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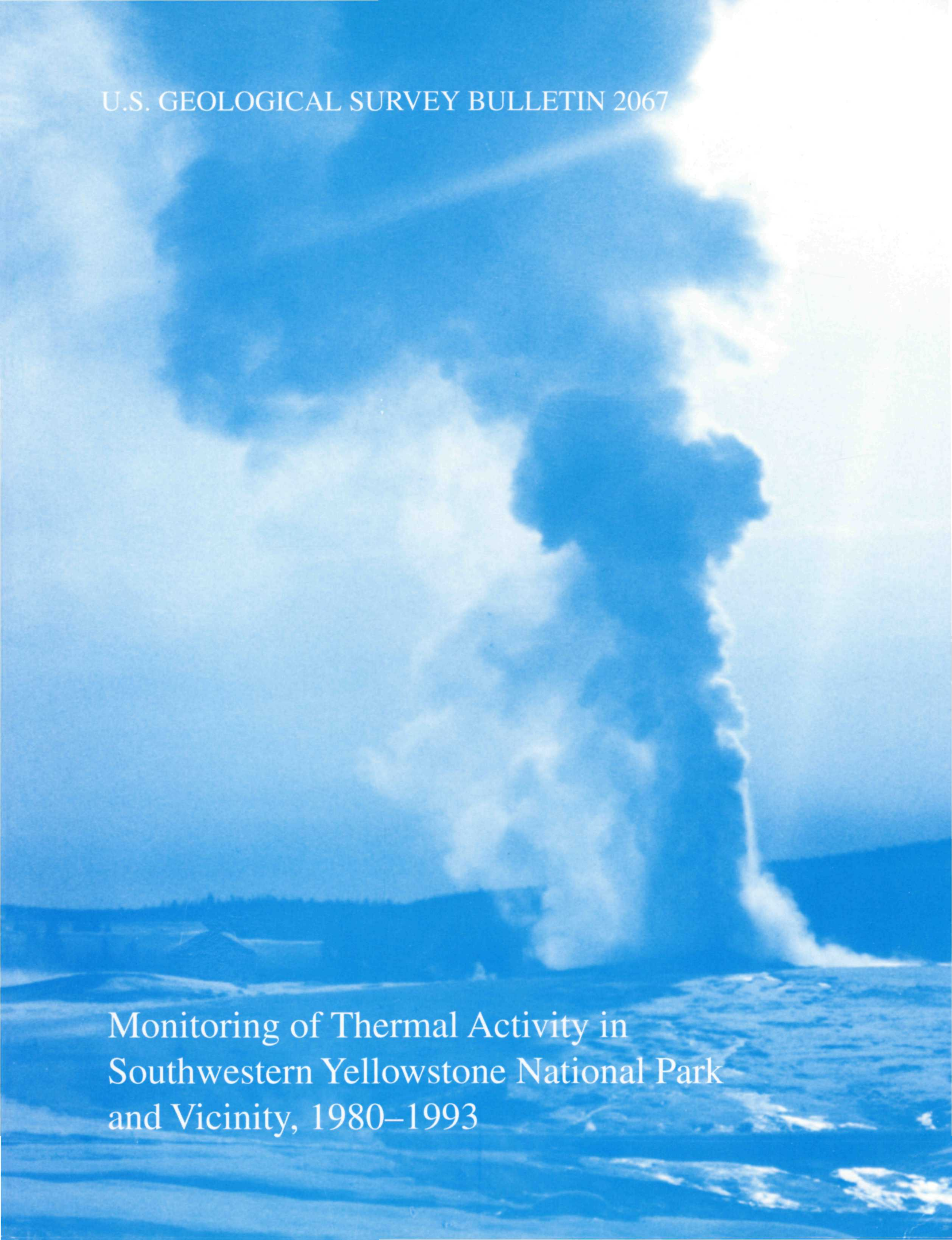

Monitoring of Thermal Activity in Southwestern Yellowstone National Park and Vicinity, 1980–1993

Cover. Old Faithful Geyser during one of its intermittent eruptions of steam and hot water, southwestern Yellowstone National Park, Wyoming.

Monitoring of Thermal Activity in Southwestern Yellowstone National Park and Vicinity, 1980–1993

By Irving Friedman, Daniel R. Norton, *and* Roderick A. Hutchinson

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METRIC CONVERSION FACTORS

Multiply	By	To obtain
feet (ft)	0.3048	meters
miles (mi)	1.609	kilometers
cubic feet per second (cfs)	0.02832	cubic meters per second

MONITORING OF THERMAL ACTIVITY IN SOUTHWESTERN YELLOWSTONE NATIONAL PARK AND VICINITY, 1980–1993

By Irving Friedman,[1] Daniel R. Norton,[1] *and* Roderick A. Hutchinson[2]

ABSTRACT

Stream monitoring in Yellowstone National Park is being carried out to obtain baseline information on the natural variations in thermal activity against which to assess possible future impacts of geothermal, oil and gas, and other types of development adjacent to the Park and to relate these variations to seismic events and the possible movement of magma under the Park. The proximity of the Island Park Geothermal Area in Idaho and its possible future development places particular emphasis on investigation of the southwestern part of the Park.

Continuous automated measurements of thermal flux from features in this remote section of the Park proved to be impractical because of the necessity of visiting the sites frequently to service the equipment. A practical protocol was developed requiring the instantaneous measurement of the flux in surface streams once a year during the winter base-flow regime. The installation of weirs and staff gauges on the thermal streams made it possible to collect data from this area during a one-day helicopter trip.

The changes in discharge of thermal streams, which originate from hot springs, correlated with changes in discharge of the major rivers draining the Park and also with changes in precipitation over the Park. Because over 94 percent of the chloride in the rivers and streams in the Park is of geothermal origin, chloride flux can also be used as a measure of thermal flux. Annual values in both discharge and chloride flux at 10 of the 11 monitoring stations during base flow fluctuated as much as 90 percent over the 1986–93 period. About 5 percent of the thermal water exits the Park along the western boundary into the Henrys Fork drainage in Idaho. Monitoring of the chloride flux in this water may be a sensitive indicator of the effects of development of energy resources adjacent to the western boundary of the Park in the Island Park area.

INTRODUCTION

Monitoring of thermal activity in Yellowstone National Park has been carried out since 1980 to obtain baseline information on the natural variations in activity against which to assess possible future impacts of geothermal, oil, gas, and other types of development adjacent to the Park. The data will also relate these variations in activity to seismic events and to the movement of magma under the Park. Because of the proximity of the Island Park Geothermal Area (IPGA) in Idaho (fig. 1) and the possibility of future development of its energy resources, this investigation concentrated on the southwestern portion of the Park. This area contains many small and medium-size thermal features that may respond to disturbance by development adjacent to the Park. Of interest to this study are streams issuing from the thermal features, which makes feasible the monitoring of chloride flux.

Jones and others (1979) published results on the amount of discharge and chloride concentration of surface waters in the Falls River drainage within the Park, which were useful in developing our experimental program. Data on the Boundary Creek thermal areas were reported by Hutchinson (1980) and by Thompson and Hutchinson (1980). To orient our program in the IPGA, we used data by Whitehead (1978) on surface waters in the Upper Henrys Fork Basin.

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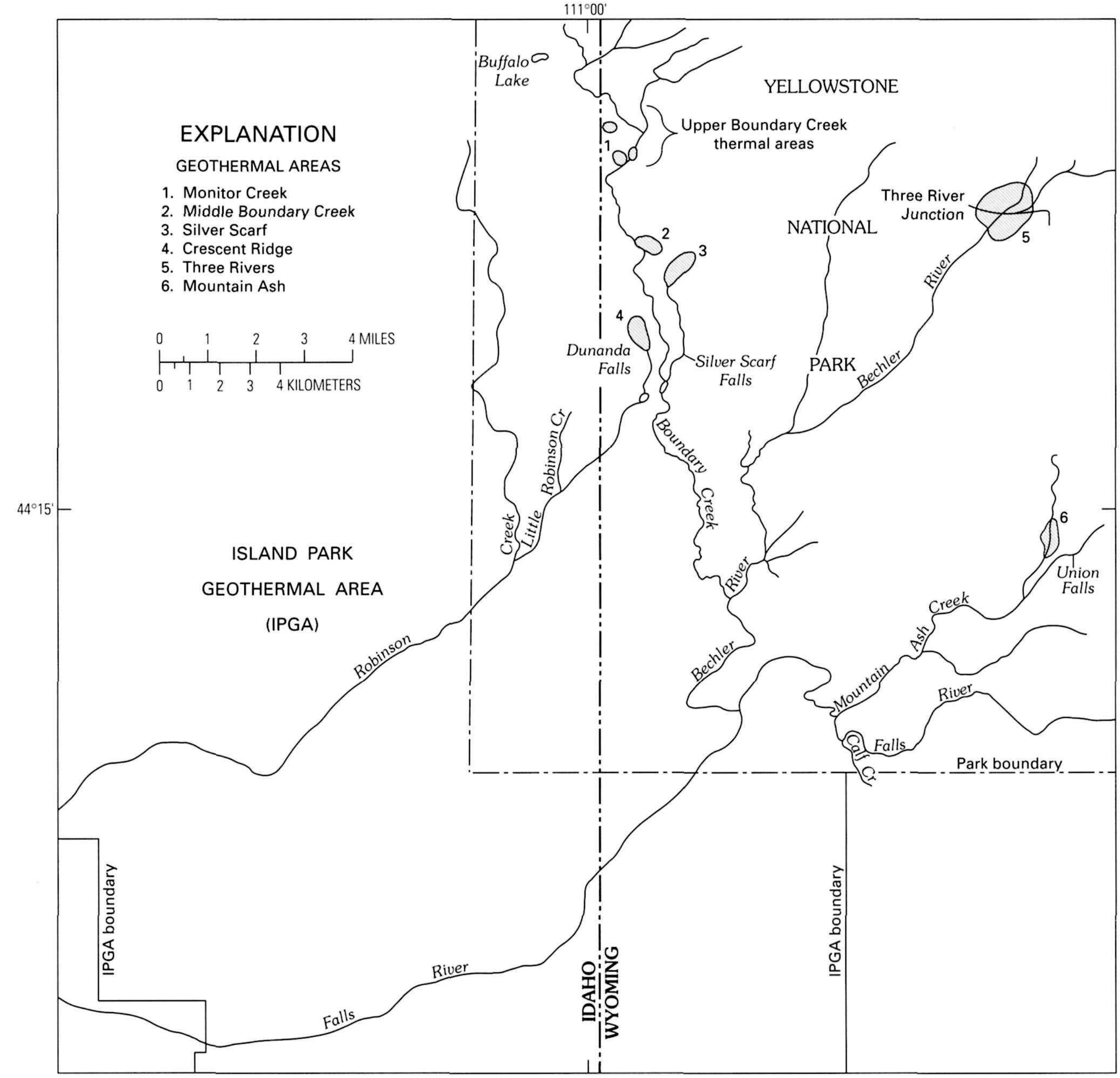

Figure 1. The southwestern portion of Yellowstone National Park and the Island Park Geothermal Area.

This is the first published report of a long-term monitoring study in this area, the conclusions of which reinforce the necessity for such long-term monitoring of streams containing thermally derived chloride. The report is divided into two sections; the first discusses monitoring of thermal features within the Park, and the second is concerned with monitoring of rivers and streams outside the Park boundary that we believe contain thermal waters heated by the Park magma system.

STREAM MONITORING IN SOUTHWESTERN YELLOWSTONE NATIONAL PARK

INITIAL INVESTIGATIONS

Because the study area was remote and difficult to access, we initially attempted to utilize automated equipment to record stream flow, water temperature, and

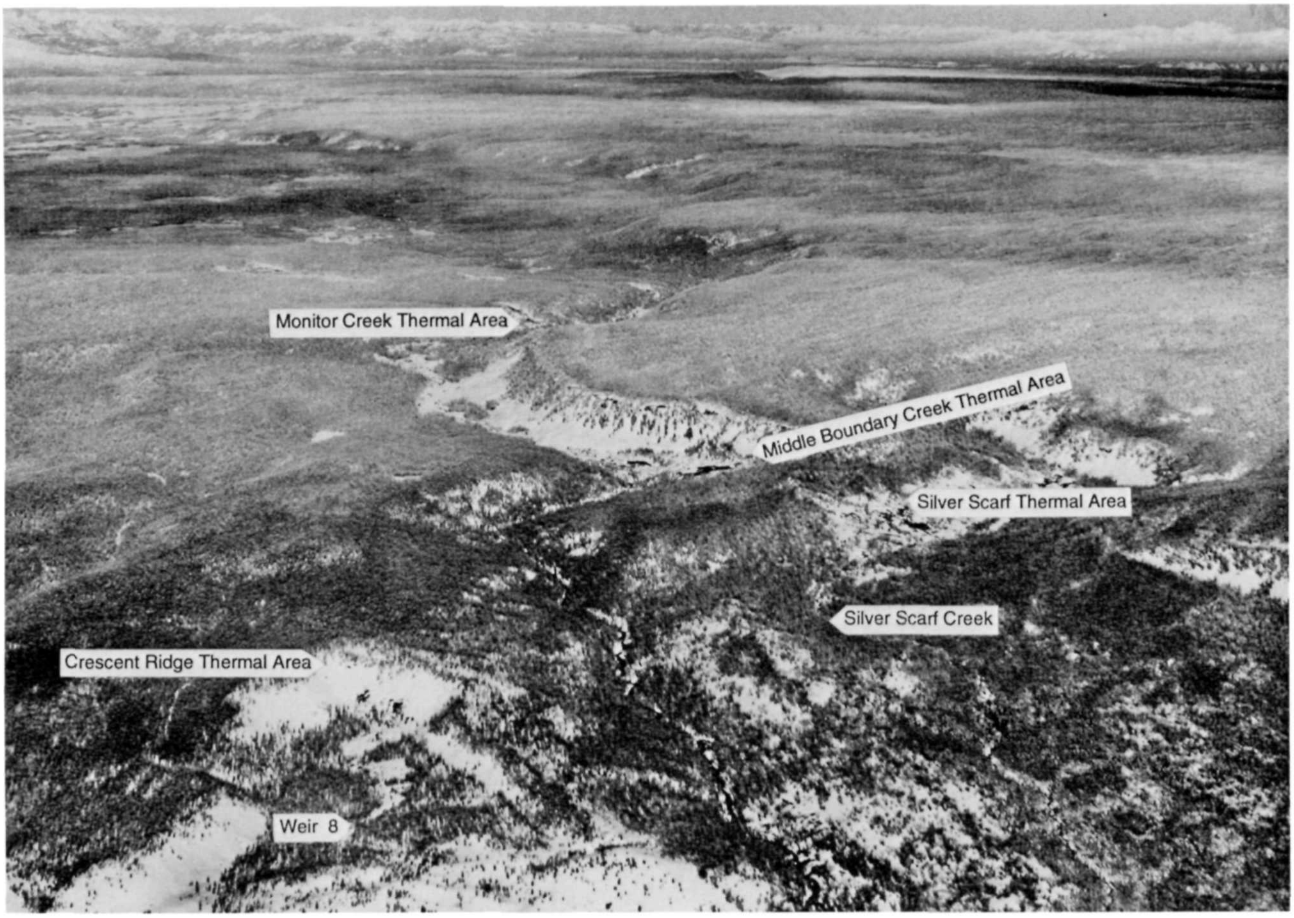

Figure 2. Aerial photograph of the Boundary Creek area, Yellowstone National Park. Photo taken January 31, 1984, looking northwest.

electrical conductivity and to store the data for later retrieval. We planned to service the monitoring sites three times a year. The initial site was established at the Monitor Creek Thermal Area (fig. 2) on a small stream draining a hot spring, identified in figure 3 as Weir 3. The data was recorded daily at noon and midnight by a Campbell Scientific Co. Micrologger (Model CE 21) and stored on a magnetic-tape cassette. Although the instrument was capable of running for nine months on internal dry cells, the site was visited several times a year to service the equipment and retrieve the cassette containing the data. The relative flow of the thermal stream was monitored by recording the depth of water in Weir 3, located about 100 meters downstream from the hot-spring source. For the first nine months, temperatures and electrical conductivity were measured at the weir. Afterwards, temperatures were also measured in the hot-spring orifice, which discharged at a temperature of about 80°C.

Figure 4 shows the data from October 1, 1980, to June 15, 1981. Cooling of the water in the stream due to snow melt was observed during April and early May, 1981. The low electrical conductivity and high water flow also reflected the input of snow melt during this period. During late May and June of 1981, the water flow remained high but the temperature and electrical conductivity increased. This was attributed to increased flow from the hot spring, offsetting a decreased contribution from snow melt.

The success of this effort encouraged us to establish a second instrumented site on a thermal stream in the Silver Scarf Thermal Area (fig. 2), located about 3.5 miles from the first site. Shortly after the equipment was installed, a series of problems arose. First, the thermistors used to measure temperature and water level in both weirs failed after time periods that varied from 1 to 10 months. Efforts to protect these devices proved unsuccessful, due probably to the continuous exposure to elevated temperatures. Secondly, the remote location, which could be accessed by foot or horseback only four months of the year and by helicopter the remainder of the year, made it impractical to service the sites frequently enough to secure continuous records.

As a result of these initial field experiments, we decided on a protocol of annual visits at a multitude of noninstrumented sites rather than continuous monitoring at a few instrumented sites. Each site was to be visited in the winter at the time of presumed base flow.

Figure 3. Aerial photograph of the Monitor Creek Thermal Area, Yellowstone National Park. Photo taken November 1, 1980, looking west and showing monitoring sites.

SUBSEQUENT INVESTIGATIONS

To determine the sites at which thermal fluids exit in the southwestern portion of the Park and adjacent areas, a survey was made of the chloride flux of streams originating in these areas. From a previous investigation (Norton and Friedman, 1985), it was determined that at least 94 percent of the chloride present in rivers draining the Park is of geothermal origin and, therefore, chloride flux can be used to assess thermal flux, as was suggested by Fournier and others (1976). To determine chloride flux, it is necessary to measure simultaneously the stream discharge and chloride concentration. The chloride flux is the product of these values (Norton and Friedman, 1985). A discussion of the experimental details and analytical protocols is given in Norton and Friedman (1991).

The locations of the sites inventoried are shown in figures 5 and 6, and the experimental data are given in tables 1 and 2. We determined that about 55 percent of the chloride leaving the southwestern part of the Park leaves via the Falls River. The remaining 45 percent leaves in streams draining the west boundary of the Park that in turn drain into the Henrys Fork (river) (fig. 6). Of the chloride that exits the Park via the Falls River, 70 percent originates in the Pitchstone Plateau and the Three Rivers Thermal Area, and the remaining 30 percent originates in the Boundary Creek drainage. Inasmuch as the latter drainage is closest to the Park boundary and the source of possible negative impact on the Park, we concentrated our efforts in this area.

As a result of this survey, we selected 11 sites for monitoring in the southwestern part of the Park. Of these, ten are located in the Boundary Creek drainage and one in the Robinson Creek drainage. Of the ten sites, seven are located near the source of small thermal streams, two on large tributaries of Boundary Creek and one on Boundary Creek itself. The small streams were judged to be sensitive indicators of environmental change, and their discharges were easily measured by small weirs. To minimize any environmental impact, the weirs were constructed of redwood with an attached stainless steel weir plate. Figure 7 shows two typical weirs. The discharges of the larger streams were measured using velocity meters.

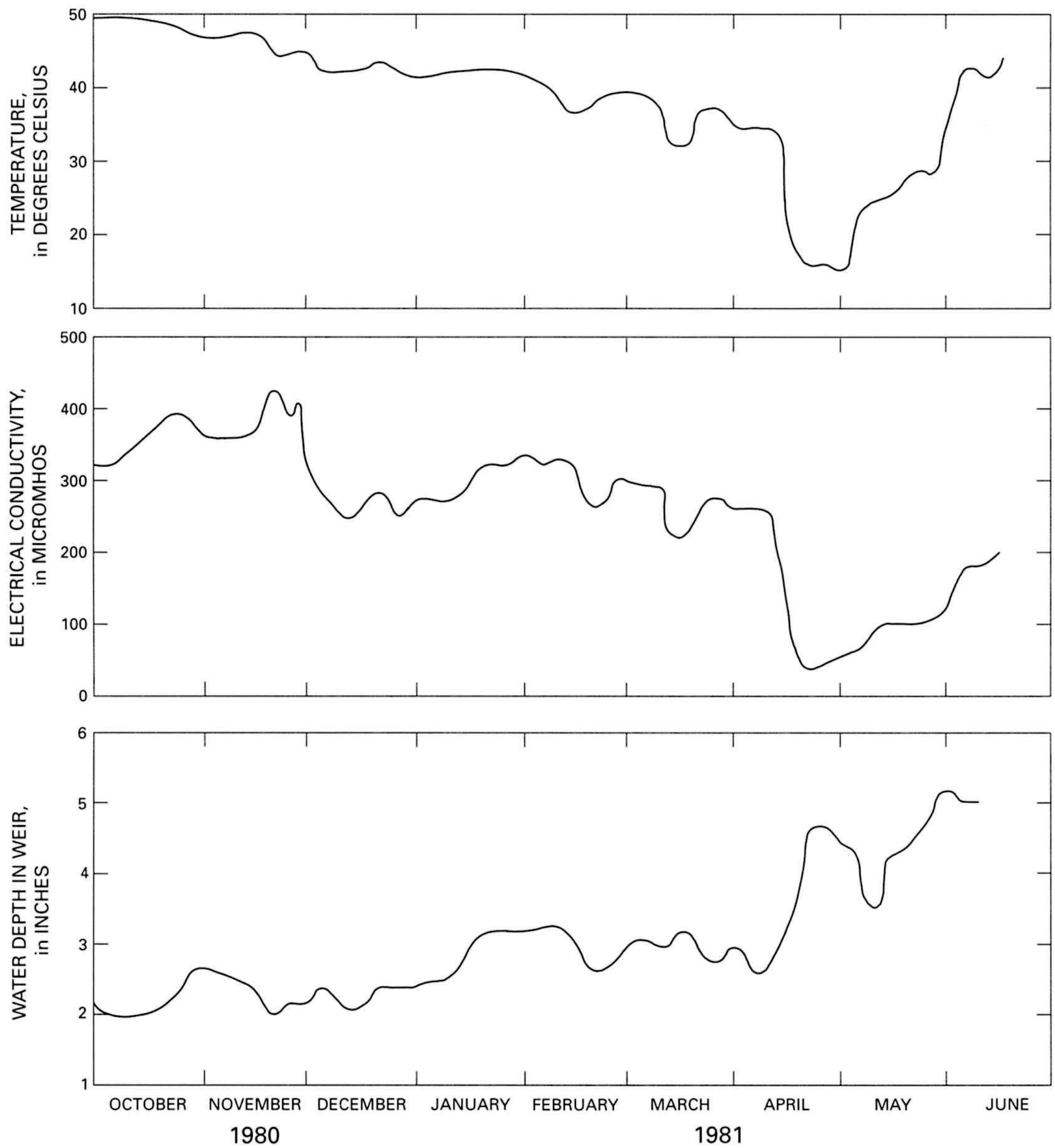

Figure 4. Physical data obtained using automated monitoring equipment at Weir 3, Monitor Creek Thermal Area, Yellowstone National Park.

The thermal areas in which these streams are located were described by Hutchinson (1980) and are listed below and shown in figure 1:

(1) Monitor Creek Thermal Area (fig. 3) is the southernmost of the Upper Boundary Creek thermal areas. The three sites being monitored constitute most of the surface flow from the thermal features at this locality:

Weir 1. The flow into this weir issues from a small thermal area containing hot acid waters and steam vents tens of meters upstream.

Weir 2. This is located on a small stream that appears to drain the large steam and acid-water vents that are the main visible features of the Monitor Creek Thermal Area.

Weir 3. This weir is on a small thermal stream that drains a hot spring located about 50 meters upstream. Occasionally, a small fraction of the streamflow is from an intermittent cold-water source.

(2) Middle Boundary Creek Thermal Area (fig. 8) was also described by Hutchinson (1980). The four sites monitored here constitute most of the surface flow from this geothermal feature. All four thermal streams are fed by springs that issue from beneath the adjacent Summit Lake rhyolite flow.

(3) Crescent Ridge Thermal Area (one site) consists of a series of low-temperature (approximately 25°C) thermal springs that flow into an unnamed creek,

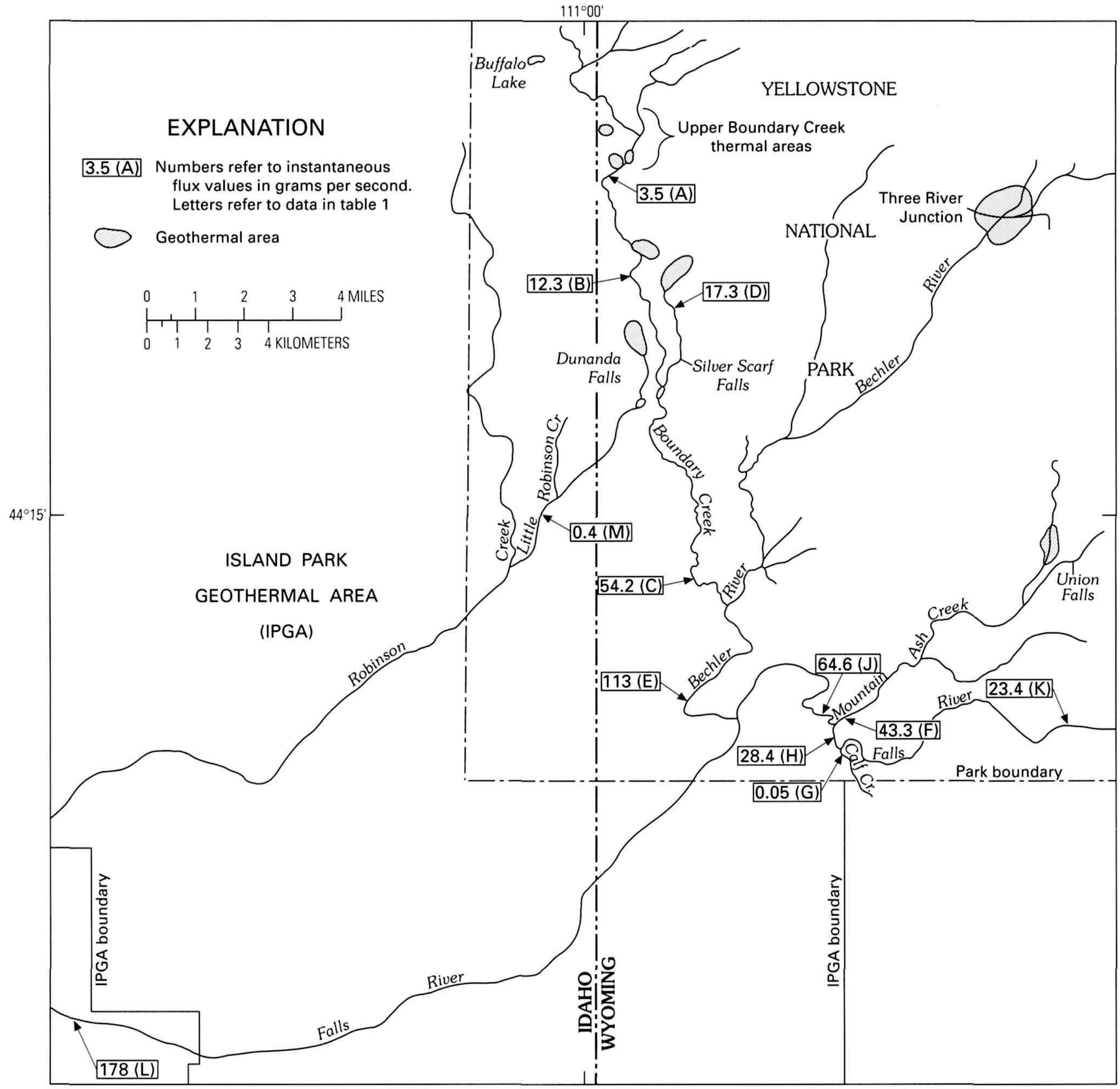

Figure 5. Map showing sites where chloride flux was measured in southwestern Yellowstone National Park and vicinity.

referred to here as Crescent Ridge Creek. This stream flows into Little Robinson Creek, which flows into Robinson Creek. The latter is a tributary of Warm River, which in turn joins the Henrys Fork. Therefore, this thermal area is not in the Boundary Creek-Falls River drainage.

In addition to the small thermal streams described above, three large streams, each of which integrate the discharge of a number of thermal features, were provided with staff gauges (calibrated using velocity meters) for the measurement of discharge. These streams are monitored as follows:

(1) Silver Scarf Creek drains a large thermal area named by Hutchinson (1980) as the Silver Scarf Thermal Area. The staff gauge is located more than 20 meters downstream from the last thermal stream that enters the creek.

(2) Boundary Creek Tributary was described by Jones and others (1979) as unnamed creek No. 1783. Our gauging site is located one-half mile upstream from

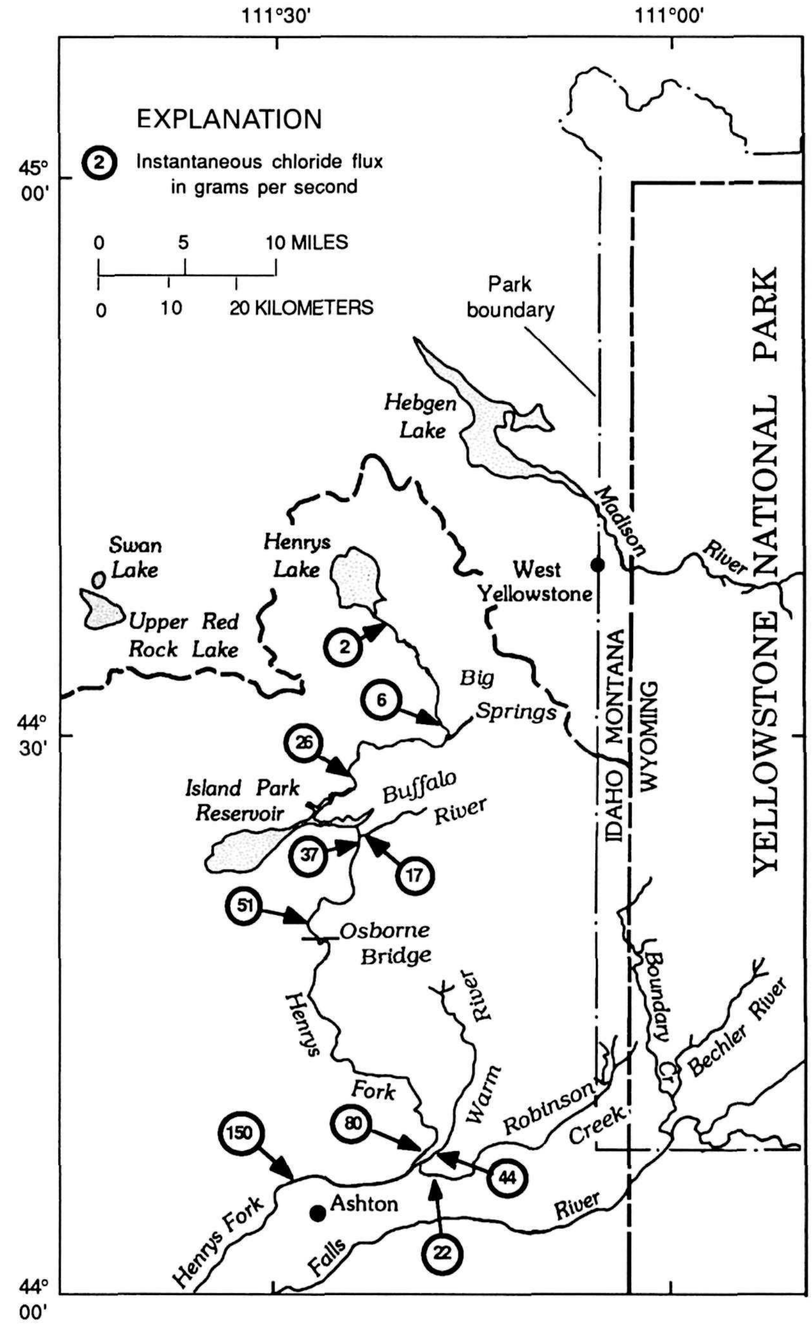

Figure 6. Map of the Henrys Fork drainage in the Island Park Geothermal Area, Idaho, showing instantaneous chloride flux at various springs and streams. Flux values are calculated from chloride and discharge data by Whitehead. (1978).

the junction of the tributary with Boundary Creek and adjacent to the "Boundary Creek Patrol Cabin" site shown on the Warm River Butte 15′ quadrangle map (1957 edition). The patrol cabin no longer exists and the site has been developed as a campground.

(3) Boundary Creek, at a location where it integrates all of the thermal waters originating in the Boundary Creek Thermal Area. The staff gauge is upstream from the area in the Bechler Meadows that is flooded annually by overflow from the Bechler River. It is located about 100 meters south of the upper bridge where the Boundary Creek Trail crosses Boundary Creek.

Table 1. Inventory of discharge, chloride concentration, and chloride flux for streams in southwestern Yellowstone National Park.

[Measurements made September 26–October 3, 1985; ppm, parts per million; cfs, cubic feet per second; g/s, grams per second]

Site	Map reference (fig. 5)	Location	Chloride concentration (ppm)	Stream disch. (cfs)	Chloride flux (g/s)
Boundary Cr.	A	Between Monitor and Mid. Boundary Cr. Th. Areas	4.8	25.8	3.5
Boundary Cr.	B	Between Dunanda Falls and Silver Scarf Creek	12.6	34.5	12.3
Boundary Cr.	C	Near confluence with Bechler River	15.7	122	54.2
Silver Scarf Cr.	D	At gauging site below Silver Scarf Thermal Area	57.1	10.7	17.3
Bechler River	E	Near confluence with Falls River	11.4	351	113
Mt. Ash Cr.	F	Near confluence with Falls River	10.7	143	43.3
Calf Cr.	G	Near confluence with Falls River	0.7	2.50	0.05
Falls River	H	Below confluence with Mountain Ash Creek	6.3	160	28.4
Falls River	J	Above confluence with Mountain Ash Creek	8.3	277	64.6
Falls River	K	Above confluence with Calf Creek	6.0	140	23.4
Falls River	L	At Squirrel, Idaho, gauging site	9.1	693	178
Little Robinson Cr.	M	Near confluence with Robinson Creek	3.3	4.47	0.42

Table 2. Inventory of discharge, chloride concentration, and chloride flux for streams in the Island Park Geothermal Area adjacent to the southwestern boundary of Yellowstone National Park.

[Chloride in parts per million; discharge in cubic feet per second; flux in grams per second; (—), no data]

Site	Property	Oct. 3 1984	Sept. 17 1985	Oct . 8 1986	Oct. 17 1988	Oct. 4 1989	Sept. 14 1990	Oct. 17 1991	Oct. 21 1992
Big Springs	Chloride	2.6	2.4	2.5	3.0	2.6	—	2.7	2.9
	Discharge	214	198	223	11.0	13.4	—	178	174
	Flux	15.8	13.5	15.8	13.4	13.7	—	13.6	14.3
Buffalo River	Chloride	3.8	3.5	2.3	2.9	2.3	—	2.2	2.7
	Discharge	237	235	184	191	215	—	209	181
	Flux	25.5	23.3	12.0	15.7	14.0	—	13.0	13.8
Robinson Creek	Chloride	6.8	6.9	7.7	7.5	7.1	8.1	8.0	7.9
	Discharge	123	108	65	62	80	59.9	63.2	53.8
	Flux	23.7	211	14.2	13.2	16.0	13.7	14.3	12.0
Warm River	Chloride	6.8	5.3	6.0	5.8	5.7	5.7	5.7	5.7
	Discharge	424	283	215	212	252	227	220	196
	Flux	81.6	42.5	36.5	34.8	40.7	35.6	35.5	31.6

Figure 7. Photographs of Weir 4 (top), located in the Middle Boundary Creek Thermal Area, and Weir 8 (bottom) in the Crescent Ridge Thermal Area, Yellowstone National Park.

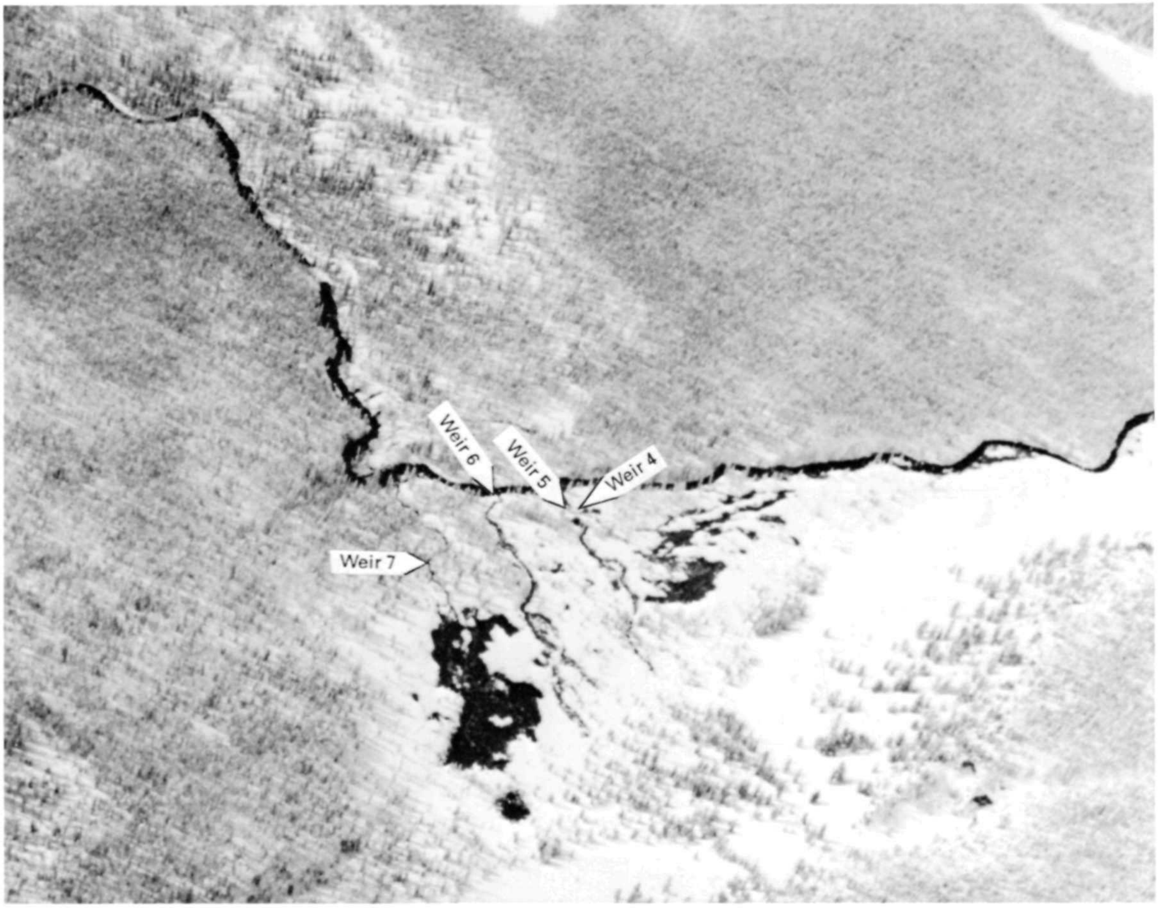

Figure 8. Aerial photograph of the Middle Boundary Creek Thermal Area, Yellowstone National Park, looking east and showing monitoring sites.

CALIBRATION OF WEIRS AND STAFF GAUGES

Calibration of the discharges through weirs is often made using velocity meters. For these small shallow streams with irregular bottoms, the measurements of discharge by stream velocity are considered to be less accurate than those made using standard weirs. Despite this, the results in table 3 show reasonable agreement between measured flows and those derived from the standard rating tables (Larsen, 1976) for weirs.

The discharges of the large streams where staff gauges were located were measured using velocity meters and standard hydrologic methods. When sufficient data have been accumulated, rating tables for these gauging sites will be prepared.

RESULTS

The results of the discharge measurements, the chloride concentrations, and the calculated chloride flux are given in table 4 and plotted in figures 9–12. For monitoring purposes, we have chosen to consider only the flux measurements made during the winter at presumed base flow. However, for future reference we also listed data from measurements made at other times of the year.

Data for the Monitor Creek weirs are plotted in figure 9. The stream at Weir 1 showed a fairly constant chloride concentration but a variable flow rate that actually dropped to zero during February and March of 1989, 1992, and 1993. The discharge and chloride content of Weir 2 fluctuated greatly for reasons that are not apparent. The results for Weir 3 resembled those for Weir 1.

Figure 10 contains similar plots of the data for Weirs 4–7 located in the Middle Boundary Creek Thermal Area. In general, the results show a decrease in discharge and chloride flux at all sites from late 1983 to March 1993, with the major portion of the decline occurring after 1986.

The results for Weir 8, located in the Crescent Ridge Thermal Area (fig. 2), are plotted in figure 11. The stream was not flowing in March, 1993. These results also display the large changes seen in the other thermal areas.

Table 3. Calibration data comparing discharges measured in weirs using velocity meters and discharges from standard weir rating tables.

[Calibrations made by four different individuals from September 1987 to March 1991. T, values from standard weir rating tables of water height versus discharge (Larson, 1976); M, values calculated using velocity meters; cfs, cubic feet per second; ND, no discharge; (—), no data; (--), not applicable]

Thermal area	Weir			Discharge (cfs)											
	No.	Type	Width	Sept. 9, 1987		Feb. 17, 1988		Feb. 25, 1989		Mar. 25, 1991		Mar. 12, 1992		Mar. 12, 1993	
			(ft)	T	M	T	M	T	M	T	M	T	M	T	M
Monitor	1	Cipoletti	0.75	0.15	0.16	0.028	0.035	ND	ND	ND	ND	ND	ND	ND	ND
Creek	2	90° V-Notch	--	0.002	0.002	ND	ND	0.026	0.02	0.023	0.026	0.081	0.037	0.031	0.013
	3	90° V-Notch	--	0.05	0.08	ND	ND	ND	ND	ND	ND	0.006	0.007	ND	ND
Middle	4	Cipoletti	1.0	0.26	0.33	0.26	0.18	0.23	0.17	0.25	0.28	0.25	0.33	0.25	0.32
Boundary	5	90° V-Notch	--	—	—	0.13	0.14	0.14	0.11	0.14	0.09	0.081	0.082	0.07	0.13
	6	Cipoletti	1.0	0.23	0.24	0.23	—	0.18	0.17	0.16	0.25	0.23	0.25	0.18	0.17
	7	Cipoletti	1.0	0.38	0.32	0.23	—	0.20	0.20	0.32	0.46	0.22	0.27	0.16	0.27
Crescent Ridge	8	Cipoletti	2.0	0.36	0.37	—	—	—	—	—	—	0.10	0.15	ND	ND

The data for the three large streams in the Boundary Creek drainage are plotted in figure 12. Boundary Creek and Silver Scarf Creek show large decreases in discharge and chloride flux after 1986. The monitoring of Boundary Creek Tributary started in February 1987, with no earlier data available for comparison.

The large decreases in discharge observed in both the small and large thermal streams can be attributed to a lowering of the water table resulting from several years of exceptionally low precipitation. The reductions in discharge of the springs parallel the observed changes in discharge of the major rivers draining the Park (Falls, Madison, Snake, and Yellowstone Rivers), which also show large decreases in 1987 and 1988 followed by a small increase in 1989 (Norton and Friedman, 1991).

A plot of the water-equivalent of the snow pack collected on April 1 (the date of maximum snow pack) from six sites in the southwestern area of the Park (locations shown in figure 13) for 1980–92 is shown in figure 14. The changes in discharge of the monitored thermal springs and rivers draining these features (table 4) tend to follow the changes in the water content of the winter snow, which is the major source of recharge of the aquifers in this region. A plot of the total precipitation received at Snake River (south entrance of the Park) and Yellowstone Lake during the same period is shown in figure 15. This diagram also shows a good correlation between thermal-spring discharge and precipitation. The decrease in precipitation during 1987 and 1988 is mirrored by the decrease in spring discharge during these two years. Weirs 1, 2, and 7 also show an increase in flow in 1989 and 1990 that correlates with increased precipitation and snow fall in 1988–89 and 1989–90 recorded at Snake River and Yellowstone Lake.

The chloride concentration of the monitored springs is relatively constant through time, although their discharge varies both seasonally and over longer time periods. As a result, the chloride flux from these springs increases during periods of increased discharge. Friedman and Norton (1990) concluded that these changes were caused by changes in the height of the local water table, which affected the discharge of the springs but not their chloride concentration. These large variations in flow and chloride flux during this five-year period demonstrate the need for long-term monitoring to secure meaningful baseline data and to relate changes in hot-spring activity to other natural phenomena.

CONCLUSIONS

Based on the experience gained and on the data accumulated in this part of the study, the following conclusions are drawn:

(1) Continuous instrumental measurement of thermal flux from features in the southwestern portion of Yellowstone National Park is impractical because of the remoteness of the area and the necessity of visiting the

Table 4. Stream discharge, chloride concentration, and chloride flux data from monitoring sites in southwestern Yellowstone National Park.

[Chloride in parts per million; discharge in cubic feet per second; flux in grams per second; (—), no data; base-flow (winter) measurements in **bold** type]

Site	Property	1983 Nov. 9	**1984 Jan. 31**	1986 Sept. 7	**1987 Feb. 5**	1987 Aug. 24	1987 Sept. 9	1987 Sept. 25	**1988 Feb. 10**	**1989 Feb. 1**	**1990 Mar. 15**	1990 June 23	1990 Sept. 26	**1991 Mar. 28**	1991 June 20	1991 Sept. 11	**1992 Mar. 12**	**1993 Mar. 12**
Weir 1	Chloride	1.5	1.7	0.9	1.3	—	1.1	—	2.6	—	2.3	1.7	1.9	2.0	1.8	1.0	—	—
	Discharge	0.52	0.33	0.4	0.21	0.18	0.15	0.13	0.06	no flow	0.052	0.47	0.18	0.028	0.486	0.15	no flow	no flow
	Flux	0.022	0.016	0.010	0.0077	—	0.00047	—	0.0044	—	0.0033	0.022	0.010	0.0016	0.025	0.0041	—	—
Weir 2	Chloride	26.0	4.0	24.7	1.4	—	0.2	—	0.3	0.3	1.3	32.5	1.6	1.3	8.3	1.0	0.3	0.50
	Discharge	0.093	0.030	0.055	0.030	0.005	0.002	0.001	0.04	0.026	0.026	0.008	0.005	0.023	0.009	0.029	0.016	0.013
	Flux	0.069	0.0034	0.038	0.0012	—	0.000001	—	0.0004	0.0002	0.0009	0.0074	0.0002	0.0008	0.0021	0.0082	0.00014	0.0002
Weir 3	Chloride	5.9	7.6	6.5	9.7	—	12.7	—	16.6	—	9.3	13.9	14.2	3.3	15.6	15.4	3.2	—
	Discharge	0.093	0.138	0.11	0.075	0.054	0.049	0.045	0.04	no flow	0.005	0.038	0.023	0.001	0.051	0.062	0.006	no flow
	Flux	0.016	0.030	0.020	0.021	—	0.018	—	0.019	—	0.0013	0.015	0.0092	0.0001	0.023	0.027	0.0005	—
Weir 4	Chloride	63.7	65.5	64.2	66.7	—	71.3	—	65.6	68.9	63.0	63.1	68.5	62.9	45.0	71.9	69.9	71.0
	Discharge	0.37	0.35	0.33	0.34	0.28	0.26	0.27	0.26	0.23	0.26	0.25	0.27	0.25	0.26	0.25	0.25	0.25
	Flux	0.67	0.65	0.60	0.64	—	0.53	—	0.48	0.45	0.46	0.45	0.52	0.45	0.33	0.51	0.49	0.50
Weir 5	Chloride	57.2	58.7	59.9	—	—	67.1	—	58.3	58.3	55.4	1.0	—	55.3	46.6	69.6	60.5	63.6
	Discharge	0.24	0.25	0.22	—	—	0.11	—	0.13	0.14	0.14	4.52	—	0.14	0.17	0.057	0.15	0.13
	Flux	0.39	0.42	0.37	—	—	0.21	—	0.22	0.23	0.22	0.13	—	0.22	0.22	0.11	0.26	0.23
Weir 6	Chloride	64.3	65.9	68.8	68.3	—	73.3	—	63.7	62.8	60.8	44.9	65.9	60.4	62.4	71.1	64.6	65.6
	Discharge	0.53	0.84	0.34	0.35	0.18	0.23	0.23	0.23	0.18	0.20	0.34	0.21	0.16	0.25	0.20	0.24	0.18
	Flux	0.97	1.57	0.66	0.68	—	0.48	—	0.42	0.32	0.35	0.43	0.39	0.27	0.44	0.41	0.44	0.33
Weir 7	Chloride	75.0	76.9	80.0	78.5	—	86.6	—	77.9	76.7	72.2	70.7	76.3	69.6	66.6	82.6	78.1	78.1
	Discharge	0.83	0.61	0.56	0.58	0.40	0.38	0.36	0.23	0.20	0.30	0.40	0.32	0.32	0.34	0.26	0.22	0.16
	Flux	1.76	1.33	1.27	1.29	—	0.93	—	0.51	0.43	0.61	0.80	0.69	0.63	0.63	0.62	0.49	0.35
Weir 8	Chloride	—	4.8	4.1	3.5	—	5.0	—	—	3.9	4.9	5.0	5.6	4.5	5.1	—	3.6	—
	Discharge	—	0.97	2.0	0.50	—	0.36	—	—	0.096	0.10	1.72	0.72	0.057	1.14	—	0.10	no flow
	Flux	—	0.13	0.23	0.050	—	0.051	—	—	0.011	0.014	0.24	0.12	0.007	0.16	—	0.010	—
Silver Scarf Creek	Chloride	—	66.7	56.7	72.5	—	83.6	—	83.4	87.4	76.4	69.4	74.8	78.7	73.1	84.2	86.2	90.8
	Discharge	—	9.35	8.60	8.67	6.80	5.54	5.54	4.81	4.64	5.22	7.20	—	5.51	—	4.82	4.80	4.07
	Flux	—	17.7	13.8	17.8	—	13.1	—	11.4	11.5	11.3	14.1	—	12.3	—	13.9	11.7	10.5
Boundary Creek	Chloride	—	16.9	17.1	22.6	—	19.7	—	19.5	19.5	19.9	11.4	—	19.2	—	18.9	18.9	22.2
	Discharge	—	83.3	93.6	78.6	—	65.7	—	50.9	57.7	60.5	98.3	—	57.2	—	71.1	60.4	47.4
	Flux	—	39.9	45.3	50.3	—	36.7	—	28.7	31.9	34.1	31.8	—	31.0	—	38.1	32.3	29.8
Boundary Creek Tributary	Chloride	—	—	—	6.5	—	6.0	—	6.3	6.2	6.4	6.1	—	6.7	—	5.6	5.9	7.2
	Discharge	—	—	—	31.6	—	32.0	—	29.6	32.8	36.1	33.3	—	35.5	—	34.3	31.2	27.8
	Flux	—	—	—	5.83	—	5.42	—	5.28	5.71	6.53	5.75	—	6.78	—	5.44	5.21	5.67

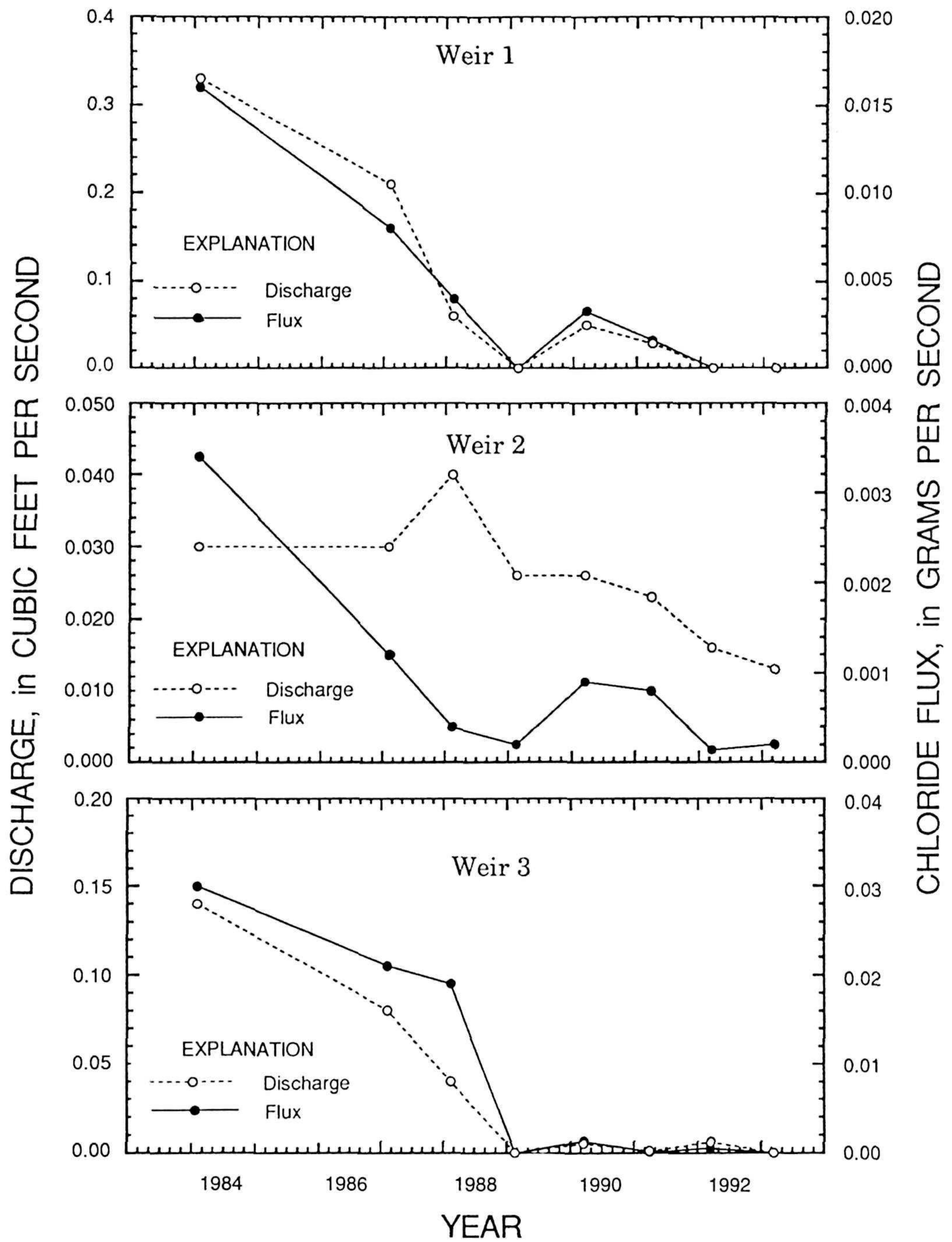

Figure 9. Plots of discharge and chloride flux at presumed base-flow conditions for weirs located in the Monitor Creek Thermal Area, Yellowstone National Park.

sites frequently to service the equipment. These visits would be prohibitively expensive because access for eight months of the year is limited to helicopter flights, and the nearest available helicopter service is in Jackson, Wyo., a distance of 75 miles from the study area.

(2) A practical protocol for monitoring thermal flux in this region of the Park is the measurement, once a year, of the instantaneous chloride flux from a number of surface thermal features during base flow. The installation of weirs on most of the thermal streams in the Boundary Creek area has made it possible to collect the necessary data during the winter by a one-day helicopter trip.

(3) The observed reductions in both discharge and chloride flux at the monitoring stations were as great as 90 percent during the 1986–92 period. These large

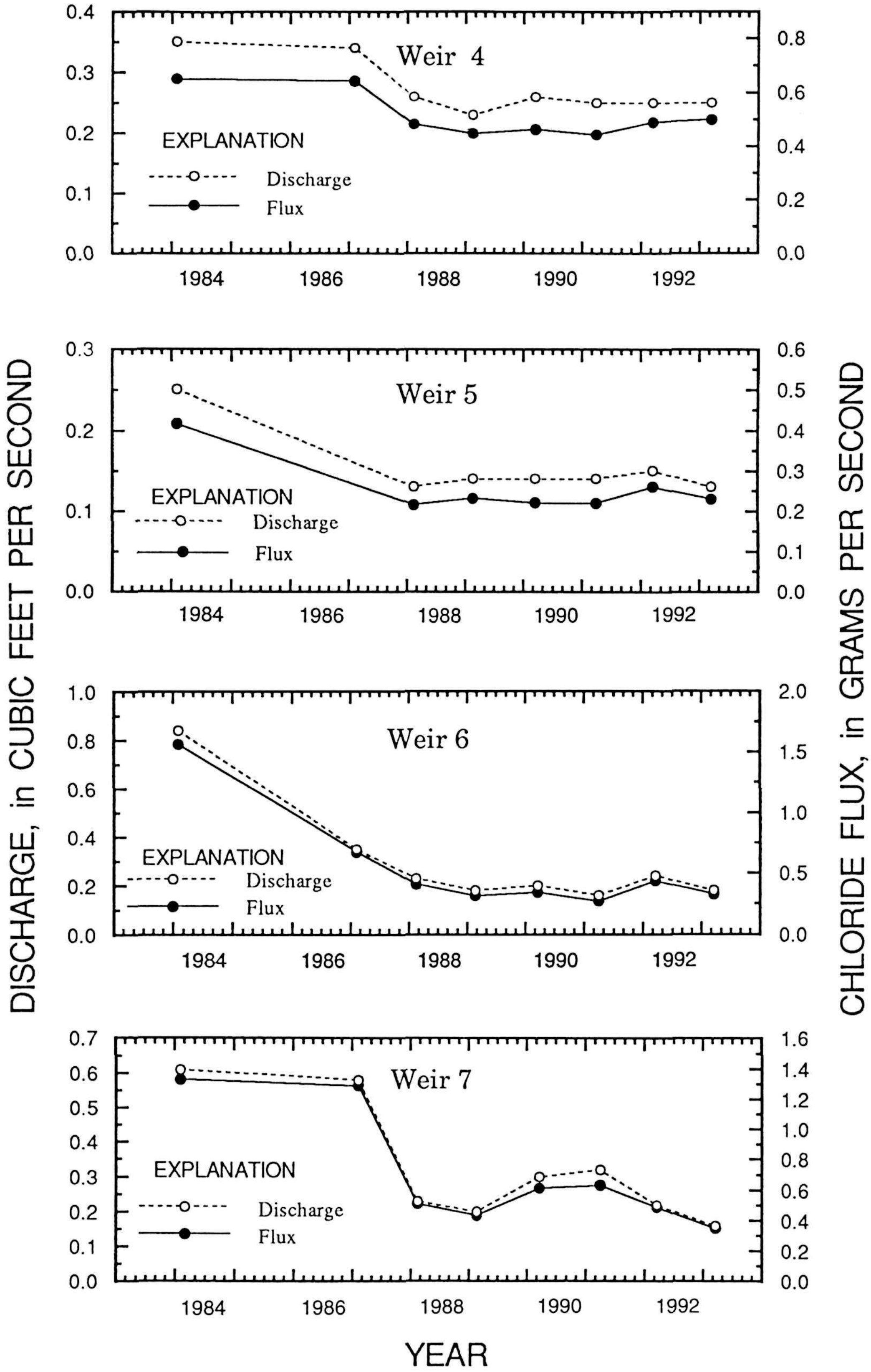

Figure 10. Plots of discharge and chloride flux at presumed base-flow conditions for weirs located in the Middle Boundary Creek Thermal Area, Yellowstone National Park.

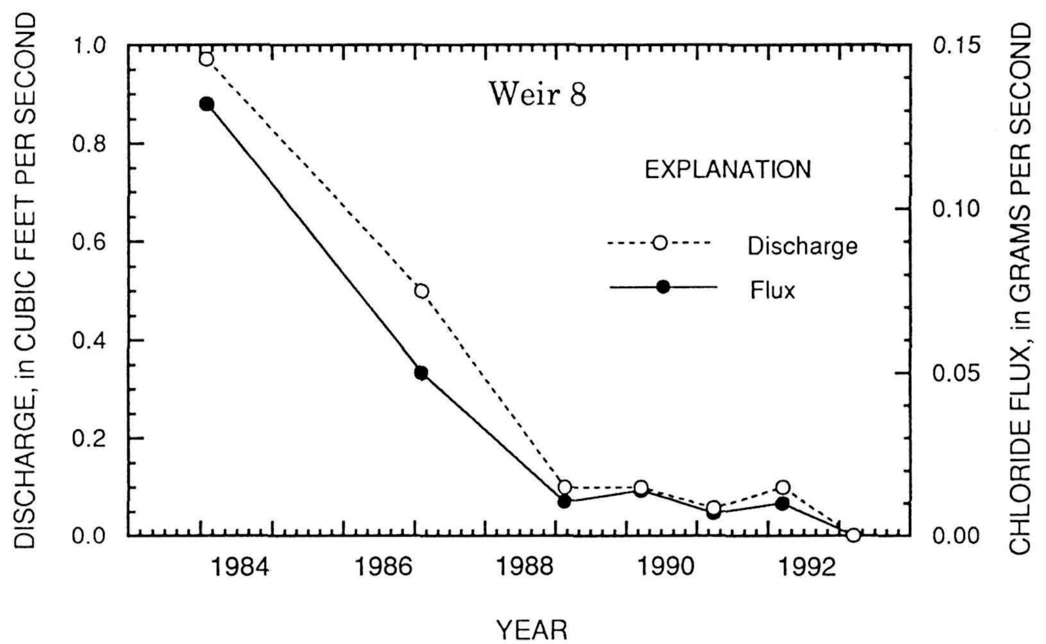

Figure 11. Plot of discharge and chloride flux at presumed base-flow conditions for Weir 8, located in the Crescent Ridge Thermal Area, Yellowstone National Park.

changes demonstrate the necessity for long-term monitoring to establish a baseline for assessing possible future effects of development west of the Park boundary, which includes extraction of gas and oil as well as geothermal water and steam.

(4) The discharge of the systems that we monitored appears to respond to the availability of meteoric water. A surprising discovery is the direct relationship between discharge of the thermal systems and chloride flux. Whether this relationship is the result of chloride storage during low-flow regimes and release of stored chloride during periods of high discharge, or whether it is the result of the direct influence of water-table height on the hydrothermal system, has been a subject of controversy. Our evidence, based on studies of hot springs where storage cannot have occurred, substantiates the latter explanation.

MEASUREMENT OF THERMALLY DERIVED CHLORIDE IN THE ISLAND PARK GEOTHERMAL AREA, IDAHO

Monitoring of thermal waters exiting the Park into the IPGA west of the Park should provide early warning of the adverse effects of development in this area of geothermal, gas, and oil resources. From an examination of published hydrologic records, Norton and Friedman (1985) concluded that about 5 percent of thermal water exiting the Park emerges in the IPGA, adjacent to the west boundary of the Park, as surface and subsurface flow. This water ultimately flows into the Henrys Fork.

Taking the December 5, 1974, data from Whitehead (1978) for discharge and chloride concentration at selected sites, we calculated instantaneous chloride flux for the sites along, and tributary to, the Henrys Fork. These values are shown in figure 6. About 70 percent of the chloride flux exiting the IPGA at Ashton, Idaho, is accounted for by the sum of the chloride flux from Big Springs, Buffalo River, Warm River, and Robinson Creek. Another 20 percent is from subsurface inflow to the Henrys Fork between Osborne Bridge and Warm River. About 3 percent is from inflow between Henrys Lake and Big Springs, and most of the remaining 7 percent is from the Island Park Reservoir.

Our data for 1984–92, shown in table 2 and plotted in figure 16, depicts discharge and chloride flux in Big Springs, Buffalo River, Warm River, and Robinson Creek. All of the streams suffered a decline in discharge and chloride flux with time. The change in the chloride flux in Big Springs is significantly less than the changes in the other three streams. The discharge of Big Springs, Robinson Creek, and Warm River also decreased after the 1985–86 period. These changes follow similar trends in the data from the major rivers draining the Park, as reported in Norton and Friedman (1991). Similar trends appear in the data that we report for the thermal streams inside the southwestern portion of the Park.

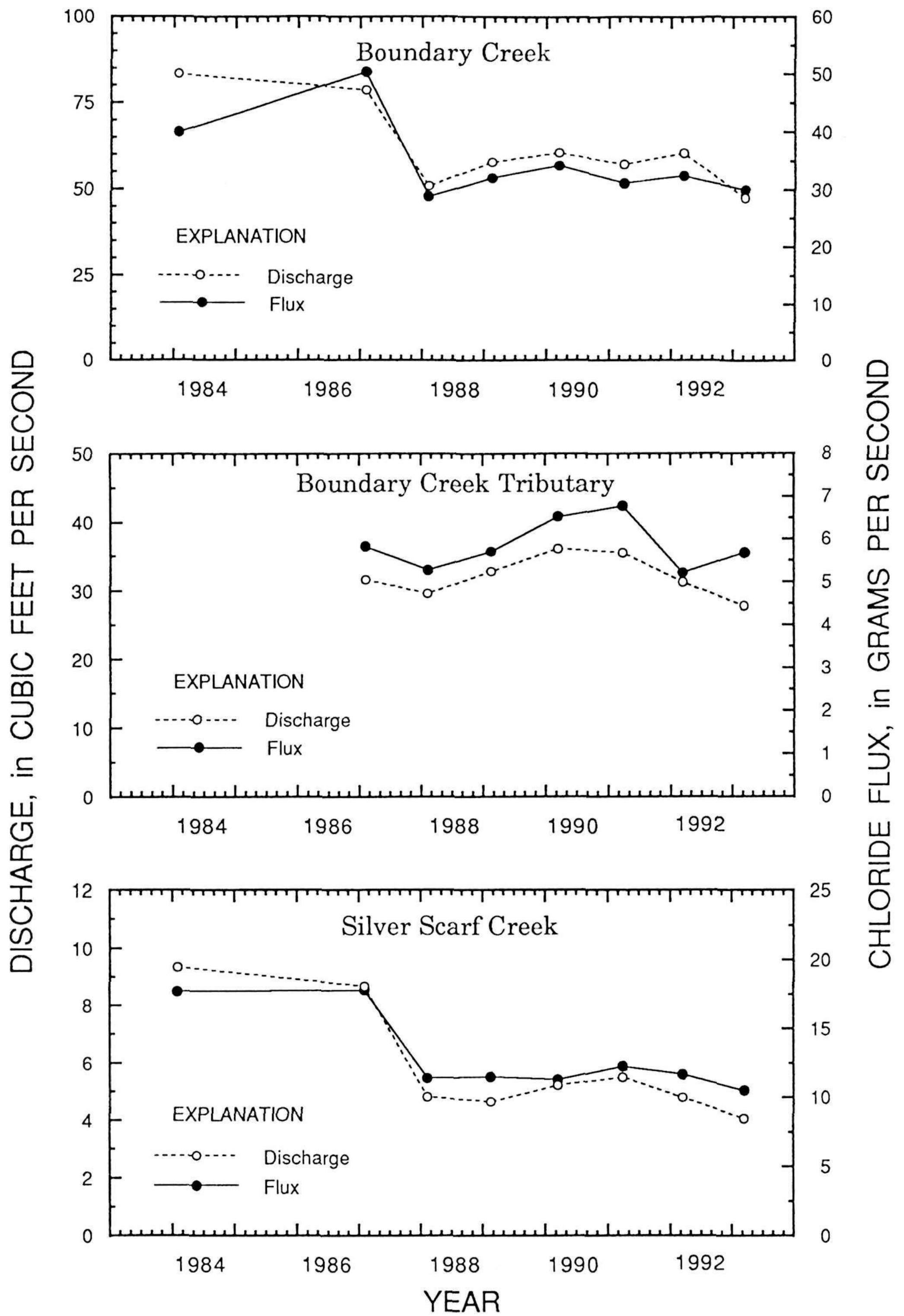

Figure 12. Plots of discharge and chloride flux at presumed base-flow conditions measured at staff gauges on major streams in the Boundary Creek drainage, Yellowstone National Park.

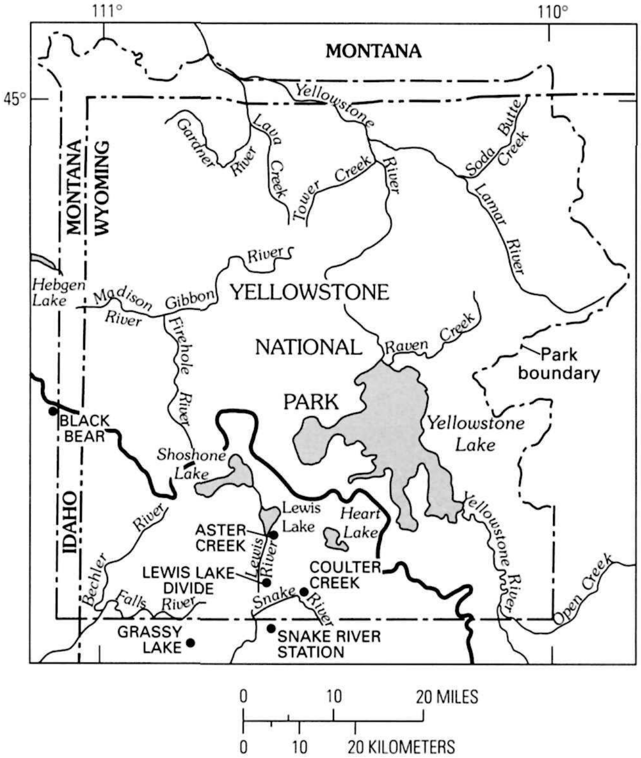

Figure 13. Locations of U.S. Department of Agriculture Soil Conservation Service snow courses in southwestern Yellowstone National Park and vicinity. Dark line denotes the Continental Divide.

CONCLUSIONS

The large variations in chloride flux shown in these data support the conclusion that long-term monitoring is necessary along the Henrys Fork and its tributaries. The large thermal-water input to the Henrys Fork between Osborne Bridge and the confluence with Warm River can be monitored by taking the difference between measurements made at these two sites. We propose that a special effort be made to monitor chloride flux at the following locations during winter base flow:

1. Henrys Fork at Macks Inn, above the confluence with Big Springs.
2. Big Springs at Big Springs, or before the confluence of Big Springs with the Henrys Fork.
3. Henrys Fork at the entrance to the Island Park reservoir.
4. Henrys Fork at the exit of the Island Park reservoir.
5. Buffalo River at the confluence with the Henrys Fork.
6. Henrys Fork at Osborne Bridge.
7. Henrys Fork above the confluence with Warm River.
8. Warm River at the confluence with the Henrys Fork.
9. Robinson Creek at the confluence with Warm River.

Inasmuch as 90 percent of the chloride flux can be accounted for by monitoring locations 2 and 5–9, we suggest that priority be placed on these. For a complete evaluation of chloride input and output to the Henrys Fork river basin, the remaining three locations should be added.

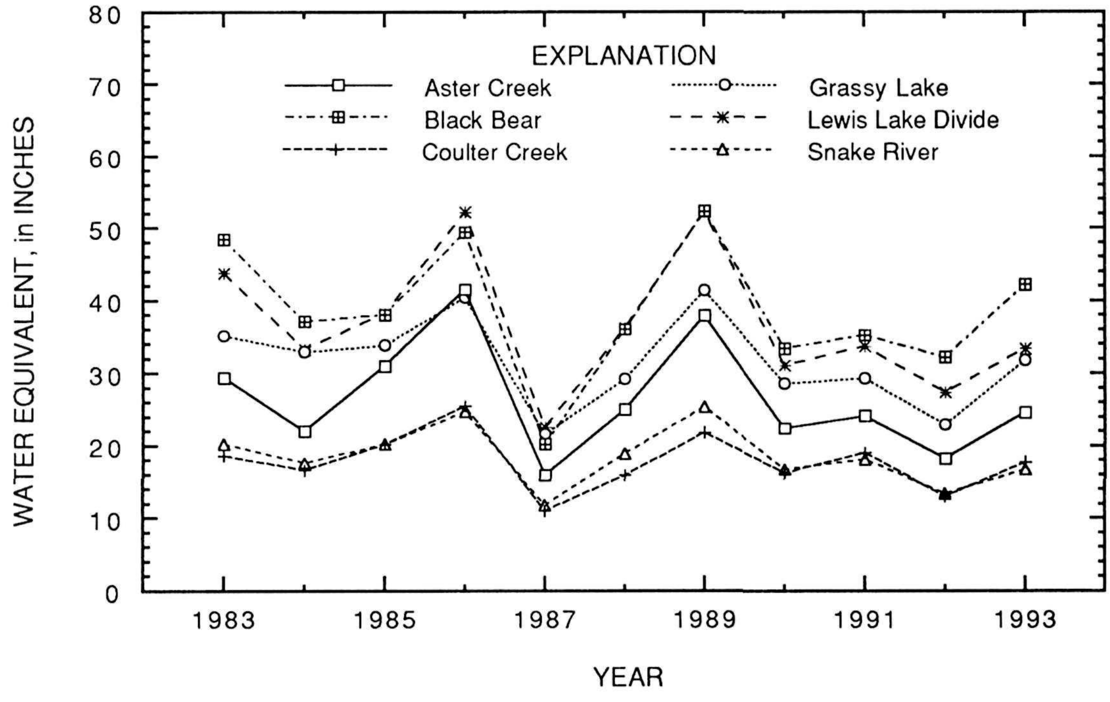

Figure 14. Plots of water equivalent of snow cores from six snow courses in southwestern Yellowstone National Park and vicinity (sites shown in fig. 13). The cores were collected each April 1, during maximum snowpack. Data from the Centralized Database System of the Soil Conservation Service, West National Technical Center, Portland, Ore.

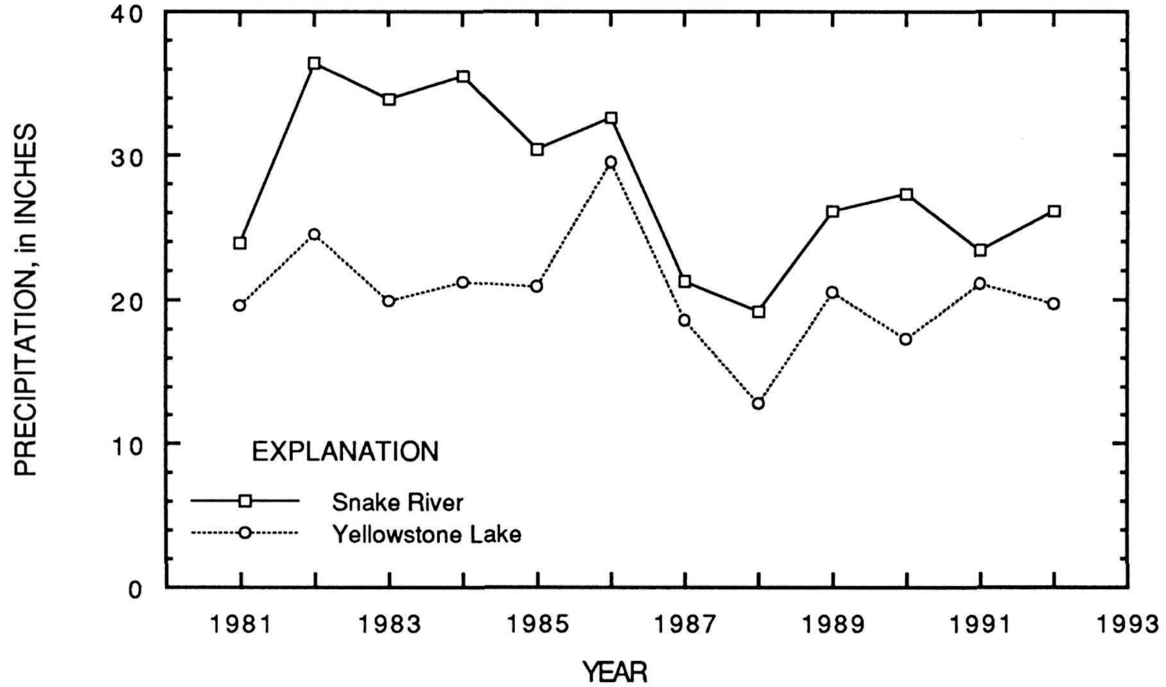

Figure 15. Plots of total yearly precipitation at two collection sites in Yellowstone National Park. Data from the National Oceanic and Atmospheric Administration's National Environmental Satellite, Data, and Information Service, National Climatic Data Center, Asheville, N.C.

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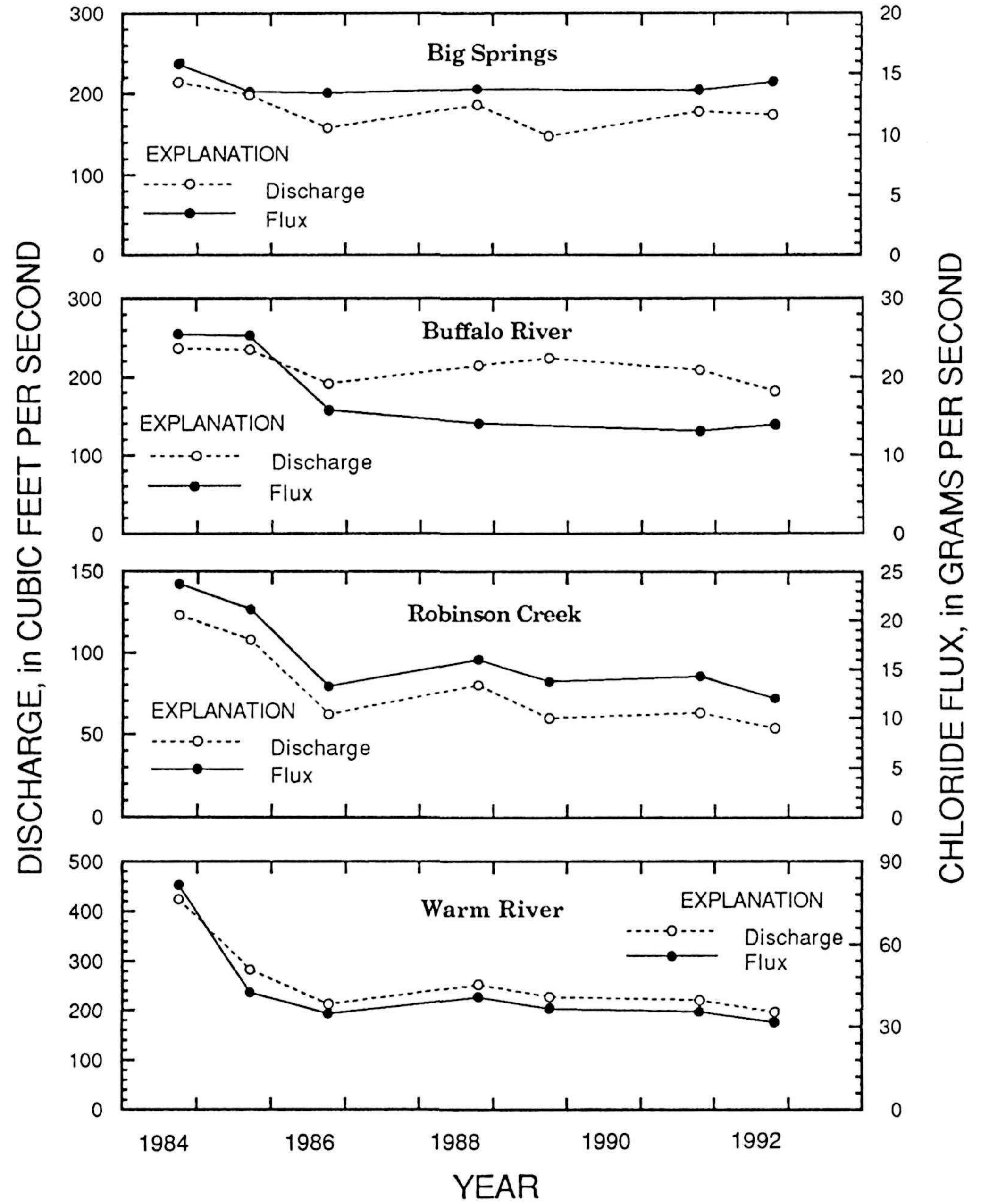

Figure 16. Plots showing discharge and instantaneous chloride flux at four sites in the Henrys Fork drainage, Island Park Geothermal Area, Idaho.

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