

Differences between conditions in Hot Creek in the Long Valley caldera, where arsenic loss does not occur, and Mill Creek and Canyon Creek, where arsenic loss is significant, may be associated with (1) amounts of iron-rich sediment, (2) oxidation state of dissolved arsenic, and (3) distances between hot-spring inputs and stream sampling sites. Speciation studies have not yet been carried out for Hot Creek, so possible differences in oxidation state of dissolved As cannot as yet be assessed. Distances to stream sampling sites are approximately 1 km in Hot Creek, and vary from 1 to 4 km at Lassen. As noted previously, however, arsenic in Mill Creek is almost completely oxidized within a distance of 1 km from the hot springs. This leaves the greater amount of adsorbent material in the Lassen streams as the most likely factor to account for loss of dissolved arsenic.

At Domingo Springs, Cl/As ratios are approximately twice the value in thermal water from Morgan and Growler Hot Springs. This difference leads to the calculation of As loss values of 29-74 percent (table 8). Conditions at this site are notably different from those in the Mill Creek area, however, in that the sampling site is very close to the spring vent and there is very little sediment in the spring flow. Thus, arsenic contributed from thermal water inputs to the flow system supplying Domingo Springs may be lost within the aquifer en route to the point of discharge. In addition, the effect of laboratory error in As concentrations reported by the CL and UURI laboratories may be more important at this site because of the low concentrations involved (0.02-0.05 mg/L). The oxidation state of the dissolved arsenic at DS has not been determined.

SUMMARY AND CONCLUSIONS

Subsurface thermal-water outflow, most likely derived from two-phase (boiling) reservoirs beneath Lassen Volcanic National Park, discharges at Morgan and Growler Hot Springs and Domingo Springs and in several streams draining the Lassen region. The hot-spring waters contain significant amounts of chloride (about 2,400 mg/L) and boron (about 85 mg/L), making it possible to determine the amount of thermal water in surface streams from measurements of chemical flux. Such measurements have been made at gaging sites along Mill and Canyon Creeks near Highway 36 and at Domingo Springs over the period 1983-94. The total discharge of Lassen-type thermal water from Morgan and Growler Hot Springs is approximately 22 L/s; an additional discharge of 1 L/s occurs in Domingo Springs. Variability in calculated thermal-water discharge is due to a combination of errors in streamflow and chemical concentration determinations and the influence of streamflow and related groundwater/surface water interactions on the rates and locations of thermal-water inputs. The relative standard deviation for this total of 23 L/s is approximately 15 percent.

One set of chloride-flux measurements made in 1994 at sites on Mill Creek as far as 30 km downstream from Highway 36 indicate an additional input of about 5 L/s from ground-water seepage below the gaging sites near Highway 36. Chloride-flux measurements made in 1989-90 suggest possible additional inputs of ≤ 18 L/s of Lassen-type thermal water in the largest streams draining the Lassen region (North Fork Feather River south of the Park and the Pit River north of the Park). Thus, the total discharge of Lassen-type thermal water in streams is ≤ 46 L/s. In terms of mass, this value is approximately equal to the rate of steam discharge within the Park, as reported by Sorey and Colvard (1994). The only evidence for additional undetected outflow of thermal water from the Park exists from temperature and lithologic data collected from one relatively deep (680 m) test hole drilled in the Lassen KGRA.

Arsenic and antimony are also present in relatively high concentrations in the Lassen thermal waters. Unlike chloride and boron, however, As and Sb are not conservative in the streams. Significant, but variable amounts of loss of the As and Sb contributed by thermal-water inputs are indicated by comparisons of measured fluxes of As and Sb with fluxes of Cl and B. The flux data along with limited determinations of arsenic oxidation state suggest that upon entering the streams, As and Sb are oxidized and adsorbed on streambed sediments at rates that depend on the concentrations of these constituents in the stream water, and thus on streamflow.

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