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Effects of Geothermal Effluents on Rainbow Trout and Brown Trout in the Firehole River, Yellowstone National Park, Wyoming

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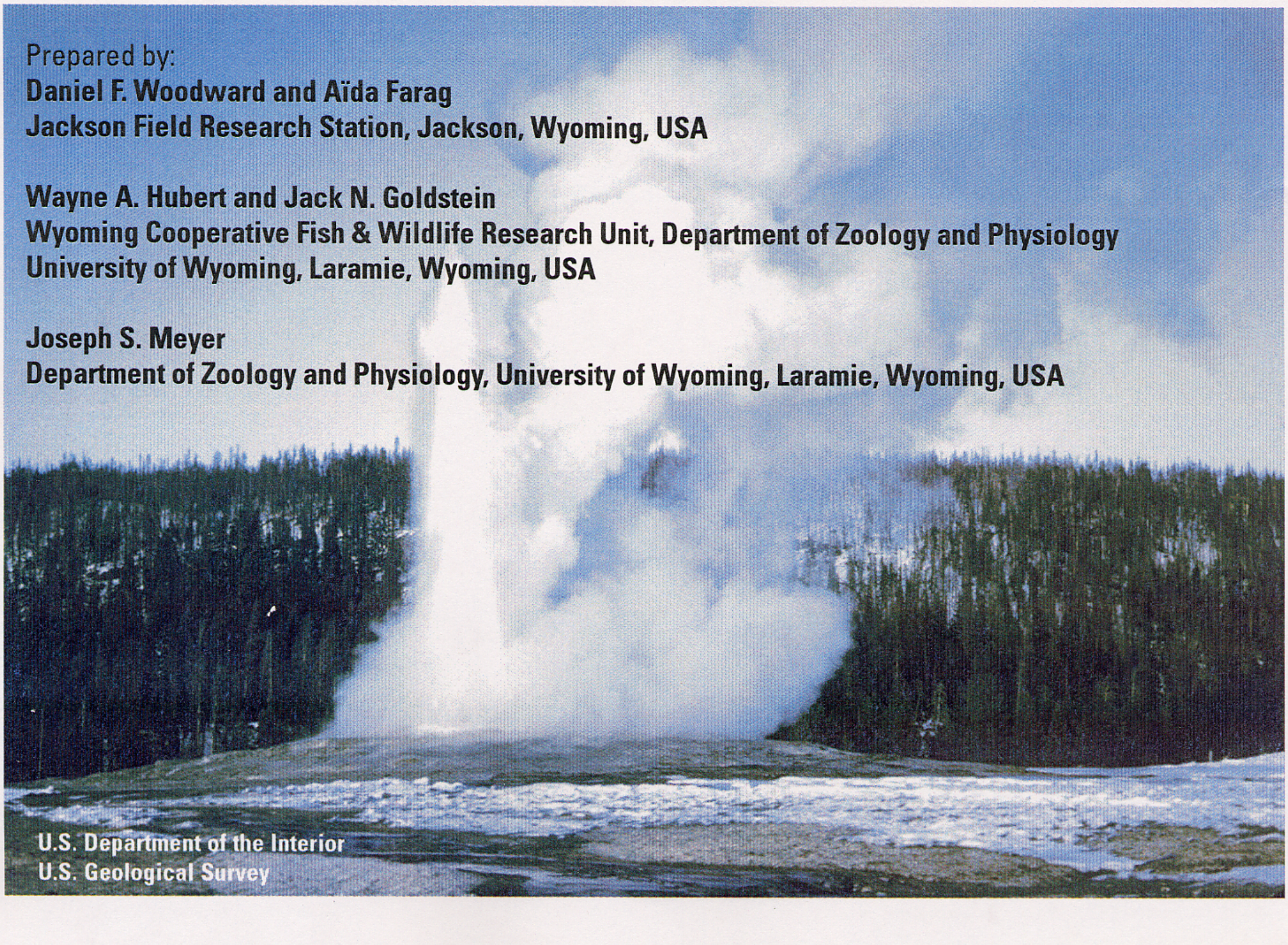

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Abstract

The effects of geothermal effluents on the distribution of rainbow trout Oncorhynchus mykiss and brown trout Salmo trutta in the Firehole River and its tributaries in Yellowstone National Park were studied from June 1997 to June 1998. The geothermal features of the Firehole River basin elevate temperature and mineral content of the river and its tributaries. Temperatures in geothermally influenced waters ranged up to 30°C and were consistently 5-10°C higher than upstream sites unaffected by geothermal effluents. Concentrations of potentially harmful elements (boron and arsenic) were elevated in geothermally influenced areas as compared to upstream sites. Boron concentrations approached the proposed limit for protection of aquatic organisms. Assessments of spatial patterns of species densities and spawning indicated that brown trout distributions were limited by the elevated temperatures but rainbow trout were not affected. However, it is also possible that brown trout were more sensitive to boron or arsenic than were rainbow trout. There is a need for further research to determine species-specific tolerances to elevated temperatures, boron, and arsenic to assess the effects on salmonids.

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Introduction

The Firehole River provides a unique opportunity to investigate the combined effects of elevated temperature and chemical contaminants on trout in a natural ecosystem. Past studies of the trout populations in the Firehole River have focused on the effects of temperature on their biology and distribution. Elevated water temperatures seem to influence the migration and reproduction of trout in the Firehole River (Kaya 1977; Kaeding and Kaya 1978; Kaeding 1996). Summer temperatures, up to 30°C in the warmest reaches of the Firehole River (Kaya 1977; Kaeding 1996), exceed lethal limits for trout (Jobling 1981). Despite these conditions, rainbow trout Oncorhynchus mykiss and brown trout Salmo trutta populations in the Firehole River sustain angling pressure (Jones et al. 1992). Previous studies have found no genetic or physiological adaptations of the rainbow trout population to these unique conditions (Cameron et al. 1978; Fisher et al. 1982; Kaya 1978); however, behavioral adaptations are suspected. Rainbow trout and brown trout have been observed to migrate into cooler tributaries and refugia during the summer months (Koch 1990; Kaeding 1996). Additionally, rainbow trout have been observed to spawn during the late fall instead of the normal spring period (Kaya 1977). However, elevated mineral concentrations from the geothermal effluents may also influence trout but their effects have not been assessed.

Concentrations of geothermal chemicals increase with progression downstream in the Firehole River, concurrent with temperature. Between Kepler Cascades and the Madison River (Figure 1), concentrations of boron in the mainstem of the Firehole River were reported to increase by a factor of seven times (Meyer et al. 1998). Boron concentrations up to 1 mg/L have been observed in this reach (Meyer et al. 1998), the concentration proposed as the maximum acceptable concentration of boron in surface water for the protection of aquatic organisms (UCCC 1988; Black et al. 1993). No past studies have evaluated the effects of boron, arsenic, or other contaminants on the biology and distribution of trout in the Firehole River.

Sympatric populations of rainbow trout and brown trout occur in many lakes and rivers throughout North America, South America, Europe, Australia, and New Zealand (MacCrimmon and Marshall 1968; MacCrimmon 1971; Hayes 1987). These trout species are treated similarly in ecological contexts and management (Binns and Eiserman 1979; Wesche and Rechard 1980; Kocik and Taylor 1996). They have analogous life histories that include similar foraging preferences (Elliot 1973; Kaeding and Kaya 1978), spawning requirements (Hayes 1987), and habitat preferences (Jenkins 1969; Shirvell and Dungey 1983; Fausch 1984). Sympatric populations have been found where one species is numerically dominant (Hayes 1987); however, few studies have explained or been able to predict these occurrences (Hearn 1987). The Firehole River provides a unique setting to study the effects of altered temperature and water quality on the spatial distributions of sympatric rainbow trout and brown trout populations.

The purpose of this study was to define how geothermal effluents affect the spatial and temporal variation in water quality and the distributions of rainbow trout and brown trout in the Firehole River drainage. The Firehole River has been used as a model for assessing the long-term ecological effects of thermal pollution (Zeikus and Brock 1972; Kaeding 1996); however, the results from this study can contribute to understanding how the combination of elevated temperatures and mineral concentrations affect freshwater fisheries.

The specific objectives of this project were to: (1) describe spatial and temporal variability in water chemistry in the mainstem and tributaries of the Firehole River over a 1-

year period, (2) describe rainbow trout and brown trout densities by life stages in the mainstem and tributaries of the Firehole River during the spring, summer, and fall, (3) describe rainbow trout and brown trout spawning locations in the mainstem and tributaries of the Firehole River from October through January, and (4) determine the influence of water temperature and water quality on rainbow trout and brown trout densities and spawning locations in the mainstem and tributaries of the Firehole River.

Study Area

The Firehole River is completely within the boundaries of Yellowstone National Park (Wyoming, U.S.A.) and joins with the Gibbon River to form the Madison River, becoming one of the headwater rivers of the Missouri River drainage (Figure 1). The Firehole River ranges from 2,070 to 2,500 m in elevation, is 44 km long, has an average channel slope of 1.1%, and drains 720 km^2 (Druse et al. 1993). Mean discharge is 8 m^3/s, with peak runoff as high as 21 m^3/s during May and June (USGS records for 1983-1993; Druse et al. 1993). Lodgepole pine Pinus contorta, grasses, and sedges Carex spp. predominate the vegetation of the Firehole River drainage (Jones et al. 1992).

Although the Firehole River is a cold-water stream in its upper segment, geothermal additions from three major geyser basins increase water temperature and mineral content in the river. The geology of the drainage is dominated by rhyolite bedrock (Meyer 1988; Jones et al. 1992). Geothermal waters that enter the Firehole River are chemically enriched by leachate from this bedrock and magmatic gases (Allen and Day 1935; Boylen and Brock 1973; Thompson 1979). These geothermal effluents can constitute up to 40% of the total Firehole River discharge during periods outside of spring run-off (Allen and Day 1935). On an annual basis, the geothermal effluents increase temperature in the warmer sections of the

Firehole River by 11°C above normal and cause increases in the mineral content of the water (Argyle 1966; Wright and Horrall 1967; Thompson et al. 1975; Burkhalter 1979). Elevated chemicals include arsenic, boron, and fluoride (Thompson 1979; Meyer et al. 1998). Increases in primary productivity and benthic invertebrate biomass are associated with the progressive downstream increase in temperature and mineralization (Armitage 1958; Armitage 1961; Wright and Mills 1967; Boylen and Brock 1973).

Trout in the Firehole River are isolated from other species and populations downstream in the Madison River drainage. The Firehole River has four natural barriers that prevent upstream migration of fish (Jones et. al 1992): (1) an unnamed cascade near the headwaters, (2) Kepler Cascades, (3) Firehole Cascades, and (4) Firehole Falls (Figure 1). Kepler Cascades, and the combination of Firehole Cascades and Firehole Falls divide the fishery into three major segments: Upper (15 km), Middle (28 km), and Lower (1.5 km).

The Firehole River was reported to be fishless before trout populations were established by stocking beginning in 1889 (Fromm 1941; Benson et al. 1959). The river was stocked with rainbow trout, brook trout Salvelinus fontinalis, brown trout and cutthroat trout O. clarki (Varley 1981). No fish occur upstream of the unnamed cascade. Brown trout and brook trout are the only species that occur in the Upper Segment between the unnamed cascade and Kepler Cascades, and they are also found throughout the Firehole River drainage (Table 1). Cutthroat trout are found in the Middle Segment, but only in tributaries above barriers to upstream fish movement. Rainbow trout are only found in the Middle and Lower segments. Stocking ceased in 1955 but trout populations in the Firehole River became self-sustaining and the river has become a renowned wild rainbow trout and brown trout fishery (Kaya and Kaeding 1979; Jones et al. 1992).

Methods

Study Sites

Eight study sites were established in the Middle Segment of the Firehole River, between Kepler Cascades and Firehole Falls, three sites were on the mainstem and five sites were on tributaries (Figure 1). The three mainstem sites represented a gradient of the influence of geothermal effluents on water quality. These mainstem sites were identified: Cold, Warm, Hot. The tributary sites were: Iron Springs Creek, Little Firehole River, Fairy Creek, Sentinel Creek, and Nez Perce Creek. The Little Firehole River and Sentinel Creek sites were selected because previous studies suggested that fish used these tributaries as refugia from elevated temperatures during summer (Koch 1990; Kaeding 1996). The other three tributaries were selected because of their potential use by fish from the Firehole River. All other tributaries to the Firehole River in this segment were surveyed and had physical barriers that appeared to prevent their use by trout from the mainstem of the river.

The Cold Site was the most upstream site below Kepler Cascades and was upstream of most geothermal inputs in the Firehole River basin. The Warm Site received moderate geothermal influence from the Upper Geyser Basin and was downstream from the mouth of the Little Firehole River, between Biscuit Basin and the Midway Geyser Basin. The Hot Site was between the mouths of Sentinel and Nez Perce creeks and had the greatest amount of geothermal influence. Almost all data on the fishery and water quality in the Firehole River had been collected at or near these mainstem sites (Benson et al. 1959; Kaya 1978; Koch 1990; Jones et al. 1992). Fairy Creek, although small, had abundant spawning habitat for trout and the highest mineral concentrations observed in preliminary sampling (Meyer et al. 1998).

Water Temperature

Water temperature was measured hourly in the middle of each survey reach at the stream bottom using a submersible temperature data-logger accurate to ±0.1°C (Optic Stowaway® Temperature Logger, Onset Computer Corporation, Pocasset, Massachusetts, USA). The gradient in water temperature within each survey reach was assessed by measuring the water temperature at 10 points along 10 stream transects within each reach. Water temperature varied less than 1°C within each survey reach. The temperature loggers were checked for proper functioning and downloaded during each sampling period.

In order to assess the effects of temperature on rainbow trout and brown trout, a literature review was conducted to compare temperature tolerances between embryonic and post-hatch lifestages and the two trout species. Results of laboratory experiments with post-hatch lifestages were used to compile information on upper incipient lethal temperatures and acclimation temperatures at different ages. Similar data were compiled for embryonic temperature tolerances; however, determinations had to be made as to what temperatures were tolerated by embryos. Temperatures were designated as being "tolerated" if survival to hatching was greater than 75%. The temperature tolerance data were compiled into tables and figures to compare tolerance ranges between lifestages and species and to compare to field conditions and observed species distributions.

Discharge

Discharge (m^3/s) was determined during each sampling period at each site using the Robins-Crawford method (McMahon et al. 1996).

Water Chemistry

Beginning in June 1997, water was sampled routinely for 1 year to describe spatial and temporal variability in water quality in the mainstem and tributary study sites in the Firehole River basin. Water samples were collected from each site at least once each month, with the exception of the Cold Site, Sentinel Creek, and Nez Perce Creek, which were only sampled for 5 months. An evaluation was conducted at each site to determine if water quality was homogenous within the reach. Measurements of conductivity and temperature across 10 transects in each study reach demonstrated that water quality was similar among points within each reach. Consequently, composite water samples were manually collected from each site using an integrated-depth sampler (Model DH81, U.S. Geological Survey, Denver, Colorado).

Specific conductivity of water samples was measured with a YSI Model 85 meter, accurate to ± 2% (Yellow Spring Instruments, Yellow Springs, Ohio). Measurements of pH were made with an Orion 290A pH meter (Orion Research Inc., Boston, Massachusetts) or a HACH EC30 meter (Hach Co., Lakewood, Colorado).

Water samples were taken for analysis of both total and dissolved mineral concentrations. Samples were collected in ICHEM® bottles and preserved with concentrated Ultrex® nitric acid. Water for measurement of total dissolved concentrations were passed through a 0.45 μm Nuclepore® cellulose fiber filter to remove particulates (Nuclepore Track-Etch Membrane, Corning Separations Division, Cambridge, Massachusetts). A preliminary analysis of the water samples was conducted using a Perkin Elmer Sciex Elan 6000 Inductively Coupled Plasma Mass Spectrometer (ICP-MS; Perkin-Elmer, Norwalk, Connecticut), equipped with a discrete dynode detector (ETP Electron Multiplier, Australia), to determine relative concentrations of the following elements: Ag, Al, As, Au, B, Ba, Be, Bi, Br, Ca, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Hf, Hg, Ho, I, In, Ir, La, Li, Lu, Mg, Mn, Mo, Na, Nb, Nd, Ni, Os, Pb, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sc, Se, Si, Sm, Sn, Sr, Ta, Tb, Te, Th, Ti, Tl, Tm, U, V, W, Y, Yb, Zn, Zr. Based on the results of the preliminary analysis, the concentrations of the following elements were measured in all samples using ICP-MS: As, B, Ca, Cr, Mg, Na, and Se. These elements were selected because their concentrations were relatively high in the most geothermally influenced sites compared to the uninfluenced sites. Selenium was also included because it is commonly from anthropogenic sources in conjunction with boron. Three other elements were over 10 times higher in the Hot and Fairy Creek sites than in other sites: Li, W, and Cs. However, further analyses of these elements were not pursued because little is known of their toxicological effects on aquatic organisms. Cation and anion balances were calculated for all samples and if the percent error was greater than 10%, the ICP-MS results were not used and omitted samples are indicated in Appendix A. Many of these samples were stored frozen for up to 1 year before being analyzed.

Arsenic speciation was conducted because the toxicity of arsenic to aquatic organisms is dependent upon the concentration of specific arsenic species (USEPA 1987). The concentrations of As(V), in the form of arsenate, were determined using a colorimetric method (Stauffer 1980). The concentrations of As(III), in the form of arsenite, were determined by difference of the total recoverable arsenic and As(V) concentrations from the two separate analytical procedures.

Samples for total organic carbon (TOC) and dissolved organic carbon (DOC) analyses were collected in level-II clean amber glass bottles and preserved with hydrochloric acid. Water samples for DOC analysis were passed through a 0.7-μm glass-fiber filter before preserving. Samples were analyzed for TOC and DOC with a Shimadzu TOC5000A Carbon Analyzer (Shimadzu, Columbia, Maryland), with a detection limit of 240 μg C/L.

Additionally, samples were collected to determine the concentrations of the following ions: potassium (K^+), sulfate (SO_4^{2-}), nitrate (NO_3^-), chloride (Cl^-), and fluoride (F^-). Concentrations of K^+ were determined by flame atomic absorption spectrophotometry, the concentrations of the other ions were performed by ion chromatography. Samples to assess ammonia concentrations were collected in acid-washed polyethylene conical tubes and frozen. Total ammonia concentrations were determined by colorimetry (Ivancic and DeGobbis 1984). Concentrations of unionized ammonia (NH_3) were calculated from total ammonia concentrations, pH, and temperature (Emerson et al. 1975). Alkalinity was determined using titrimetric methods described by APHA et al. (1985).

Fish Population Surveys

Study sites were defined as 200-m reaches where the channel had a gradient of 1.0-1.5%, meandered on an alluvial plane, contained no islands, and riparian and instream habitat were homogenous. Aquatic habitat at each site was surveyed during base flows (September and October 1997) using the Habitat Quality Index (HQI), a procedure developed to evaluate habitat for fluvial trout streams in Wyoming (Binns and Eiserman 1979). Measurements of several habitat attributes were made to compare habitat among sites: stream discharge (late summer and annual variation), water velocity, trout cover, stream width, bank stability, substrate composition, water temperature, and nitrate-nitrogen concentrations. HQI ratings range from 0 to 4, with 4 being the best. Ratings of nitrate-nitrogen concentrations were based on mean values during the 1-year study period. Attribute measurements were rated according to the HQI method and an estimate of the number of habitat units for each site was computed using Model II. Two estimates of habitat quality were calculated for each site because of the extreme variation in water temperature among sites. One estimate used actual water temperatures to rate the maximum summer water temperature attribute and the second set the rating for the maximum summer temperature equal among sites. A rating of 3 for the maximum summer temperature was used among all sites to compare physical habitat because this is the most common rating for mountain streams in Wyoming.

Estimates of trout densities at each site were made by snorkeling (Thurow 1994) once every 2 weeks from July 1997 through November 1997, concurrent with water quality sampling. Fairy and Sentinel creeks were surveyed by one snorkeler, whereas all other sites were surveyed by two snorkelers. Snorkelers entered the water downstream of each site. A single snorkeler counted all fish in the stream by either zigzagging from bank to bank or by moving up one bank and counting all fish visible to the opposite bank. Two snorkelers divided the channel into two lanes and counted all fish within their lanes. Fish were counted by species and length class: young of year (YOY; < 10 cm TL), juvenile (10-30 cm TL), adult (> 30 cm TL). Each snorkeler recorded their counts on a plastic cuff with a grease pen as they swam upstream. Only the presence or absence of YOY trout by species were reported because observations varied widely.

An observed length of 30 cm was used to separate counts of juvenile and adults because it corresponds to the separation between age-II from age-III+ trout in the Firehole River (Jones et al. 1992). This division has also been used for trout in other studies (Mullner et al. 1998). Species composition and density (number/ha) of juvenile and adult brown trout and rainbow trout were estimated for each site. The surface area of each site was determined as part of the HQI procedure and was used to convert counts to density estimates.

Underwater visibility was measured before each survey. A white PVC cuff marked with black letters was held underwater against the bank while one snorkeler proceeded out into the channel. When the letters were no longer visible to the snorkeler, the distance from the bank to the observer was measured. A site was not surveyed if visibility was less than 1 m.

Effects of Water Chemistry on Fish Populations

Linear-regression analysis was used to determine if relationships existed between water chemistry parameters and trout densities (SAS Institute 1996). Variation in density estimates within sites was assessed for relationships with water temperature, underwater visibility, and conductivity for each species and for both juvenile and adult length classes. Data were plotted and significance was assigned at $P \leq 0.05$ for all tests. Regression lines were plotted when a significant relationship was identified.

Spawning Surveys and Fry Identification

From November 1997 through February 1998, portions of the Firehole River, Little Firehole River, Fairy Creek, and Nez Perce Creek were surveyed for the presence of spawning trout. The reach near the Warm Site was not surveyed because spawning habitat was rare in this area. Iron Springs Creek was not surveyed because temperatures seemed to be too high for successful spawning (>12°C). During each survey observed redds were counted and the location of each was identified using a precision GPS receiver, accurate to ±

15 m (Rockwell PLGR+, Rockwell International, Cedar Rapids, Iowa). The locations of redds were mapped using ArcVIEW (ESRI Inc., Redlands, California).

From March through May 1998, trout fry were collected in the reaches where spawning had been observed. Fry were collected with a hand-held net while snorkeling or by seining (1.8 x 6.4 m, 5-mm bar mesh). The fish were euthanized in MS-222, fixed in Davidson's solution, and transferred to 65% ethanol for preservation. All fry collected were examined under a dissecting microscope to determine if they were either rainbow trout or brown trout. Several meristic and morphometric measurements were made on each fish to determine the species. These measurements included anal fin ray counts, parr markings, and pigmentation patterns on the adipose fin (Martinez 1984; Wallus et al. 1990; Darrel Snyder, personal communication, Colorado State University, Fort Collins, Colorado).

Results

Water Temperature

Monthly mean water temperatures were consistently higher in the downstream sites in the mainstem of the Firehole River. Temperatures in the Warm and Hot sites averaged 5 and 10°C higher, respectively, than the Cold Site (Figure 2). Temperatures in the Little Firehole River and Sentinel Creek (Figure 3) were similar to the Cold Site; however, the temperatures approached freezing only in the Cold Site and in Sentinel Creek. Temperature regimes varied among the geothermally influenced sites. Iron Springs Creek did not follow the seasonal trends observed in the mainstem sites. Temperatures in Iron Springs Creek were very stable and were elevated in comparison to the Cold Site and the Little Firehole River (Figure 2). From June through August 1997, the monthly mean temperature at the Hot Site was greater than 20°C but still followed the seasonal trends of the Cold and Warm sites. Temperatures in Fairy Creek during the summer were higher than temperatures in the Hot Site; however, Fairy Creek was cooler than both the Warm and Hot sites during the winter. Monthly mean temperature in Fairy Creek averaged 7°C from November 1997 through February 1998, compared to 10°C at the Warm Site and 12°C Hot Site. The water temperature regime in Nez Perce Creek was almost identical to the Hot Site.

The highest temperatures observed among the geothermally influenced sites occurred during July 1997 (Table 2). The maximum water temperatures observed among these sites were: Fairy Creek (30°C; 21 July 1997), Hot Site (26°C; 21 July 1997), Nez Perce Creek (26°C; 21 July 1997), Warm Site (22°C; 16 July 1997), Iron Springs Creek (25°C; 15 July 1997).

Discharge

Peak flows occurred in the mainstem of the Firehole River and the Little Firehole River during late June and early July 1997 (Figure 4). At the Hot Site, discharge peaked at over 14 m^3/sec, and base flow was 8-10 m^3/sec during the winter. However, discharge in Fairy and Irons Springs creeks did not vary much, even during spring. Discharge ranged from 0.3 to 0.4 m^3/sec in Fairy Creek and from 1.9 to 3.1 m^3/sec in Iron Springs Creek. Discharge varied the greatest in the Little Firehole River, where the maximum discharge (May 1998) was over three times the base flow observed during winter.

Water Chemistry

Conductivity.--Conductivity was higher in geothermally influenced sites and peak values occurred during winter months concurrent with base flows (Figure 5). Conductivity was greatest and most variable in Fairy Creek (398-620 μS/cm) and the Hot Site (230-492 μS/cm). The highest conductivity at these sites occurred during January 1998 in Fairy Creek and during March 1998 in the Hot site (Appendix A).

Hydrogen ion concentration.--Measurements of pH ranged from 6.5 to 9.0 among sites (Figure 6). The highest variability was observed among the Iron Springs Creek, Hot, and Fairy Creek sites.

Alkalinity.--Alkalinity ranged from 13 to 106 mg/L (as $CaCO_3$) among sites (Figure 7). Alkalinity was greatest and most variable in Fairy Creek (62-134 mg/L as $CaCO_3$) and the Hot Site (42-111 mg/L as $CaCO_3$).

Ammonia.--Total ammonia concentrations were low at all sites except Fairy Creek (Figure 8). Total ammonia concentrations were almost always less than 100 μg NH_4^+-N/L, but ranged up to 256 μg/L during the spring. Unionized ammonia concentrations never exceeded 5 μg NH_3-N/L at any site except Fairy Creek. The unionized ammonia concentration in Fairy Creek was generally low (mean = 4.4 μg NH_3-N/L); however, one measurement of 40 μg NH_3-N/L was observed.

Organic Carbon.--Measurements of TOC and DOC concentrations in the Fairy Creek and Hot sites ranged from 18 to 25 mg/L during April 1998 (Figure 9). However, TOC and DOC concentrations were less than 5 mg/L throughout the rest of the study at all sites.

Cations and anions.-- The ICP-MS analyses of Ca, Mg, Na, B, As, Cr, and Se concentrations were excluded for 34 out of the 105 samples because cation-anion balances differed by greater than 10%. Most of the rejected samples were taken during August and September 1997 when sampling was conducted twice per month. Concentrations of these elements were relatively low during this 2 month period as compared to the winter months.

The cation and anion analyses indicated that water in the Firehole River and tributaries was dominated by the following ions: sodium (Na^+), bicarbonate (HCO_3^-), and chloride (Cl^-; Table 3). Cation and anion concentrations were highest at the Fairy Creek and Hot Site, up to 20 times the concentrations at the other sites. Temporal trends in the concentrations of cations and anions followed those of conductivity and alkalinity (Figures 10-17). The highest concentrations were during the winter, December 1997 - February 1998. Calcium, magnesium, and potassium concentrations were low and did not contribute more than 10% to the total concentration of cations (Figures 12 -14). Nitrate, sulfate, and fluoride concentrations were also low and contributed less than 10% to the total concentrations of anions (Figures 15-17).

Boron.--Mean concentrations of total recoverable boron were 13-20 times greater in the Hot and Fairy Creek sites than in the Cold and Little Firehole River sites (Figure 18). The highest average concentrations of boron were in the Hot (572 µg/L) and Fairy Creek (956 µg/L) sites. The highest concentrations of boron were during March 1998: Fairy Creek (1,150 µg/L), Hot Site (820 µg/L), Warm Site (355 µg/L), and Iron Springs Creek (315 µg/L; Appendix A). Measurements of total acid-recoverable boron indicated that boron was present mostly in the dissolved fraction.

Arsenic.--Concentrations of arsenic were elevated among the geothermally influenced sites, with the highest concentrations at the Fairy Creek and Hot sites (Figure 19). Total recoverable arsenic concentrations ranged from 160 to 500 µg/L at the Fairy Creek and Hot sites, compared to 10-25 µg/L at the Cold and Little Firehole River sites (Appendix A). Mean concentrations of total recoverable arsenic were also elevated at the Iron Springs Creek and Warm sites, but were lower than the Hot and Fairy Creek sites, ranging from 60 to 140 µg/L. Measurements of total dissolved arsenic indicated that arsenic was present mostly in the dissolved fraction.

Analysis of arsenic speciation indicated that the majority of arsenic was present as As(V) among all sites (Figure 20). Concentrations of As(V) and As(III) were also highest at the Fairy Creek and Hot sites and ranged from 50 to 250 µg As(III)/L and concentrations of As(V) ranged from 110 to 380 µg/L. Concentrations of As(III) at the Iron Springs Creek and Warm site ranged from less than 35 to 100 µg/L and concentrations of As(V) ranged from less than 35 to 140 µg/L. The detection limit for As(III) and As(V) was 35 µg/L and concentrations at the Cold and Little Firehole River sites were almost always below this limit.

Chromium.--Chromium concentrations were usually below detection limits at all sites; however, concentrations were sporadically elevated (up to 250 µg/L) in the Warm, Hot, and Fairy Creek sites (Figure 21). Measurements of total acid-recoverable concentrations indicated that the chromium was present mostly in the dissolved form (Appendix A).

Selenium.-- Selenium concentrations were low and remained less than 3 µg/L at all sites (Figure 22).

Linear correlations with conductivity.--Alkalinity, chloride, sodium, potassium, and fluoride were significantly correlated with conductivity (Figure 23 and 24), as were boron and arsenic (Figure 25). Measurements of pH, organic carbon (TOC and DOC), total ammonia, calcium, sulfate, and magnesium were not correlated with specific conductivity

(Figures 23 and 24); however, these data included both the Nez Perce Creek and Sentinel Creek samples. Additionally, water temperatures were not correlated with conductivity (Figure 26).

Conductivity was used as a surrogate for boron and arsenic concentrations in evaluating the effects of boron and arsenic concentrations on trout densities because of the high correlations of these elements with conductivity ($P < 0.01$, $R^2 > 0.90$).

Fish Population Surveys - Temporal Trends in Trout Density

Cold Site.--Temporal trends in trout density were evident in the Cold Site among rainbow trout juveniles and adults (Figure 27). Densities were low in the early summer, increased to a maximum during August, and then declined. This trend was not as evident among brown trout juveniles (Figure 28) and no trend was evident for adult brown trout.

Underwater visibility during snorkeling was 2.9-3.9 m and no relationship of visibility to density estimates were observed (Figures 27 and 28). Conductivity and mineral concentrations were low at the Cold Site and did not seem to be related to temporal trends in trout density. However, temperature was significantly correlated with the density of brown trout juveniles ($P = 0.02$, $R^2 = 0.65$). Juvenile brown trout density decreased with temperature. Although a similar linear relationship was observed among rainbow trout, the lowest density of rainbow trout juveniles and adults were also associated with the lowest temperatures observed during the surveys (< 12°C).

Little Firehole River.--Temporal trends were observed among juvenile rainbow trout and juvenile brown trout densities in the Little Firehole River (Figures 29 and 30). Juvenile trout density increased from July through September 1997, but declined rapidly in October

1997. Visibility and conductivity were not related to density of juveniles; however, temperature had a significant relationship with the density of brown trout juveniles ($P = 0.04$, $R^2 = 0.49$). The density of juvenile brown trout decreased with decreased water temperatures. A linear relationship between rainbow trout juveniles and temperature was not observed but the lowest densities of rainbow trout juveniles and adults were associated with the lowest temperatures during the surveys (< 12°C). Conductivity was correlated with the density of adult brown trout ($P = 0.01$, $R^2 = 0.62$); the density of brown trout declined as conductivity increased.

Warm Site.--Temporal trends were observed among juvenile and adult trout in the Warm Site (Figures 31 and 32). Trout density peaked during August 1997 and declined through the fall months. Underwater visibility was not related to trout density; however, correlations were observed between temperature and the density estimates for juvenile rainbow trout ($P = 0.02$, $R^2 = 0.54$), juvenile brown trout ($P < 0.01$, $R^2 = 0.70$), and adult brown trout ($P = 0.04$, $R^2 = 0.42$). Declines in trout density were associated with declines in temperature. Increases in conductivity was associated with declines in the density of juvenile brown trout ($P = 0.01$, $R^2 = 0.60$).

Iron Springs Creek.--Trout density in Iron Springs Creek was highest during July and August 1997, but declined rapidly in late September 1997 (Figures 33 and 34). Densities of juvenile and adult rainbow trout were not correlated with underwater visibility, temperature, or conductivity. However, declines in juvenile brown trout density were associated with underwater visibility ($P = 0.02$, $R^2 = 0.62$), temperature ($P < 0.01$, $R^2 = 0.86$), and conductivity ($P < 0.04$, $R^2 = 0.55$).

Nez Perce Creek.--Trout density in Nez Perce Creek was highest during July and August 1997, but declined in late September 1997 (Figures 35 and 36). Variations in the densities of brown trout and rainbow trout were not accounted for by underwater visibility, temperature, or conductivity.

Hot Site.--Temporal trends were observed among rainbow trout but not among brown trout (Figures 37 and 38). The density of juvenile and adult rainbow trout was low during the summer and increased during the fall. However, the density of rainbow trout and brown trout were not correlated to underwater visibility, temperature, or conductivity. Rainbow trout were present when temperatures approached 25°C, and the highest density of rainbow trout was observed when conductivity was highest.

Fairy Creek.--The densities of rainbow trout increased during the fall; however, no brown trout were observed during the population surveys in Fairy Creek (Figures 39 and 40). Visibility was correlated with the density of juvenile rainbow trout ($P = 0.01$, $R^2 = 0.70$) and reflected the reduced underwater visibility (1-2 m) that prevailed in Fairy Creek. The density of adult rainbow trout was negatively correlated with temperature ($P = 0.05$, $R^2 = 0.50$) and positively correlated with conductivity ($P < 0.01$, $R^2 = 0.77$).

Sentinel Creek.--Population data for Sentinel Creek were not collected because visibility was continuously less than 1 m during the study period.

Fish Population Surveys - Spatial Trends in Trout Density

Spatial trends in species composition.--Brown trout dominated the study sites without geothermal influence, whereas rainbow trout dominated the sites with the greatest geothermal influence (Table 4). In the Cold Site, brown trout composed 99% of the juvenile trout and

80% of the adult trout. Although brown trout dominated the adult trout species in the Cold Site, the proportion of adult brown trout present in the Cold Site varied, ranging from 56 to 100%, while the proportion of adult rainbow trout ranged from 0 to 42%, reaching a high during August 1997. Brown trout also dominated the Little Firehole River: 84% of the juvenile trout and 70% of the adult trout. However, the composition of adult rainbow trout varied greatly, ranging from 0 to 66% and again reaching a peak in August 1997.

In Iron Springs Creek and the Warm Site (areas of relatively moderate geothermal influence) it was not evident that a specific trout species consistently dominated these sites. In the Warm Site, the composition of juvenile trout species varied with brown trout averaging 60%, and rainbow trout averaging 40%. Among adult trout, brown trout averaged 52% and rainbow trout averaged 48%. In Iron Springs Creek, rainbow trout composed 71% of the juvenile trout and 71% of the adult trout. The composition of trout species in the Warm Site and Iron Springs Creek varied similarly during the study period. In the early summer (July 1997) brown trout were the dominant trout species in each site, but by fall (September 1997) brown trout numbers decreased and rainbow trout dominated these areas.

In the most geothermally influenced sites (Hot and Fairy Creek), rainbow trout dominated. In the Hot Site, rainbow trout composed 94% of the juvenile trout and 88% of the adult trout. In Fairy Creek, rainbow trout comprised 100% of the juvenile trout and 100% of the adult trout.

Nez Perce Creek was the only site where a complete absence of fish was observed at some time during the study. Adult trout were not observed in Nez Perce Creek and very few juvenile trout were observed. However, brown trout were the dominant trout species among juvenile fish (mean = 74%).

Young-of-year fish were observed from July through October 1997 in all sites except the Hot Site. The composition of YOY trout species among sites was similar to the composition of adults and juveniles.

Habitat Quality Index.--Habitat was similar among sites with the exception of water temperature (Tables 5 and 6). Habitat quality ranged from 250 to 388 habitat units (predicted standing stock of trout from 259 to 403 kg/ha) among sites when the rating for maximum summer temperature was the same among sites. When actual maximum summer temperatures were used in the model, the rating of habitat quality at the Iron Springs Creek, Hot, Fairy Creek, and Nez Perce Creek sites decreased (Tables 5 and 6). Predicted standing stocks of trout were much less when actual temperatures were used because the model rates these high temperatures as being very poor for trout. Predicted standing stock decreased from 268 to 57 kg/ha at the Hot Site and from 259 to 2 kg/ha in Fairy Creek when actual temperatures were used. The ratings from the HQI model demonstrated that physical habitat and cover was relatively similar among sites, but elevated water temperatures in the geothermally influenced sites substantially reduce habitat quality for trout.

Effects of Water Chemistry on Fish Populations

Density and Water Temperature.--Rainbow trout were more abundant in the sites with higher temperatures, whereas brown trout were more abundant in the sites with lower temperatures. Rainbow trout density among sites increased as maximum summer stream temperature increased (Figure 41). Furthermore, the highest mean density of rainbow trout occurred in the site with the highest maximum summer stream temperature. This trend was observed for both adults and juveniles, but was more evident among the juvenile trout.

Density of rainbow trout tended to increase with water temperature up to 25°C. The trend among brown trout was the opposite, higher densities were observed at sites with lower temperatures (Figure 41).

Density and Conductivity.--Rainbow trout were present across a wide range of conductivities and were observed at relatively high densities when conductivity exceeded 400 µS/cm (Figure 42). However, brown trout densities were highest at low conductivities and they were not observed when conductivity exceeded 400 µS/cm. Furthermore, densities of rainbow trout tended to increase with conductivity among sites, whereas brown trout densities tended to decrease with conductivity.

Density and Boron.--Rainbow trout were present across a wide range of boron concentrations and were observed at relatively high densities where boron concentrations were highest (Figure 43). Brown trout densities were highest where boron concentrations were low and they were not observed when boron concentrations were greater than 500 µg/L.

Spawning Surveys and Fry Identification

The mainstem of the Firehole River, from the Upper Geyser Basin (just upstream from Old Faithful) upstream to Kepler Cascades, and the Little Firehole River, from its mouth to Mystic Falls (a barrier to upstream fish passage), were surveyed on 5 November 1997. The mainstem of the Firehole River, from the mouth of Nez Perce Creek upstream to Ojo Caliente Bridge was surveyed on 3 December 1997 and 21 January 1998. The mainstem of the Firehole River, from Ojo Caliente Bridge upstream to Tangled Creek, was surveyed on 23 December 1997. Sections of Fairy Creek, from its mouth upstream to Fairy Falls, were surveyed on 2 December 1997, 21 January 1998, and 5 February 1998. Nez Perce Creek was surveyed from its mouth upstream to the bridge of the park's highway on 23 December 1997 and 5 March 1997.

Fry were collected within the study site on the Little Firehole River on 27 April 1998 and 28 May 1998. Fry were collected around the Hot Site in the mainstem of the Firehole River, between the mouths of Nez Perce Creek and Fairy Creek, on 3 March 1998 and 28 May 1998. Fry were collected from Nez Perce Creek within the study site on 3 March 1998, and from Fairy Creek on 5 March 1998 and 29 April 1998.

Numerous redds were observed in all of the sites that were surveyed but the timing of spawning varied among sites. Redds were observed in the upper Firehole River, from Old Faithful upstream to Kepler Cascades, including the Cold Site (Figure 44). In the 2 km surveyed, a total of 34 redds were observed (Table 7). Several brown trout were observed actively spawning, but most redds were completed before the survey was conducted (5 November 1997).

The Little Firehole River was surveyed on 5 November 1997 and 44 redds were observed in the 2 km of stream surveyed (Figure 45). Most of the redds were observed in the lower section of the Little Firehole River, including the study site. Trout were observed actively spawning on six of the redds and several of the fish were identified as brown trout. Trout fry sampled from this area after spawning were comprised of 22 (63%) brown trout and 13 (37%) rainbow trout (Table 8).

Redds were observed in the lower Firehole River from the mouth of Nez Perce Creek upstream to Ojo Caliente Bridge on 3 December 1997 and 21 January 1998. Redds were concentrated between Sentinel Creek and Nez Perce Creek in two large spawning areas (Figure 46). On 3 December 1997, 54 redds were observed (59 to 63 estimated spawning pairs) and almost 90% of the redds were in two large spawning areas in this reach. No fish were observed actively spawning during the survey; however, it was estimated that these redds were created during mid-November 1997, based on periphyton regrowth and deposition of detritus material on the redds. On 21 January 1998, the reach was resurveyed and 19 additional redds were observed. Seven of these redds were superimposed on redds observed during the previous survey. These redds were estimated to have been created during early January 1998. The Firehole River, upstream of this area, was surveyed from Ojo Caliente Bridge upstream to Tangled Creek on 23 December 1997; however, only two redds were observed in this reach. Trout fry collected from the mainstem of the lower Firehole River after spawning were identified and composed of 94% rainbow trout and 6% brown trout (Table 8).

Fairy Creek was surveyed on 2 December 1997 and 42 redds were observed from its mouth upstream to Fairy Falls, a barrier to fish passage (Figure 47). It was estimated that these redds were created during mid-November 1997 based on periphyton regrowth and deposition of detritus material on the redds. Only one pair of fish was observed actively spawning, although large aggregations of trout of all length classes were observed throughout the survey reach. Some of the fish were identified as rainbow trout. The same reach of Fairy Creek was surveyed again on 21 January 1998 but only three new redds were observed, just upstream of the study site. The upper reach of Fairy Creek was surveyed on 5 February 1998, from Fairy Falls downstream for 6 km; however, no redds were observed. Spawning habitat was limited in this reach; however, trout of all length classes were present. Trout fry sampled from this area after spawning were identified as follows: 21 rainbow trout and 1 brown trout (Table 8).

Nez Perce Creek was surveyed on 23 December 1997 from its mouth upstream to the highway bridge, and five redds were observed. No trout were observed actively spawning during this survey. Nez Perce Creek was surveyed again on 5 March 1997, from its mouth upstream to the Freight Road Bridge, and 11 redds were observed. Trout fry collected from this area after spawning were identified as follows: 9 rainbow trout and 3 brown trout (Table 8).

Discussion

Rainbow trout were found in sites with high water temperatures and high mineral concentrations in the Firehole River basin. Rainbow trout densities tended to increase among sites as the effects of geothermal influences on temperature and mineral concentrations increased. However, the brown trout population in the Firehole River basin seemed to be limited by geothermal effluents. Brown trout densities decreased with elevated temperature, conductivity, and boron concentrations and they were rare or absent in the lower Firehole River and Fairy Creek where the most elevated temperatures and boron concentrations were observed. Low densities of brown trout in geothermally influenced areas were observed previously in other studies (Koch 1990; Kaya 1977; David Zafft, Wyoming Game and Fish Department, Laramie, Wyoming, personal communication). The reasons for difference in spatial distributions between rainbow trout and brown trout are explored in this discussion.

Effects of Temperature on Trout

It was expected that the high temperatures at the geothermally influenced sites would lead to the displacement of juvenile and adult trout of both species. However, rainbow trout were consistently observed in geothermally influenced areas through the summer. The low densities of brown trout were not attributed to differences in upper temperature tolerance between species. The upper incipient lethal temperature (UILT) for brown trout and rainbow trout has been determined to range from 24-25°C (Jobling 1981). The UILT is the temperature at which 50% of a population of fish species can survive indefinitely. Summer water temperatures exceeded the UILT in Fairy Creek (29°C) and occasionally exceeded the

UILT in Iron Springs Creek, Hot, and Nez Perce sites (25-26°C). Past studies have suggested that trout in the Warm and Hot reaches moved upstream into cooler tributaries during the summer (Little Firehole River and Sentinel Creek; Kaya et al. 1977; Koch 1990; Kaeding 1996). These trout were believed to have sought thermal refugia from lethal summer temperatures, but no declines in trout densities in the Warm and Hot sites were observed during maximum summer temperatures in this study. Maximum summer water temperatures in the mainstem of the Firehole River during 1997 were comparable to those observed during 1974 and 1975 (Kaeding and Kaya 1978) and during 1991 (Kaeding 1996). Maximum monthly air temperatures during July and August 1997 were less than 1°C lower than the 30-year mean (Western Regional Climate Center, Desert Research Institute, Reno, Nevada) indicating that climatic conditions were not substantially cooler during this study.

Studies of preferred temperatures suggest that rainbow trout prefer higher temperatures than brown trout. Juvenile and adult trout select temperatures that provide optimal growth and will seek cooler water when thermally challenged (Kaya 1977; Spigarelli et al. 1983; Headrick and Carline 1993). Rainbow trout have been shown to prefer temperatures up to 24°C (Garside and Tait 1958; Cherry et al. 1977; Houston 1982; McMichael and Kaya 1991), whereas brown trout have been shown to prefer temperatures from 12 to 19°C (Cherry et al. 1977; Reynolds and Casterlin 1979, Spigarelli et al. 1983; Garrett and Bennett 1995). Preferred temperatures may explain the spatial distribution of the two trout species in the Firehole River; however, brown trout densities remained low in geothermally influenced areas during fall and winter when temperatures were within their preferred range.

Species-specific embryonic temperature tolerances may explain the differences in distribution of rainbow trout and brown trout in the Firehole River. Recent research has suggested that winter temperatures limit the distribution of trout species. Jowett (1990) studied the distributions of rainbow trout and brown trout in New Zealand and demonstrated that species distributions were related to minimum winter temperatures. Rainbow trout were allopatric when minimum winter temperatures averaged 10.4°C and sympatric with brown trout when minimum winter temperatures averaged 5.9-7.5°C. Scott and Poynter (1991) also studied the distribution of rainbow trout and brown trout in New Zealand. They observed that maximum summer temperatures were similar between sites, but maximum winter temperatures varied with the presence of rainbow trout and brown trout populations. They suggested that winter temperatures limit species distributions because of differences in embryonic temperature tolerances between rainbow trout and brown trout.

The current literature on temperature tolerance suggests that the UILT for post-hatch lifestages of rainbow trout is 22.6 to 27.0°C (Table 9). Included in these data are the results of tests conducted by Kaya (1978) on rainbow trout from the Firehole River that demonstrated that the UILT of rainbow trout in the Firehole River was similar to other rainbow trout strains. However, the UILT for post-hatch brown trout ranged from 21.0 to 26.4°C (Table 10). Thus, brown trout seem to have a slightly lower UILT than rainbow trout.

Embryonic temperature tolerance ranges differ between rainbow trout and brown trout. Temperatures tolerated during embryonic development by rainbow trout range from 5 to 15°C (Table 11), and temperatures outside of this range cause increased mortality. Brown trout seem to have lower embryonic temperature tolerances that ranged from 1 to 11°C (Table 11). The distinct differences between embryonic temperature tolerance and UILT for these trout species are compared graphically (Figures 48 and 49). The embryonic temperature tolerances are much lower than the UILTs. Furthermore, there is an obvious difference in embryonic temperature tolerance ranges between the two trout species. The embryonic temperature tolerance ranges seem to be much more limiting for trout than their respective UILTs and these ranges differ substantially between species.

Salmonid embryos seem to be physiologically adapted to the specific incubation temperatures of their spawning seasons (Murray and McPhail 1987). Embryos of spring-spawning rainbow trout are not tolerant of near freezing temperatures (0-3°C), whereas embryos of fall-spawning brown trout are not tolerant of temperatures over 12°C. Most fish embryos are not tolerant of temperature changes exceeding ±6°C during development (Rombough 1997). The lack of tolerance to temperature changes has been attributed to the inability of fish embryos to compensate at the cellular level until they have hatched (Buddington et al. 1993). Thus, embryos of most fish are not tolerant of temperature extremes until hatching. Although it has been observed that trout embryos begin to temperature compensate earlier than most other fishes (about 2 weeks after fertilization when neural tube closure is complete; Marten 1992; Hubert et al. 1994; Hubert and Gern 1995), they are still limited by species-specific embryonic temperature tolerance ranges.

The lower UILT, embryonic temperature tolerance range, and preferred temperatures of brown trout may limit them to the less geothermally influenced areas in the Firehole River basin. Winter water temperatures in the Hot and Fairy Creek sites were consistently above the 10°C upper temperature tolerance limit of brown trout embryos and may preclude the survival of brown trout embryos spawned in the most geothermally influenced areas. Winter temperatures were acceptable for brown trout embryos only in the Cold and Little Firehole

River sites. Rainbow trout in the geothermally influenced areas have shifted their spawning time to winter, which coincides with water temperatures that are more optimal for the development of their embryos (5-15°C). Thus, embryonic temperature tolerances may be the most limiting thermal factor in determining trout species distributions in the Firehole River drainage because trout may not disperse far from their natal areas (Beard and Carline 1991).

Effects of Discharge on Trout

Discharge had little effect on trout in the Firehole River basin because the seasonal variation among sites was low. However, temporal changes in water quality were associated with the flow regimes. The concentrations of geothermal minerals tended to increase in the winter in the Firehole River and its tributaries when base flows occurred.

Effects of Geothermal Chemicals on Trout

Water quality analyses indicated that arsenic and boron were the most critical elements to consider for possible toxic effects on trout in the Firehole River and tributaries. The concentrations of other minerals were consistently low and should not affect the trout populations.

Arsenic.--The highest arsenic concentrations in the Firehole River and tributaries were below toxic thresholds, but arsenic concentrations should continue to be monitored in further studies in this drainage. The toxicity of arsenic to aquatic organisms is affected by temperature, pH, organic content, phosphates, and other water quality parameters (Eisler 1994). The chronic ambient water quality criterion (AWQC) for the protection of aquatic organisms for As(III) is 190 μg/L (USEPA 1987). As(III) is the form of arsenic that is more toxic to aquatic organisms. Limited aqueous exposure studies of rainbow trout embryos to arsenite have demonstrated an LC_{50} of 540 μg/L (USEPA 1980). As(V) is acutely toxic to rainbow trout at concentrations of 1,800-3,600 μg/L (McGeachy and Dixon 1992). The highest concentrations of arsenic occurred during the late fall and winter concurrent with low flows. Concentrations of As(III) approached toxic limits in Fairy Creek (208 μg/L) and in the Hot Site (256 μg/L). The highest As(V) concentrations (377 μg/L) were below the toxic thresholds; however, arsenic may bioconcentrate in prey organisms and expose trout to arsenic through dietary pathways. Arsenic has been observed to cause depression of growth and impaired feeding in rainbow trout fed arsenic-contaminated diets (Cockell and Hilton 1985). The interpretation of the possible effects of As(III) concentrations should be made with reservation because they were estimated from the differences between two independent analyses. However, the potential for arsenic to cause toxic effects on trout in this drainage should be studied further.

Chromium.--Chromium concentrations were occasionally high (up to 250 μg/L in the Warm, Hot, and Fairy Creek sites) and should be monitored. Chromium is commonly found in surface waters in the two oxidation states Cr(III) and Cr(VI), with Cr(VI) being more toxic than Cr(III); however, chromium was not speciated for this study. The occasionally high chromium concentrations in study sites were above the USEPA Ecotox and chronic AWQC for Cr(III) (USEPA 1987). These elevated concentrations may affect the health of fish and other aquatic organisms and should be considered for investigation in future studies.

Ammonia.--Trout health may be compromised at unionized ammonia concentrations greater than 12.5 μg NH_3-N/L (Piper et al. 1982). Unionized ammonia concentrations were occasionally greater than this recommended concentration, but probably did not affect trout populations.

Boron.-- Trout in the lower Firehole River and Fairy Creek are exposed consistently to high boron concentrations, but it could not be determined if boron concentrations were affecting the distributions of rainbow trout and brown trout. Boron was present mostly in the dissolved form. Among the study sites, boron concentrations were highest in the Fairy Creek and Hot sites where rainbow trout densities were highest. Boron concentrations were highest during the winter months and exceeded the proposed water quality limit for boron (1,000 μg/L ECETOC 1997) in Fairy Creek. Rainbow trout spawned in these areas during winter and fry were collected from March through June 1998. Thus, it does not seem that the elevated boron concentrations in Fairy Creek and the Hot site had a negative impact on rainbow trout. However, it is not known if low densities and low occurrence of spawning by brown trout in these areas may be attributed to brown trout being more sensitive than rainbow trout to the elevated concentrations of boron, arsenic, or the combination of these elements.

It is critical to accurately assess the effects of boron on aquatic organisms because of its use in residential, agricultural, and industrial applications. Boron is widely distributed and naturally occurs as inorganic borates. The commercial source of boron is borax ($Na_2B_4O_7 \cdot 10H_2O$), which is an odorless white crystalline granule or powder. The predominant species in aqueous solution at circumneutral pH is boric acid (H_3BO_3). The bleaching agent, sodium perborate, can constitute up to 15% of detergents by weight (Roberts 1995). In common agricultural and residential uses, boron products are discharged directly into surface waters (Butterwick et al. 1989; Hamilton and Buhl 1990; Hamilton and

Wiedmeyer 1990). Both the World Health Organization and the European Union are currently reviewing their environmental health criteria for boron. However, the U.S. Environmental Protection Agency (USEPA) has not yet established a water quality criterion for boron. Conductivity was highly correlated with concentrations of boron at the study sites in the Firehole River basin and it can be used as a surrogate in this system to infer trends in boron concentrations in further studies.

The no effect concentration (NOEC) and the lowest observed effect concentrations (LOEC) for boron and aquatic organisms indicated that boron is more toxic in reconstituted water than in surface water (ECETOC 1997). The NOEC ranged up to 750 µ/L boron in surface water and up to 18,000 µg/L in well water. The LOEC in natural waters ranged from 1,100 to 1,730 µ/L. Rainbow trout have shown the greatest sensitivity in aqueous-exposure tests (Eisler 1990; Black et al. 1993; ECETOC 1997); however, brown trout have not been tested. Laboratory studies of rainbow trout determined the LOEC ranged from 100 to 18,000 µg/L (Black et al. 1993). The embryo-larval lifestage of rainbow trout was shown to be the most sensitive to acute lethal boron exposures among several aquatic organisms tested (Black et al. 1993; Eckhert 1997). Testing performed generally required a concentration of at least 1,000 µg/L boron to achieve a consistent increase in mortality. However, the few studies of boron toxicity on rainbow trout embryos are contradictory. Birge and Black (1977, 1981; Birge et al. 1984) observed boron-induced teratogenesis in rainbow trout embryos at 1 µg/L; however, Rowe et al. (1998) did not observe effects on embryos until boron concentrations were greater than 10,000 µg/L. Currently, a boron concentration of 1,000 µg/L has been recommended as the proposed surface water quality limit (ECETOC 1997). However, boron toxicity testing has focused on rainbow trout and only lethal endpoints from aqueous exposures have been used to determine a safe water quality criterion for boron. No other salmonids have been tested and sublethal endpoints have not been assessed.

Although no detailed studies on transfer of boron through the food web have been conducted, boron has been observed to bioconcentrate in plants. Boron concentrations up to 3,500,000 μg/L have been observed in aquatic plants exposed to agricultural runoff (Schuler 1987). Benthic invertebrates feed at many trophic levels that include sediments and aquatic plants. Metals can bioaccumulatee in benthic invertebrates (Woodward et al. 1994, 1995; Farag et al. 1998). While boron does not seem to bioconcentrate in fish (ECETOC 1997), elevated boron concentrations have been observed in whole-body tissue samples from bluegill Lepomis macrochirus and common carp Cyprinus carpio exposed to elevated boron in agricultural runoff (Saiki and May 1988). Trout in the Firehole River feed mostly on immature benthic invertebrates, emerging insects and molluscs (Armitage 1958, 1961). Thus, in addition to cutaneous exposure to boron in surface water, trout in the Firehole River may be exposed through their consumption of benthic invertebrates.

Sublethal concentrations of boron may affect the behavior, physiology, and reproduction of freshwater fishes and other vertebrates. It has been demonstrated that sublethal concentrations of contaminants can cause behavioral avoidance (Woodward et al. 1997; Goldstein et al. 1999), reduce fitness (Farag et al. 1998), and disrupt endocrine systems in salmonids (Heath 1995). Decreased fecundity in bluegills exposed to sublethal boron concentrations in the Salt Slough, California, were observed, but other factors may have also influenced reproductive health in these fish (Nakamoto and Hassler 1992). Boron toxicity has been studied in other vertebrates and repeatedly shows testicular toxicity and other effects on reproductive systems (Ku et al. 1993a, 1993b; Ku and Chapin 1994; ECETOC

1995). Weir and Fisher (1972) tested dogs, rats, and mice and observed severe testicular atrophy, reduced spermatogenesis, and reduced ovulation. Dietary effects of boron on mallard duck reproduction, behavior, and growth were observed at 30-100 mg B/kg fresh diet weight in laboratory studies (Smith and Anders 1989; Hoffman et al. 1990; Whitworth et al. 1991).

Furthermore, Kaya (1977) documented evidence of reproductive impairment among brown trout from the geothermally influenced areas of the Firehole River. Females showed pre-spawning atresia of ova and 50% of the adult-sized males had immature gonads. However, the combined effects of boron and elevated temperature on the reproductive impairment observed in brown trout cannot be separated.

Species-specific differences in tolerances to contaminants could also explain the low densities of brown trout in the geothermally influenced areas. Tolerance of contaminants can vary by species among salmonids (Atchison 1987; Marr et al. 1995). Rainbow trout may be more tolerant of specific contaminants than brown trout. Thus, further research is needed to assess if sublethal boron concentrations impair the health of trout and if there are differences in tolerance among species.

Other Possible Factors Affecting Trout Distributions

Effects of Temperature on Snorkeling.--Differences in water temperatures among sites may have affected estimates of trout densities due to decreased snorkeling efficiency at cold temperatures. Several studies have shown that juvenile salmonids concealed themselves in interstitial spaces at temperatures less than 8°C (Chapman and Bjornn 1969; Heggenes et al. 1993; Riehle and Griffith 1993; Contor and Griffith 1995). Furthermore, Thurow (1994) recommends against snorkeling at low temperature because of the potential for biased estimates due to reduced efficiency of observing inactive trout. Low temperatures at the Cold and Little Firehole River sites may have led to underestimates of trout densities at these sites; however, estimates of trout densities in the geothermally influenced sites do not seem to have been biased by low temperatures.

Snorkel counts provided a relative index of trout abundance at study sites in the Firehole River basin; however, it is not certain how these estimates compared to depletion methods by electrofishing (Heggenes et al. 1990). Studies have shown that snorkeling methods enumerate only 40-80% of the trout determined to be present by electrofishing (Mullner et al. 1998). Complex in-stream cover and underwater visibility seem to affect the ability to predict trout abundance from snorkel counts. Low variability among repeated snorkel counts has been observed (Thurow 1994), but comparisons of abundance among sites must still be made with caution. Overall, we believe snorkeling provided accurate information on species composition and distributions of trout.

Habitat Availability.--Variation in physical habitat features among sites did not seem to have a substantial influence on densities of rainbow trout and brown trout. Rainbow trout and brown trout are commonly found in sympatry (Gatz et al. 1987; Jowett 1990) and in-stream cover seems to be a critical factor for determining densities of brown trout (Lewis 1969; Jowett 1990). In-stream cover among study sites in the Firehole River was similar (Cold and Little Firehole River sites: 13-14% surface area; Hot and Fairy Creek sites: 6-11% surface area). Wesche et al. (1987) suggested that overhead bank cover is critical in determining standing stocks of brown trout but overhead bank cover was rarely present at any site. Thus, differences in physical habitat and cover types among sites did not account for differences in the trout distributions.

Competition.-- Differences in habitat use by rainbow trout and brown trout may occur as a result of interspecific competition, but does not seem to account for the low densities or absence of brown trout in geothermally influenced sites. Competition can be expected between rainbow trout and brown trout because they have similar habitat preferences (Jenkins 1969; Shirvell and Dungey 1983; Fausch 1984) and foraging habits (Elliot 1973; Kaeding and Kaya 1978). Gatz et al. (1987) observed that rainbow trout were displaced from preferred micro-habitats when in sympatry with brown trout because brown trout were more aggressive (Fausch and White 1981). However, gross displacement of rainbow trout by brown trout has not been observed.

Variation in water temperatures among sites may create differences in physiological and behavioral advantages for rainbow trout or brown trout. A temperature-mediated reversal in competitive ability may explain the distribution of rainbow trout and brown trout in the Firehole River. Rainbow trout can forage optimally at temperatures up to 24°C (Houston 1982; McMichael and Kaya 1991), but brown trout food consumption decreases at temperatures from 22-25°C because they experience thermal stress (Taniguchi et al. 1998). Taniguchi et al. (1998) demonstrated that competitive ability (measured as food consumption and aggression) can be temperature mediated. They demonstrated that brook trout and brown trout were more aggressive than creek chubs Semotilus atromaculatus at 3-22°C, but above this temperature the creek chub had a competitive advantage over the trout. The creek chub had increasing success obtaining forage items and decreasing the amount of forage available to the trout at higher temperatures. A similar reversal in competitive dominance across a temperature gradient has also been shown for sculpins and dace (Baltz et al. 1982). Thus, the distribution of rainbow trout and brown trout in the Firehole River and tributaries may be partially due to a temperature-mediated reversal in exploitative competition ability. Further research on this mechanism and its role in affecting the spatial distribution patterns of rainbow trout and brown trout in the Firehole River drainage is needed.

Conclusions

Rainbow trout seemed to be tolerant of the water quality in the most geothermally influenced sites in the Firehole River and its tributaries. Water temperatures approached upper lethal limits for rainbow trout (>25°C) in the Hot and Fairy Creek sites and boron concentrations were seasonally elevated above a proposed surface water quality limit in Fairy Creek (1,000 µg/L). However, population surveys, redd counts, and fry collections indicated that rainbow trout were abundant and occurred in these sites throughout the year. Adult rainbow trout were present during gametogenesis and spawned in the most geothermally influenced reaches of the mainstem and its tributaries. It does not seem that rainbow trout were negatively impacted by boron concentrations up to approximately 1,000 µg/L.

Brown trout did not seem to be tolerant of the combination of elevated temperatures and mineral concentrations in the most geothermally influenced sites. Low densities of brown trout were observed in the most geothermally influenced areas of the Firehole River drainage; and they showed very limited spawning in these areas, apparently due to water temperatures exceeding the tolerance limits of brown trout embryos. However, it is also possible that brown trout are more sensitive to boron or arsenic than are rainbow trout.

Controlled laboratory studies should be conducted to assess if there are differences in tolerances of boron and arsenic between rainbow trout and brown trout. Chronic exposure studies should also be conducted to determine if boron has specific effects on reproductive fitness at sublethal concentrations. These studies will help refine surface water quality criteria for boron to protect aquatic organisms and further explain the distribution of trout in the Firehole River basin.

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Table 1. Fish species in the Firehole River, Yellowstone National Park (from Jones et al. 1992). Stream reaches (from upstream to downstream) are defined as (1) Unnamed cascades to Kepler Cascades, (2) Kepler Cascades to Firehole Falls, and (3) Firehole Falls to Madison River. Presence is indicated by an X.

Species		Reach		
Common name	Scientific name	1	2	3
Rainbow trout	*Oncorhnychus mykiss*		X	X
Brown trout	*Salmo trutta*	X	X	X
Brook trout	*Salvelinus fontinalis*	X	X	X
Cutthroat trout	*O. clarki*		X	X
Mountain whitefish	*Prosopium williamsoni*			X
Arctic grayling	*Thymallus arcticus*			X
Longnose dace	*Rhinichthys cataractae*			X
Mountain sucker	*Catostomus platyrhynchus*			X
Mottled sculpin	*Cottus bairdi*			X

Table 2. Water temperatures at the mainstem and tributary study sites. Values are monthly means and annual means based on hourly measurements for June 1997 to June 1998. LFHR = Little Firehole River, Iron = Iron Springs Creek, FC = Fairy Creek, SC = Sentinel Creek, and NP = Nez Perce Creek. COLD, WARM, HOT = mainstem sites.

		Site							
Month	Statistic	COLD	LFHR	SC	WARM	IRON	NP	FC	HOT
June	mean	9.0	13.4	14.3	13.4	19.4	17.1	19.2	16.0
	minimum	3.6	6.5	8.0	7.3	14.4	12.8	11.8	11.0
	maximum	15.4	19.3	21.4	19.8	24.5	22.9	29.6	21.6
July	mean	11.8	15.6	14.4	16.9	18.6	19.8	20.2	20.7
	minimum	5.9	10.0	8.5	10.7	15.3	14.4	12.5	14.4
	maximum	16.5	20.6	20.9	22.3	24.6	25.6	29.8	25.6
August	mean	11.8	15.0	13.5	16.8	17.2	19.8	19.5	20.6
	minimum	7.8	11.0	8.2	13.2	14.1	15.3	13.5	16.9
	maximum	16.4	19.6	20.3	22.3	22.4	25.1	28.9	25.0
September	mean	9.8	12.8	10.5	14.9	15.7	17.4	16.3	18.3
	minimum	5.5	8.8	4.6	10.8	12.8	12.0	9.3	13.3
	maximum	14.3	16.6	16.9	19.7	20.1	23.2	25.2	23.5
October	mean	5.7	8.8	5.0	11.4	13.5	12.7	10.5	14.2
	minimum	0.6	3.5	0.0	7.1	9.6	7.3	2.6	9.1
	maximum	11.2	13.7	12.0	17.3	18.2	18.8	20.0	19.8
November	mean	3.4	6.9	2.1	9.9	12.6	10.5	8.3	12.4
	minimum	0.1	3.2	0.0	6.8	10.5	6.5	4.7	8.5
	maximum	6.9	9.6	6.0	13.6	15.6	13.9	14.9	16.4
December	mean	2.2	5.6	1.0	8.8	12.1	8.4	6.2	10.9
	minimum	0.0	1.3	0.0	5.9	9.9	4.0	0.4	7.4
	maximum	5.2	9.0	3.7	11.8	14.2	12.2	11.2	14.7
January	mean	3.2	6.2	1.3	9.8	12.7	9.4	5.9	11.7
	minimum	0.0	-1.4	0.0	5.9	9.4	5.1	0.1	6.5
	maximum	5.6	9.6	4.1	13.3	15.3	12.5	12.2	15.5
February	mean	3.9	7.3	2.3	10.8	13.4	10.5	8.5	13.2
	minimum	0.0	2.4	0.0	7.0	10.8	5.7	1.8	9.6
	maximum	6.7	10.2	5.7	14.2	16.4	13.6	14.1	16.6
March	mean	5.0	8.1	3.2	11.8	14.1	11.4	9.0	14.3
	minimum	0.0	2.6	0.0	6.7	10.8	5.1	4.3	8.7
	maximum	10.1	12.2	10.7	17.9	18.8	17.2	19.0	21.0
April	mean	7.2	9.9	5.8	13.7	15.7	13.7	11.7	17.0
	minimum	1.7	5.1	0.7	9.8	13.1	8.8	5.7	11.5
	maximum	13.5	15.9	18.3	21.0	21.6	20.4	23.6	24.0
May	mean	7.3	6.9	9.6	11.2	15.1	14.0	14.6	15.3
	minimum	3.9	2.4	1.8	6.4	11.4	9.9	6.8	9.7
	maximum	13.5	14.8	19.0	18.5	21.9	20.1	26.2	22.3
Annual	mean	6.7	9.7	6.8	12.5	15.0	13.7	12.4	15.4
	minimum	0.0	-1.4	0.0	5.9	9.4	4.0	0.1	6.5
	maximum	16.5	20.6	21.4	22.3	24.6	25.6	29.8	25.6

Table 3. Concentrations of cations and anions at study sites in the Firehole River and tributaries. Values are ueq/kg. LFHR = Little Firehole River, IRON = Iron Springs Creek, FC = Fairy Creek, SC = Sentinel Creek, and NP = Nez Perce Creek. COLD, WARM, HOT = mainstem sites.

	Cations				Anions			
Site	Na^+	Ca^{++}	K^+	Mg^{++}	HCO_3^-	Cl^-	SO_4^{2-}	F^-
July 14, 1997								
LFHR	389	194	70	35	1060	73	85	135
WARM	1233	166	102	33	880	360	69	282
IRON	1619	193	138	35	460	663	78	297
FC	4090	205	146	35	2080	1484	150	516
HOT	2462	189	152	29	1160	912	113	294
November 24, 1997								
LFHR	565	263	82	37	500	117	144	166
WARM	1917	191	132	31	1220	895	110	272
IRON	1558	187	132	34	1000	652	85	258
FC	4679	195	161	34	2220	2195	181	537
HOT	3558	248	184	29	1860	1687	163	383
February 4, 1998								
LFHR	610	284	87	41	680	129	138	173
WARM	1850	200	195	33	1140	1047	126	348
IRON	1799	211	159	36	1140	931	85	299
FC	5416	196	240	39	2680	2702	198	616
HOT	3922	263	243	30	2160	2050	172	403
April 28, 1997								
LFHR	575	264	84	44	620	118	119	142
WARM	1975	208	140	37	1100	894	108	253
IRON	1901	196	150	36	1220	812	98	295
FC	3942	169	164	41	1240	1862	146	484
HOT	3571	231	205	31	1920	1907	173	389

Table 4. Relative composition (%) of rainbow trout and brown trout juveniles and adults in the Firehole River drainage, Wyoming, among eight observation periods combined from July to November 1997.

	Adults		Juveniles	
Site	Rainbow trout	Brown trout	Rainbow trout	Brown trout
Cold	20.5	79.5	1.2	98.8
Warm	48.0	52.0	39.6	60.4
Hot	88.0	12.0	93.5	6.5
Little Firehole River	30.0	70.0	16.2	83.8
Iron Springs Creek	71.4	28.6	70.8	29.2
Fairy Creek	100.0	0.0	100.0	0.0

Table 5. Data used in Habitat Quality Index (HQI) evaluations of study sites in the Firehole River and tributaries, Yellowstone National Park,Wyoming, 1997. LFHR = Little Firehole River, IRON = Iron Springs Creek, FC = Fairy Creek, SC = Sentinel Creek, and NP = Nez Perce Creek. COLD, WARM, HOT = mainstem sites.

	Site							
HQI Parameters	COLD	LFHR	SC	WARM	IRON	NP	FC	HOT
Late Summer Stream Flow (%)	96	97	91	113	116	95	96	101
Rating	4	4	4	4	4	4	4	4
ASFV = annual stream flow variation	2.9	3.6	1.3	2.3	1.6	1.7	1.4	1.7
Rating	4	4	4	4	4	4	4	4
Maximum Summer Stream Temperature (°C)	16.5	20.6	21.4	22.3	24.6	25.6	29.8	25.6
Rating	4	3	3	2	1	1	0	1
Mean Nitrate-Nitrogen (mg/L)	0.2	0.3	0.8	0.3	0.3	0.2	0.2	0.2
Rating	4	3	2	3	3	4	4	4
Cover (% surface area)	13	14	33	47	6	4	11	6
Rating	1	1	2	3	0	0	1	0
Eroding Stream Banks (% surface area)	0	1	4	0	0	0	7	0
Rating	4	4	4	4	4	4	4	4
Substrate (% surface area)	0	2	20	18	31	10	13	35
Rating	2	2	3	4	4	3	2	4
Water Velocity (cm/s)	55	58	59	130	62	49	33	137
Rating	4	4	4	3	4	4	3	3
Stream Width (m)	13.5	9.0	2.9	18.3	10.7	11.9	2.7	21.9
Rating	3	3	2	2	3	3	2	2

Table 6. Predictions of standing stock and habitat quality units from the Habitat Quality Index (HQI) evaluations of study sites in the Firehole River and tributaries, Yellowstone National Park, Wyoming, 1997. LFHR = Little Firehole River, IRON = Iron Springs Creek, FC = Fairy Creek, SC = Sentinel Creek, and NP = Nez Perce Creek. COLD, WARM, HOT = mainstem sites.

	Site							
HQI Parameters	COLD	LFHR	SC	WARM	IRON	NP	FC	HOT
	Actual Temperatures							
Standing Stock of Trout (kg/ha)	524	277	291	219	57	57	2	57
Habitat Quality Units	505	267	280	211	55	55	2	55
	Constant Acceptable Temperatures							
Standing Stock of Trout (kg/ha)	332	277	291	403	268	268	259	268
Habitat Quality Units	320	267	280	388	258	258	250	258

Table 7. Numbers of spawning redds observed in the Firehole River and tributaries, Wyoming, 1997-1998. Numbers are included for sites surveyed on a particular date.

	Date					
Site	Nov 5	Dec 3	Dec 23	Jan 21	Feb 5	Mar 5
Firehole River - Upper	34					
Little Firehole River	44					
Firehole River - Lower		54	2	19		
Fairy Creek		42		3	0	
Nez Perce Creek			5			11

Table 8. Number of rainbow trout and brown trout fry collected near spawning areas in the Firehole River and tributaries, Yellowstone National Park, Wyoming, 1998.

	Rainbow trout				Brown trout			
Site	March	April	May	Total	March	April	May	Total
Little Firehole River	0	3	10	13	0	12	10	22
Fairy Creek	12	9		21	0	1		1
Hot Site	23		26	49	1		2	3
Nez Perce Creek	9			9	3			3

Table 9. Temperature tolerances for post-hatch lifestages of rainbow trout Oncorhynchus mykiss. Young of year (YOY; < 10 cm), juvenile (10-30 cm), adult (> 30 cm). UILT = upper incipient lethal temperature.

Age Class	Lengths mean (range)	Weight mean (range)	Acclimation temperature (°C)	Exposure method	UILT (°C)	Reference
YOY	4.5 cm		18	24-hr TL50	26.5	Alabaster and Welcomme 1962
YOY	n/a		15	24-hr TL50	25.0	Bidgood and Berst 1969
YOY	50-100mm FL		18	7-day no mortality	25.0	Cherry et al. 1977
YOY	30 mm TL	245 mg	16	24 and 96-hr TL50	25.6	Hokanson et al. 1977
YOY	30 mm TL	245 mg	16	diel fluctuations[1]	24.0	Hokanson et al. 1977
YOY	20-70 mm		5	7-day TL50	23.7	Kaya 1978; Ennis strain
YOY	20-70 mm		9	7-day TL50	24.2	Kaya 1978; Ennis strain
YOY	20-70 mm		13	7-day TL50	25.2	Kaya 1978; Ennis strain
YOY	20-70 mm		17	7-day TL50	25.7	Kaya 1978; Ennis strain
YOY	20-70 mm		21	7-day TL50	26.2	Kaya 1978; Ennis strain
YOY	20-70 mm		24.5	7-day TL50	26.2	Kaya 1978; Ennis strain
YOY	20-70 mm		24.5	7-day TL50	26.2	Kaya 1978; Firehole River strain
juvenile			6	24-hr TL50	24.3	Alabaster 1964
juvenile			15	24-hr TL50	25.9	Alabaster 1964
juvenile			20	24-hr TL50	26.7	Alabaster 1964
juvenile		26 (14-54) g	11	24-hr TL50	24.0	Black 1953
juvenile	18-23 cm FL	65-123 g	12	24-hr TL50	24.9	Charlon et al. 1970
juvenile	18-23 cm FL	65-123 g	14	24-hr TL50	25.2	Charlon et al. 1970
juvenile	18-23 cm FL	65-123 g	16	24-hr TL50	25.4	Charlon et al. 1970
juvenile	18-23 cm FL	65-123 g	18	24-hr TL50	25.3	Charlon et al. 1970
juvenile	18-23 cm FL	65-123 g	20	24-hr TL50	25.8	Charlon et al. 1970

Table 9. Continued.

Age Class	Lengths mean (range)	Weight mean (range)	Acclimation temperature (°C)	Exposure method	UILT (°C)	Reference
juvenile	18-23 cm FL	65-123 g	24	24-hr TL50	26.4	Charlon et al. 1970
juvenile			20.0	96-hr TL50	27.0	Craigie 1963
juvenile				FTDMS-derived[2]	24.0	Eaton et al. 1995 - FTDMS
juvenile	110-130 mm		5	7-day TL50	25.0	Kaya 1978; Firehole River strain
juvenile	110-130 mm		9	7-day TL50	25.2	Kaya 1978; Firehole River strain
juvenile	110-130 mm		13	7-day TL50	25.2	Kaya 1978; Firehole River strain
juvenile	110-130 mm		17	7-day TL50	25.7	Kaya 1978; Firehole River strain
juvenile	110-130 mm		21	7-day TL50	26.2	Kaya 1978; Firehole River strain
juvenile	110-130 mm		24.5	7-day TL50	26.2	Kaya 1978; Firehole River strain
juvenile	110-130 mm		5	7-day TL50	23.2	Kaya 1978; Winthrop strain
juvenile	110-130 mm		9	7-day TL50	24.7	Kaya 1978; Winthrop strain
juvenile	110-130 mm		13	7-day TL50	24.7	Kaya 1978; Winthrop strain
juvenile	110-130 mm		17	7-day TL50	25.2	Kaya 1978; Winthrop strain
juvenile	110-130 mm		21	7-day TL50	25.7	Kaya 1978; Winthrop strain
juvenile	110-130 mm		24.5	7-day TL50	26.2	Kaya 1978; Winthrop strain

Table 9. Continued.

Age Class	Lengths mean (range)	Weight mean (range)	Acclimation temperature (°C)	Exposure method	UILT (°C)	Reference
juvenile		3 ± 1.1 g	4.0	96-hr TL50[3]	22.6	Threader and Houston 1983
juvenile		3 ± 1.1 g	8.0	96-hr TL50	24.0	Threader and Houston 1983
juvenile		3 ± 1.1 g	12.0	96-hr TL50	24.5	Threader and Houston 1983
juvenile		3 ± 1.1 g	16.0	96-hr TL50	25.1	Threader and Houston 1983
juvenile		3 ± 1.1 g	20.0	96-hr TL50	25.5	Threader and Houston 1983
juvenile		3 ± 1.1 g	12.0 ± 4	96-hr TL50	24.8	Threader and Houston 1983
juvenile		3 ± 1.1 g	12.0 ± 6.5	96-hr TL50	25.0	Threader and Houston 1983
				mean	25.2	
				SD	1.0	
				range	22.6-27.0	

[1] Hokanson (1977) exposed fish to diel fluctuations in temperature of ± 3.8°C; 24°C is the mean daily temperature under this pattern for the UILT.

[2] FTDMS: UILT determined as the 95th percentile of mean weekly temps of field data from the "Fish and Temperature Database Matching System" (Eaton et al. 1995)

[3] Threader and Houston (1983) diel fluctuations of temperature: 12 ± 4°C and 12 ± 6.5°C.

Table 10. Temperature tolerances for post-hatch lifestages of brown trout Salmo trutta. Young of year (YOY; < 10 cm), juvenile (10-30 cm), adult (> 30 cm). UILT = upper incipient lethal temperature.

Age Class	Lengths mean (range)	Weight mean (range)	Acclimation temperature (°C)	Exposure method	UILT (°C)	Reference
YOY			6	16-day no mortality	21.0	Bishai 1960
YOY			5	7-day no mortality	22.0	Bishai 1960
YOY			10	7-day no mortality	23.0	Bishai 1960
YOY			20	7-day no mortality	23.0	Bishai 1960
juvenile	50-100 mmFL		12	7-day no mortality	23.0	Cherry et al. 1977
juvenile	13 cm		16.7	1000-min TL50	24.9	Alabaster1967
juvenile	21 cm		16.7	1000-min TL50	24.0	Alabaster1967
juvenile	n/a			FTDMS-derived[1]	24.1	Eaton et al. 1995 - FTDMS
juvenile			23	7-day no mortality	25.3	Frost and Brown 1967
juvenile					26.4	Alabaster1967
juvenile			5	7-day TL50	22.5	Frost and Brown 1967
juvenile			10	7-day TL50	24.2	Frost and Brown 1967
juvenile			15	7-day TL50	24.5	Frost and Brown 1967
juvenile			20	7-day TL50	24.8	Frost and Brown 1967
juvenile			23	7-day TL50	25.3	Frost and Brown 1967
				mean	23.9	
				SD	1.4	
				range	21.0-26.4	

[1] FTDMS: UILT determined as the 95th percentile of mean weekly temps of field data from the "Fish and Temperature Database Matching System" (Eaton et al. 1995).

Table 11. Temperature tolerances for embryonic development of rainbow trout Oncorhynchus mykiss, brown trout Salmo trutta.

	Temperature Tolerance (°C)			
Temperatures tested (°C)	Lower mortality limit	Tolerated	Upper mortality limit	Reference
	Rainbow trout			
2,4,7	2	4,7		Stonecypher et al. 1994
5.5-15.2		5.5-15.2		Estay et al. 1994
3,7,11,15,19	3	7,11	15,18	Humpesch 1985
3,5,7,10,15	2	5,7	10,13	Timoshina 1972
3,5,7,10,15	3,5	7,10	15	Kwain 1975
5,8,9.5,12	5	8,9.5	12	Danzmann and Ferguson 1988
6-12		6-12		Hokanson et al. 1977
3.2-15.5	6	7-15.5		Embody 1934[2]
	Brown trout			
2,4,7		2,4,7		Stonecypher et al. 1994
1,5,8,13,15		1,5,8	13,15	Humpesch 1985
4,6,7,8,11,13		4,6,7,8	11,13	Jungwirth and Winkler 1984
field		3.3-7.4		Elliot 1984
1.9-11.2		1.9-11.2		Embody 1934[2]

Note: temperatures assigned to lower and upper mortality limits when survivorship to hatching < 75%

[1] temperatures are nominal ± 95% CL and percent survivial is mean (SE)

[2] tested 23 separate temperatures between 3.2-15.5°C for rainbow trout, and 29 individual temperatures between 1.9-11.2°C for brown trout.

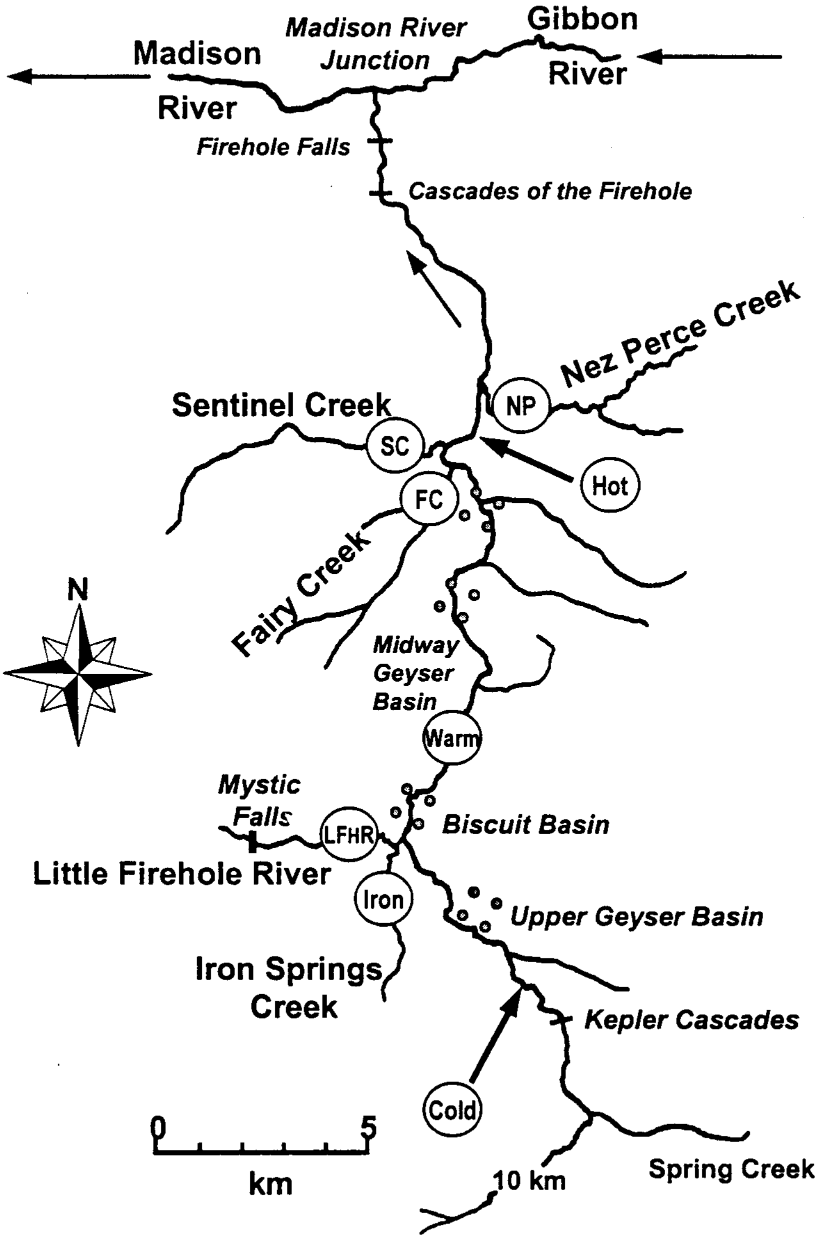
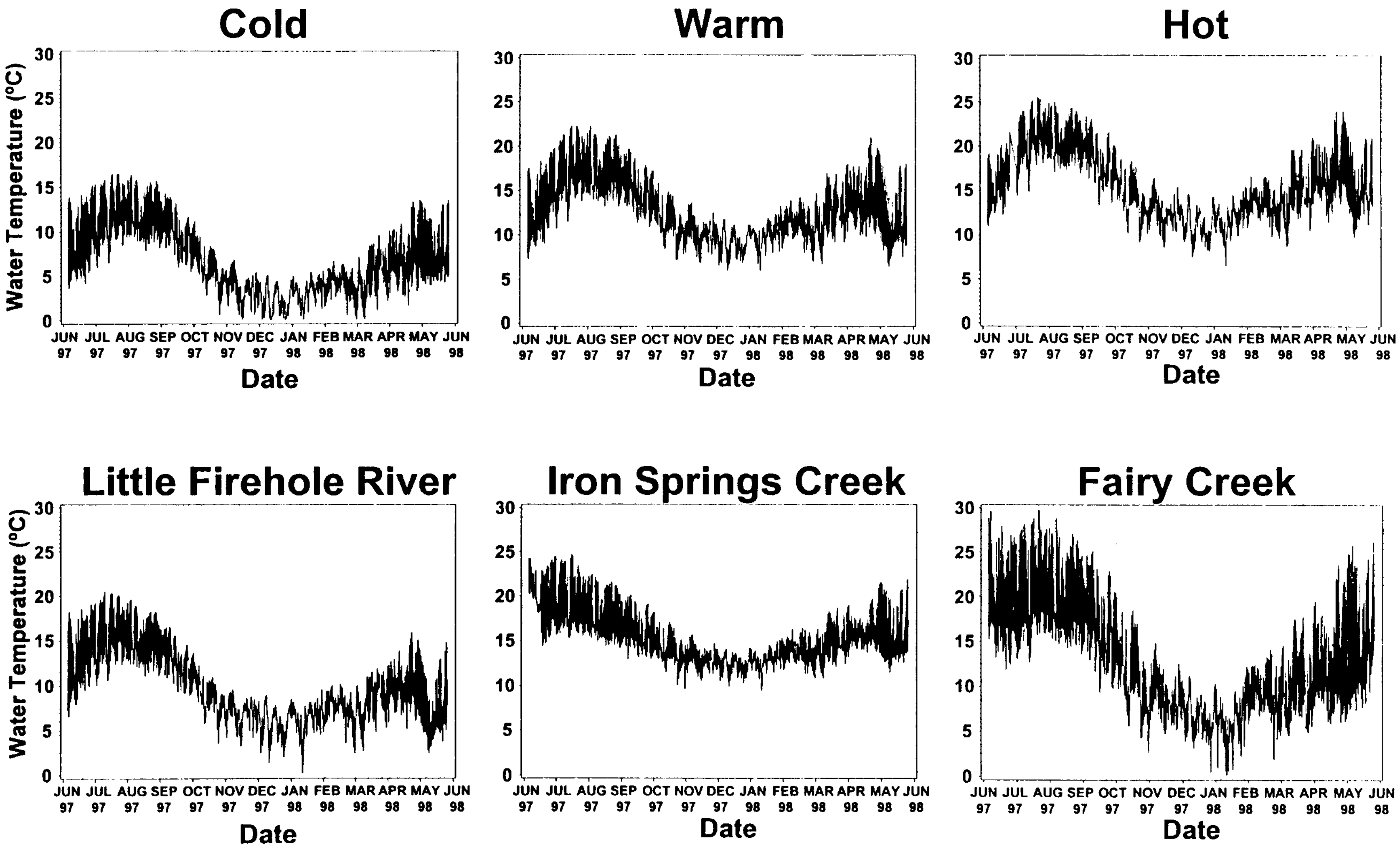


Figure 1. Map of the Firehole River drainage, Yellowstone National Park, Wyoming. Circles indicate study sites for water quality sampling and trout population surveys. IRON (Iron Springs Creek), LFHR (Little Firehole River), FC (Fairy Creek), SC (Sentinel Creek), NP (Nez Perce Creek). Study sites in the mainstem of the Firehole are identified as the Cold, Warm, and Hot sites.


Cold

Warm

Hot

Little Firehole River

Iron Springs Creek

Fairy Creek

Figure 2. Hourly water temperatures at study sites in the Firehole River and tributaries, June 1997 - June 1998.

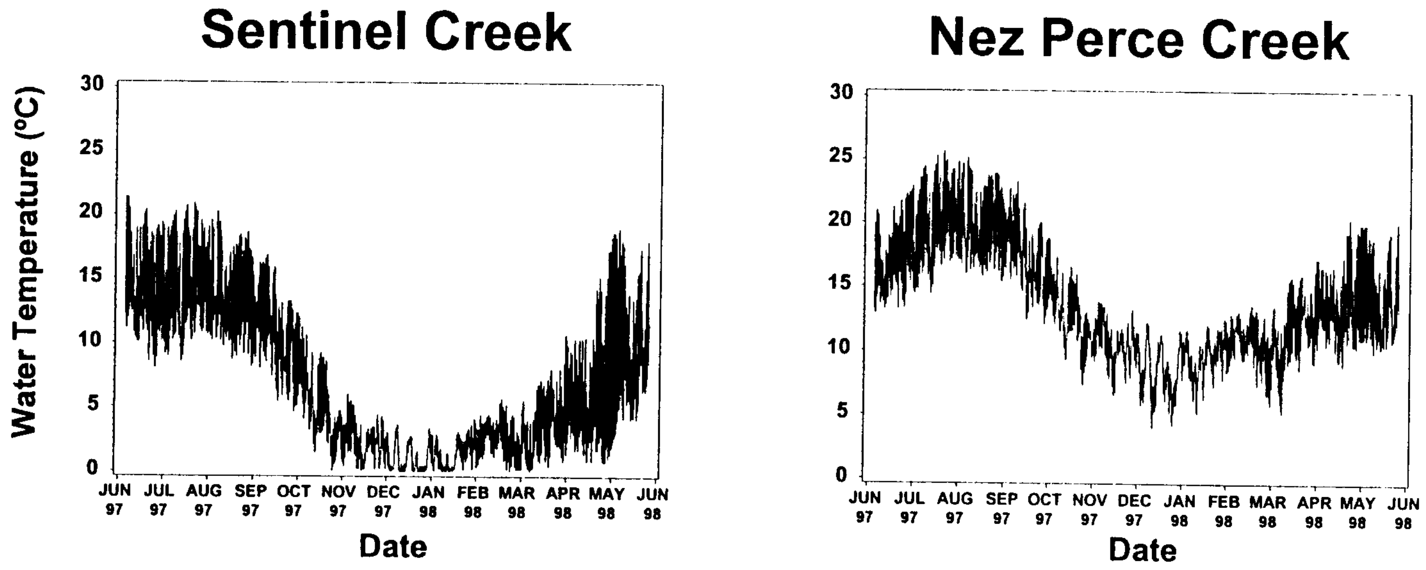


Figure 3. Hourly water temperatures at the Sentinel Creek and Nez Perce Creek study sites in the Firehole River and tributaries, June 1997 - June 1998.

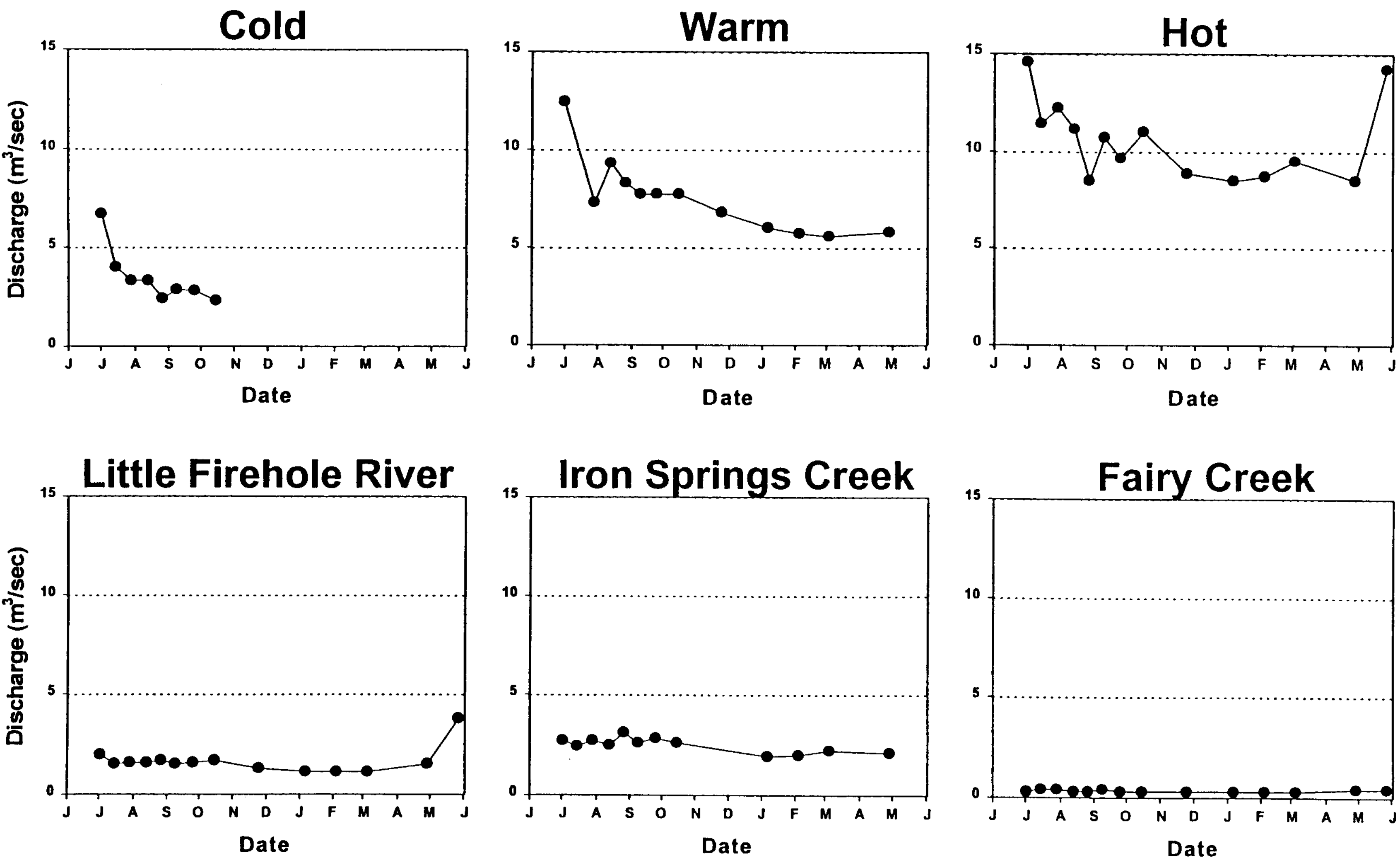


Figure 4. Discharge in the study sites on the Firehole River and tributaries, June 1997 - June 1998.

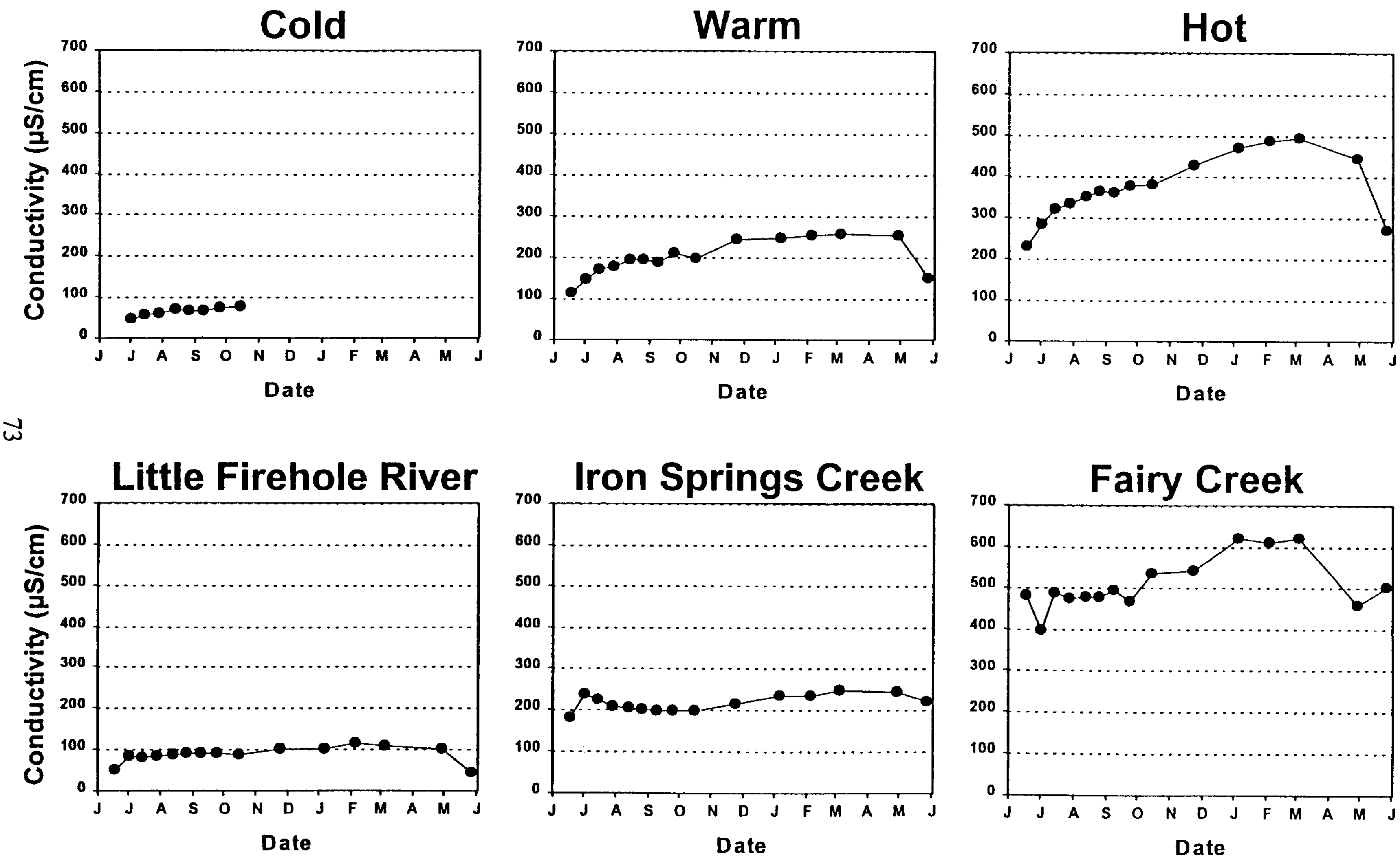


Figure 5. Specific conductivity in the study sites on the Firehole River and tributaries, June 1997 - June 1998.

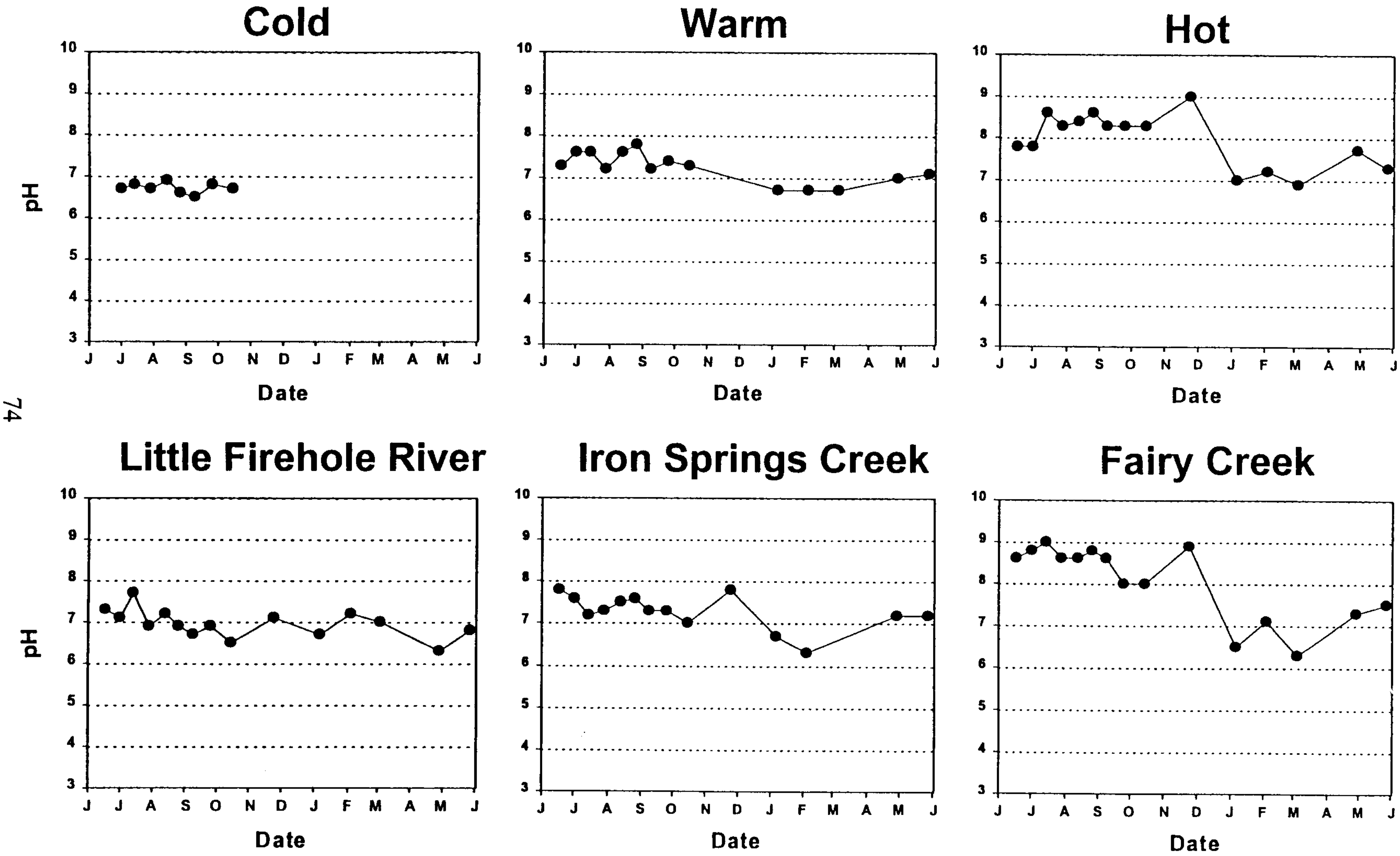


Figure 6. pH in the study sites on the Firehole River and tributaries, June 1997 - June 1998. Values are standard units.

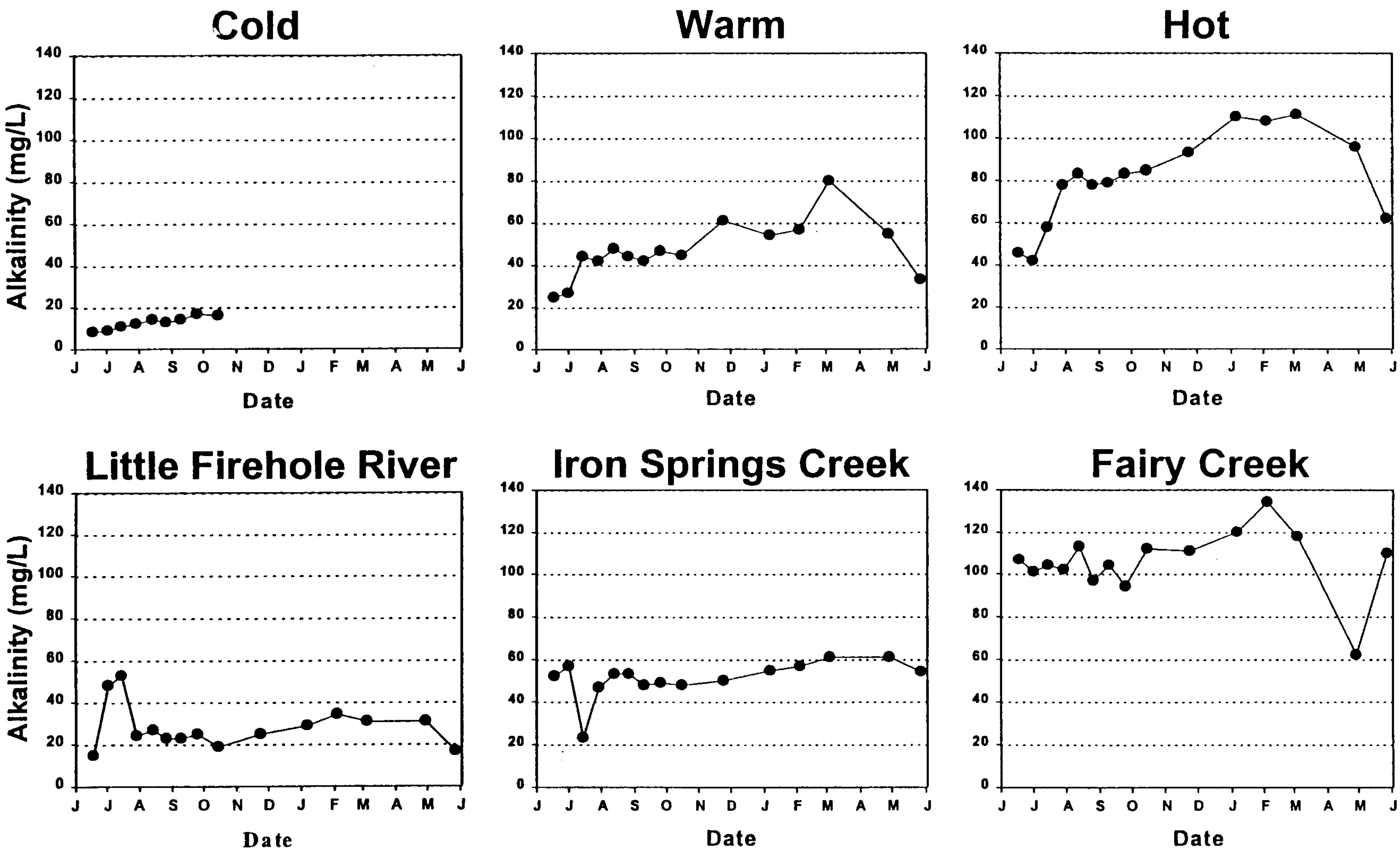


Figure 7. Alkalinity concentrations (as mg $CaCO_3$/L) measured at the study sites on the Firehole River and tributaries, June 1997 - June 1998.

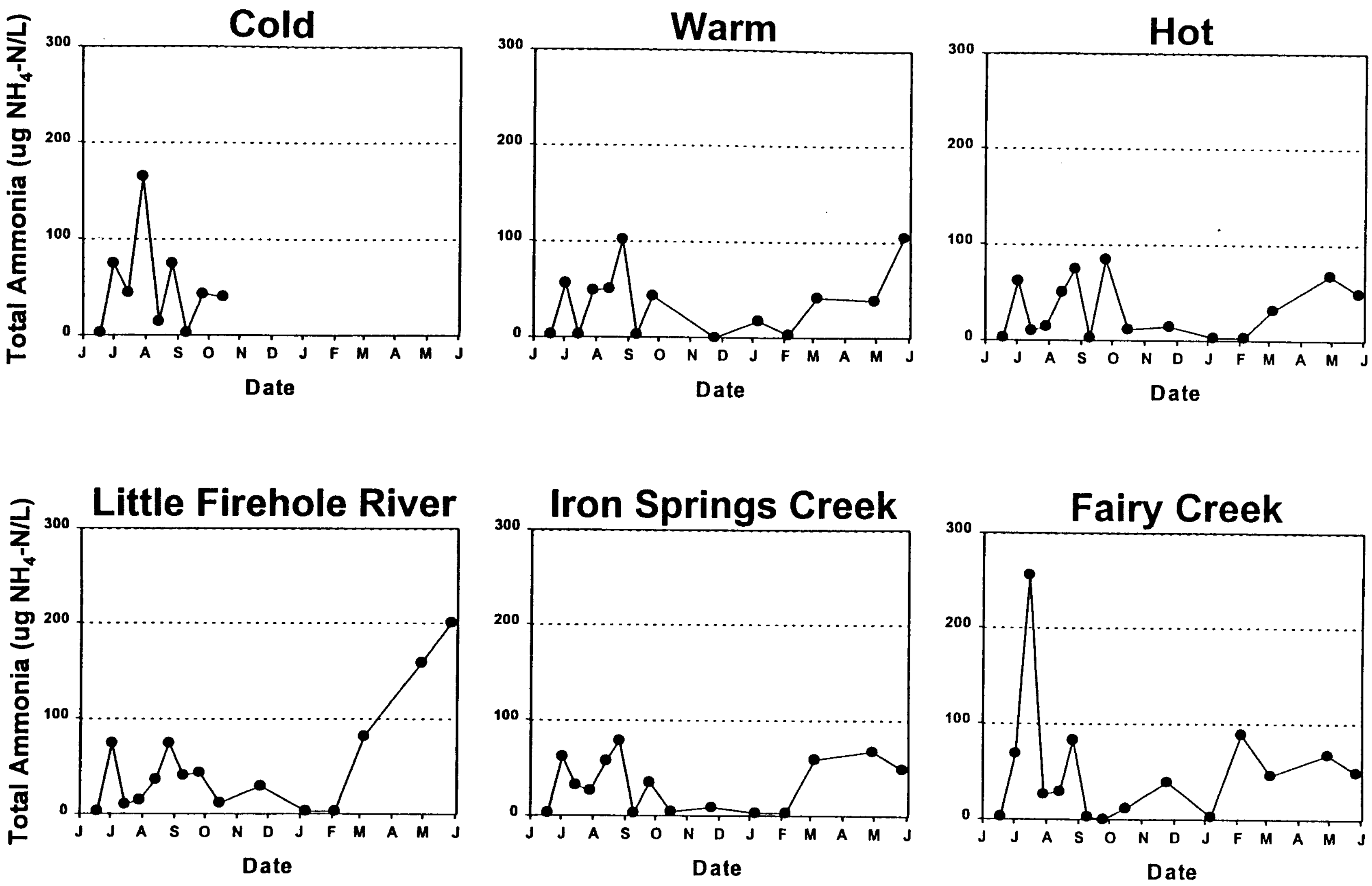


Figure 8. Total ammonia (µg NH_4-N/L) concentrations measured at the study sites on the Firehole River and tributaries, June 1997 - June 1998.

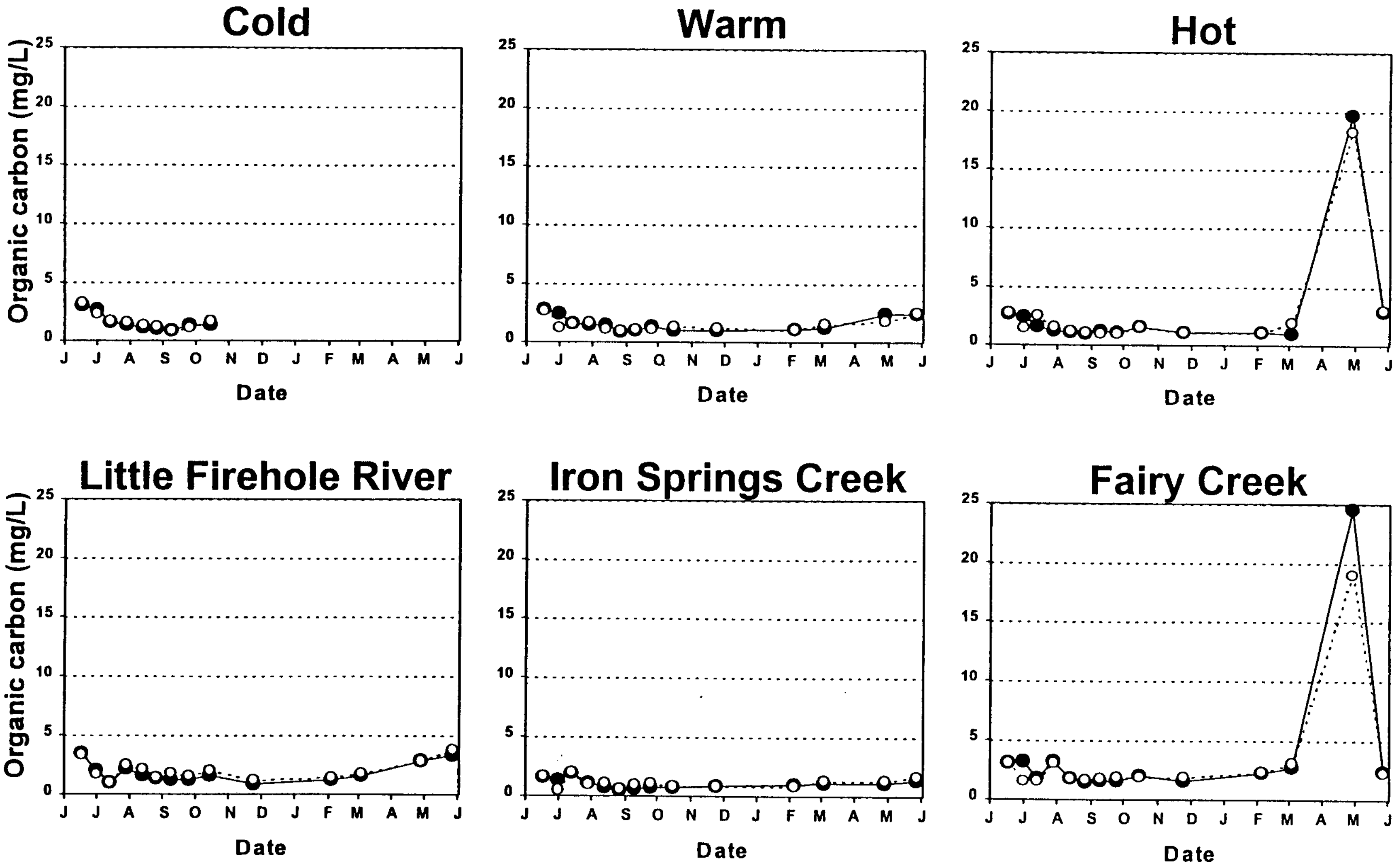


Figure 9. Total (●) and dissolved (○) organic carbon concentrations measured in the study sites on the Firehole River and tributaries, June 1997 - June 1998.

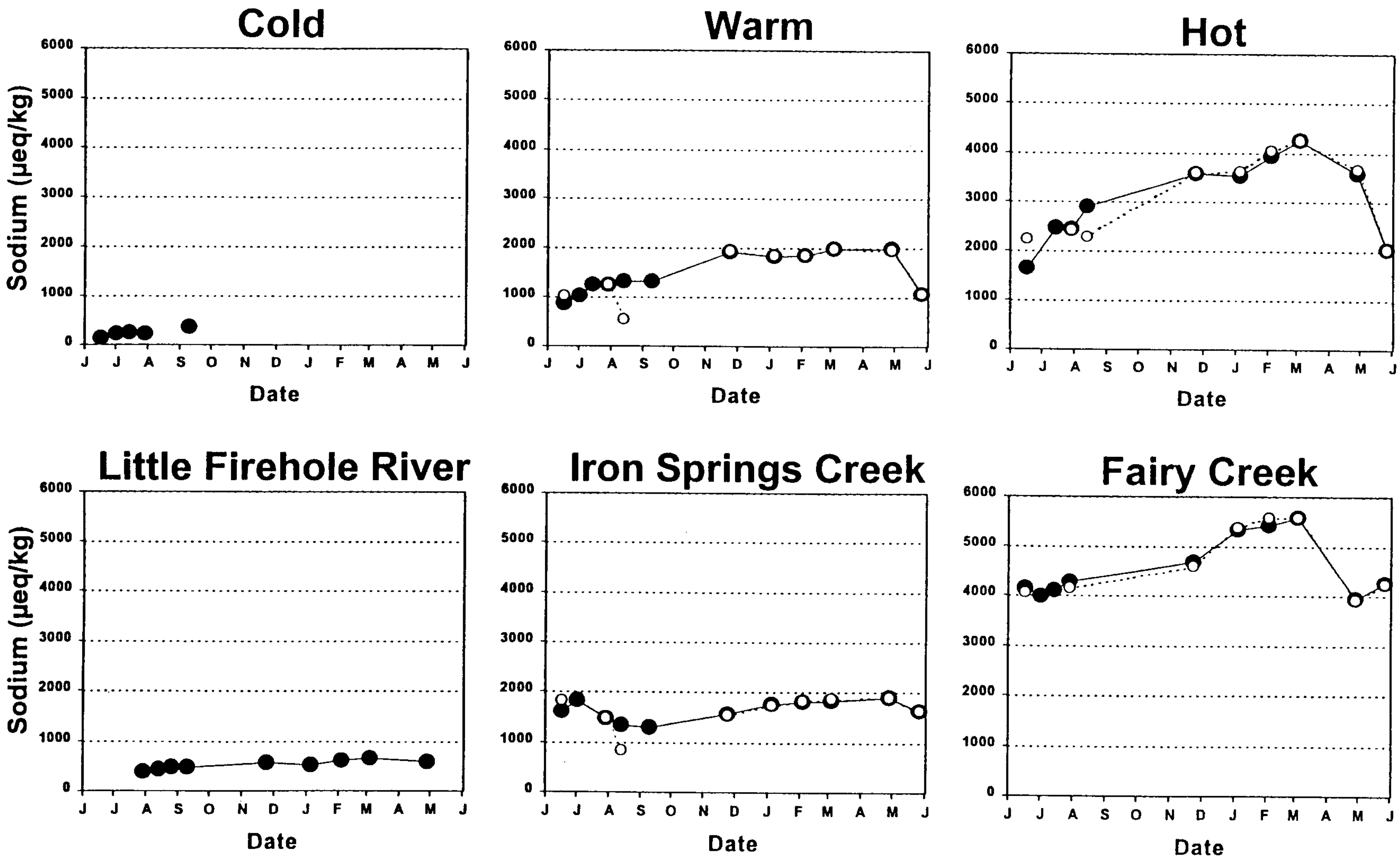


Figure 10. Total (●) and dissolved (O) sodium (Na$^+$) concentrations measured in the study sites on the Firehole River and tributaries, June 1997 - June 1998.

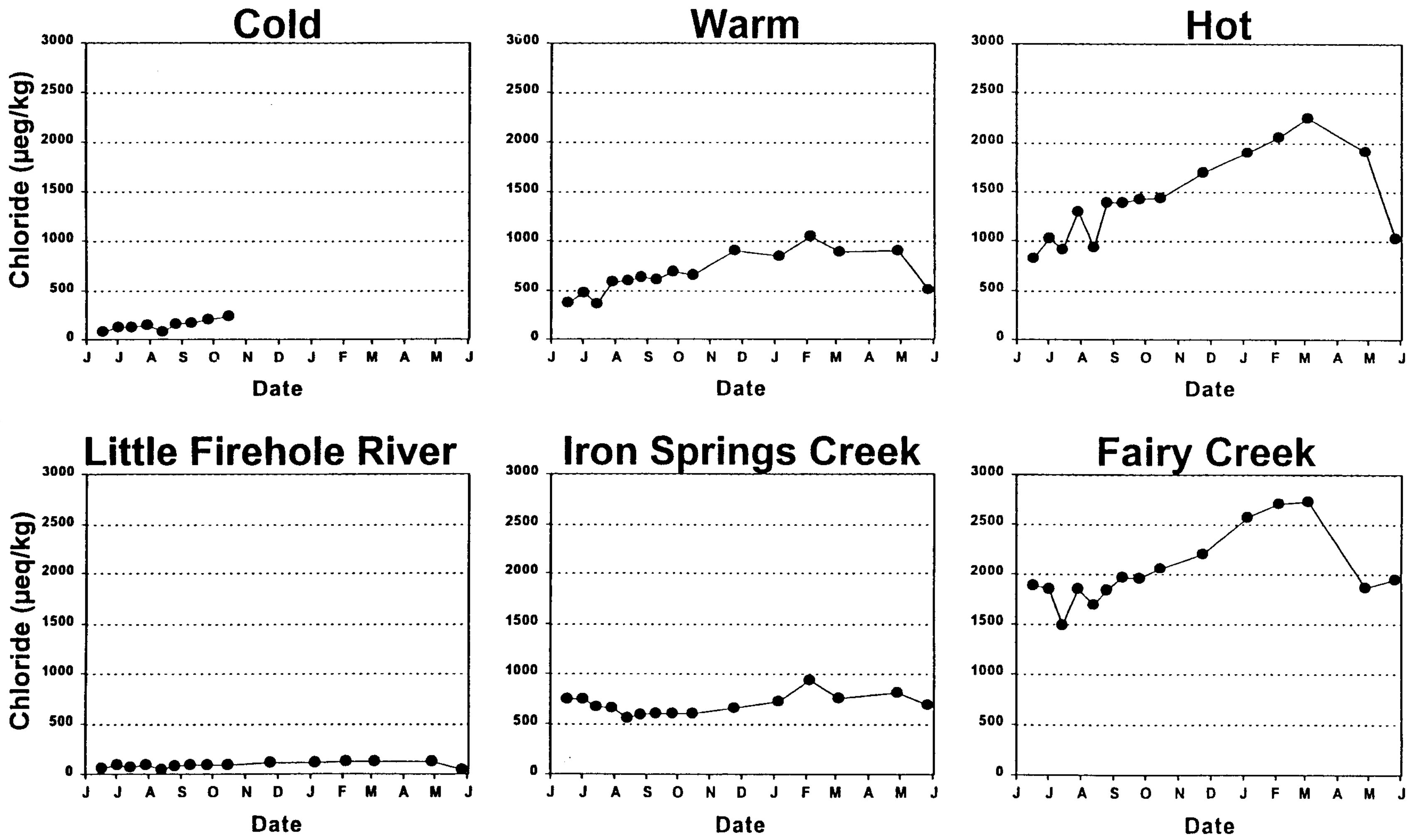


Figure 11. Chloride (Cl⁻) concentrations measured in the study sites on the Firehole River and tributaries, June 1997 - June 1998.

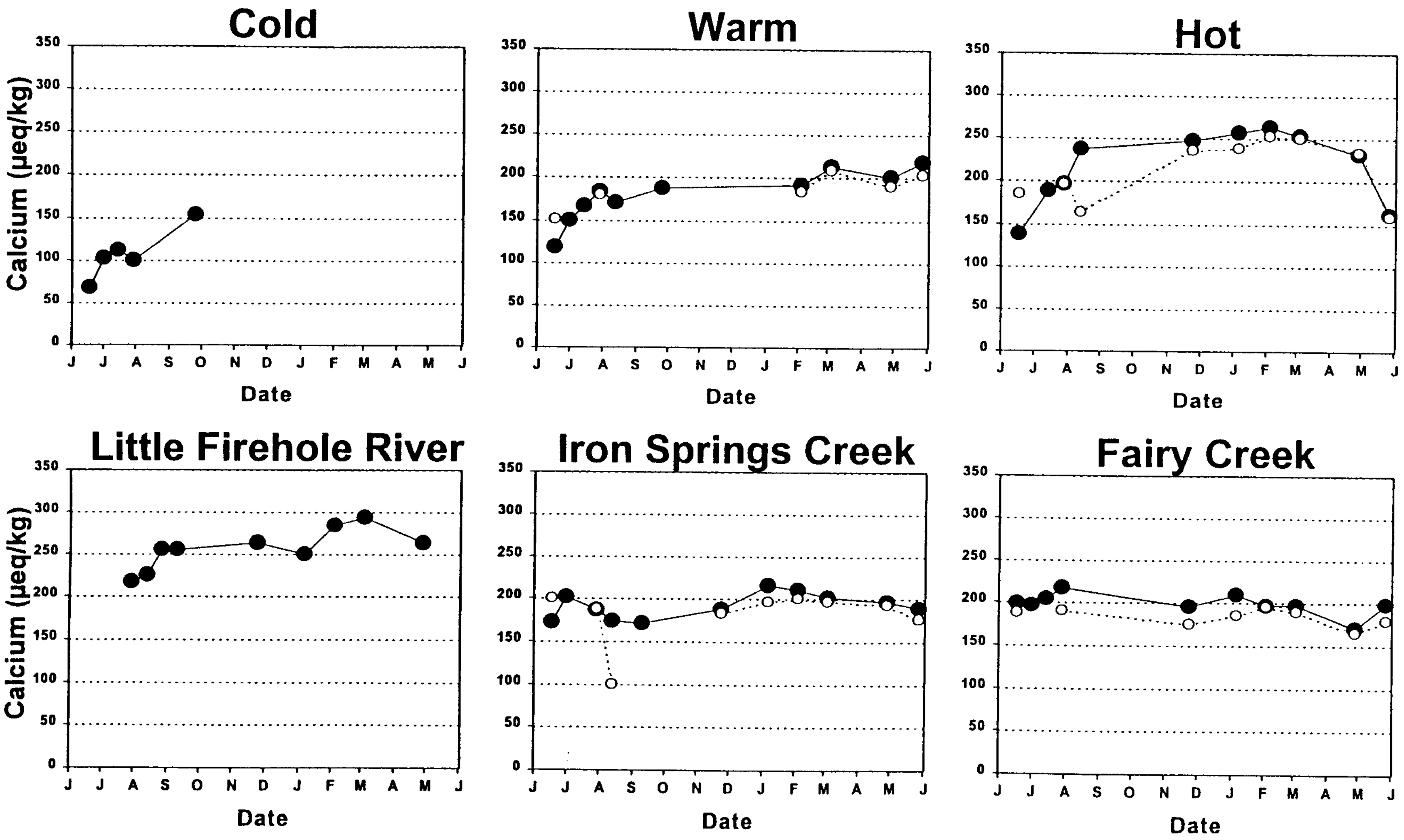


Figure 12. Total (●) and dissolved (○) calcium (Ca^{+}) concentrations measured at the study sites on the Firehole River and tributaries, June 1997 - June 1998.

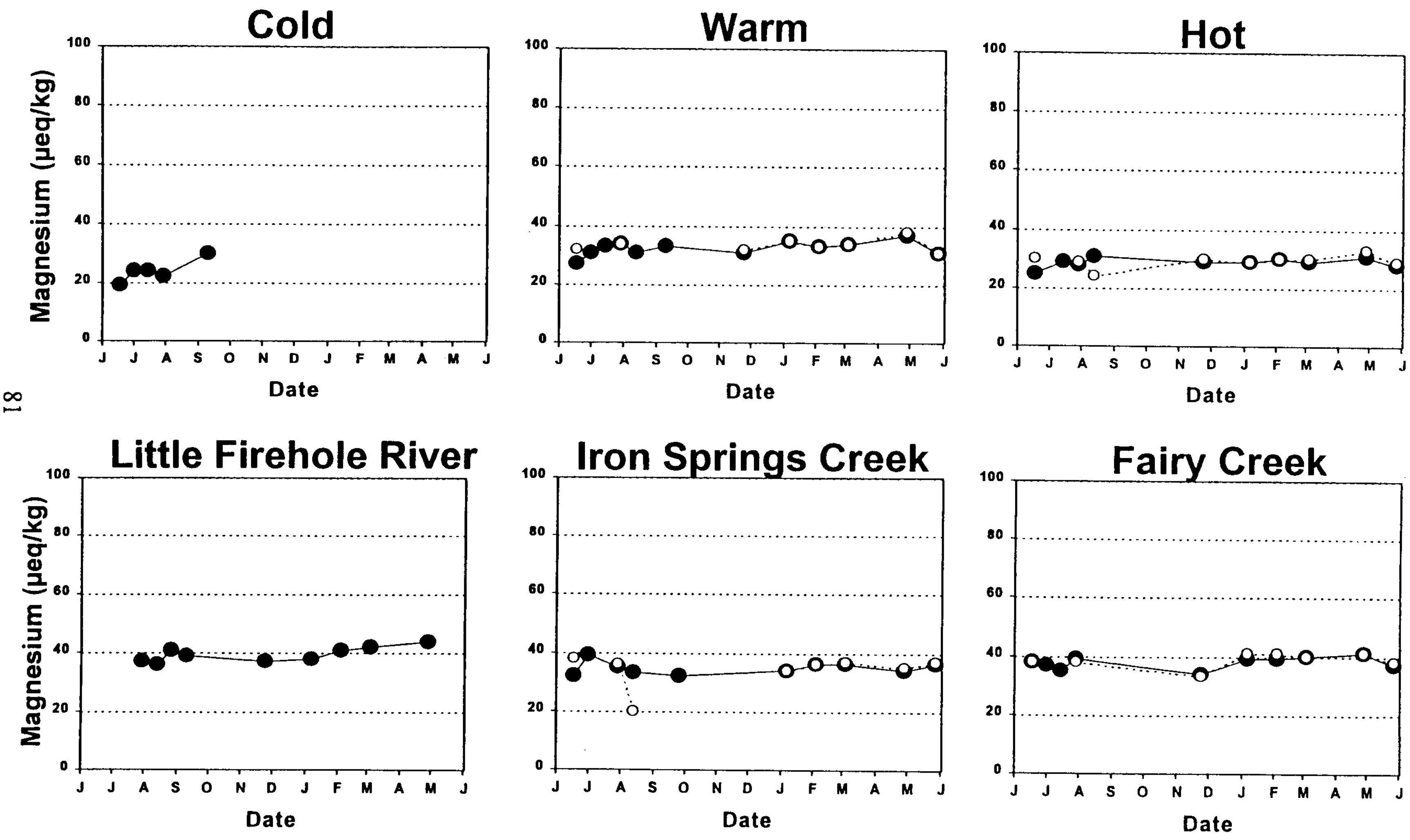


Figure 13. Total (●) and dissolved (○) magnesium (Mg^{2+}) concentrations measured at the study sites on the Firehole River and tributaries, June 1997 - June 1998.

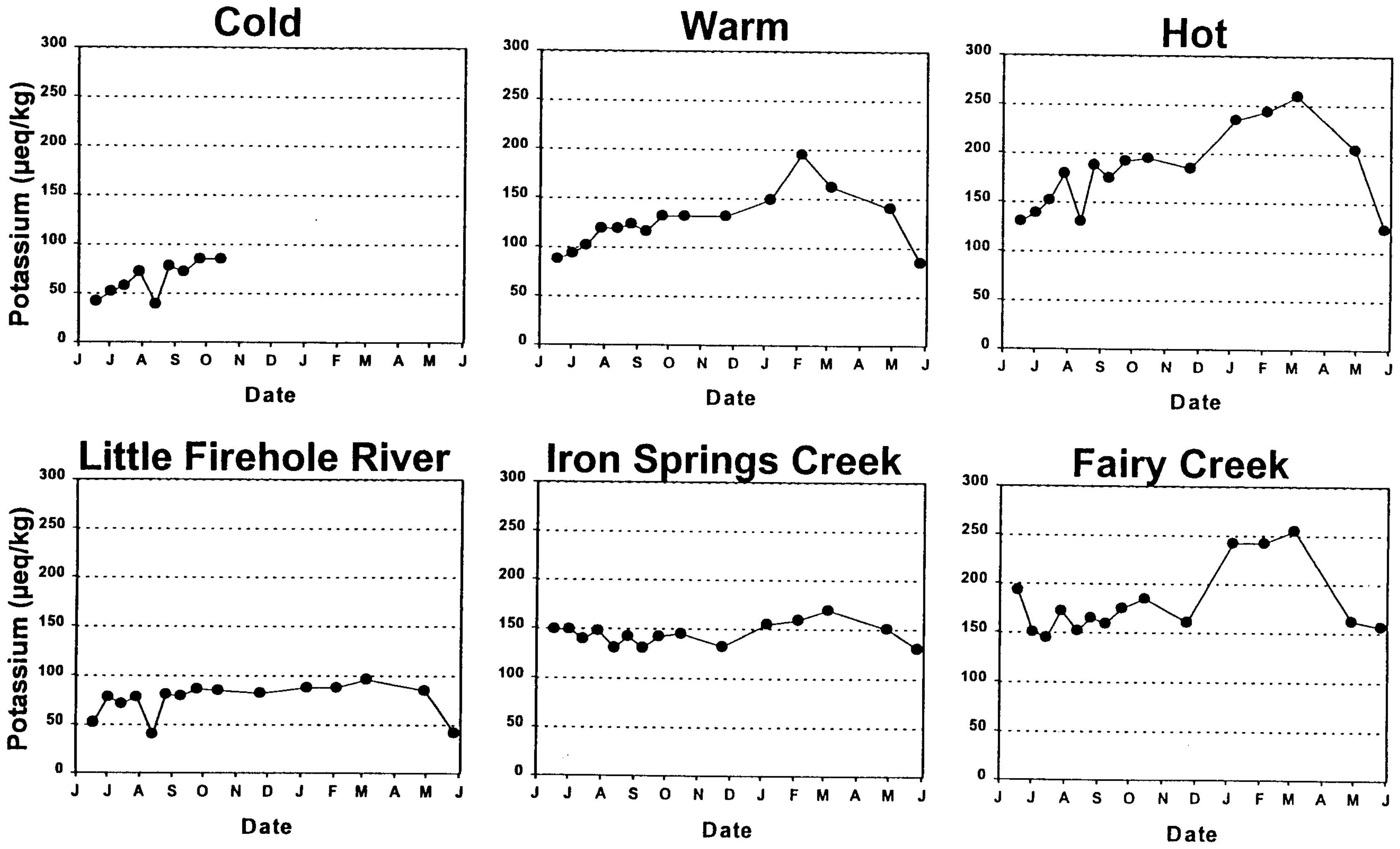


Figure 14. Potassium (K^+) concentrations measured at the study sites on the Firehole River and tributaries, June 1997 - June 1998.

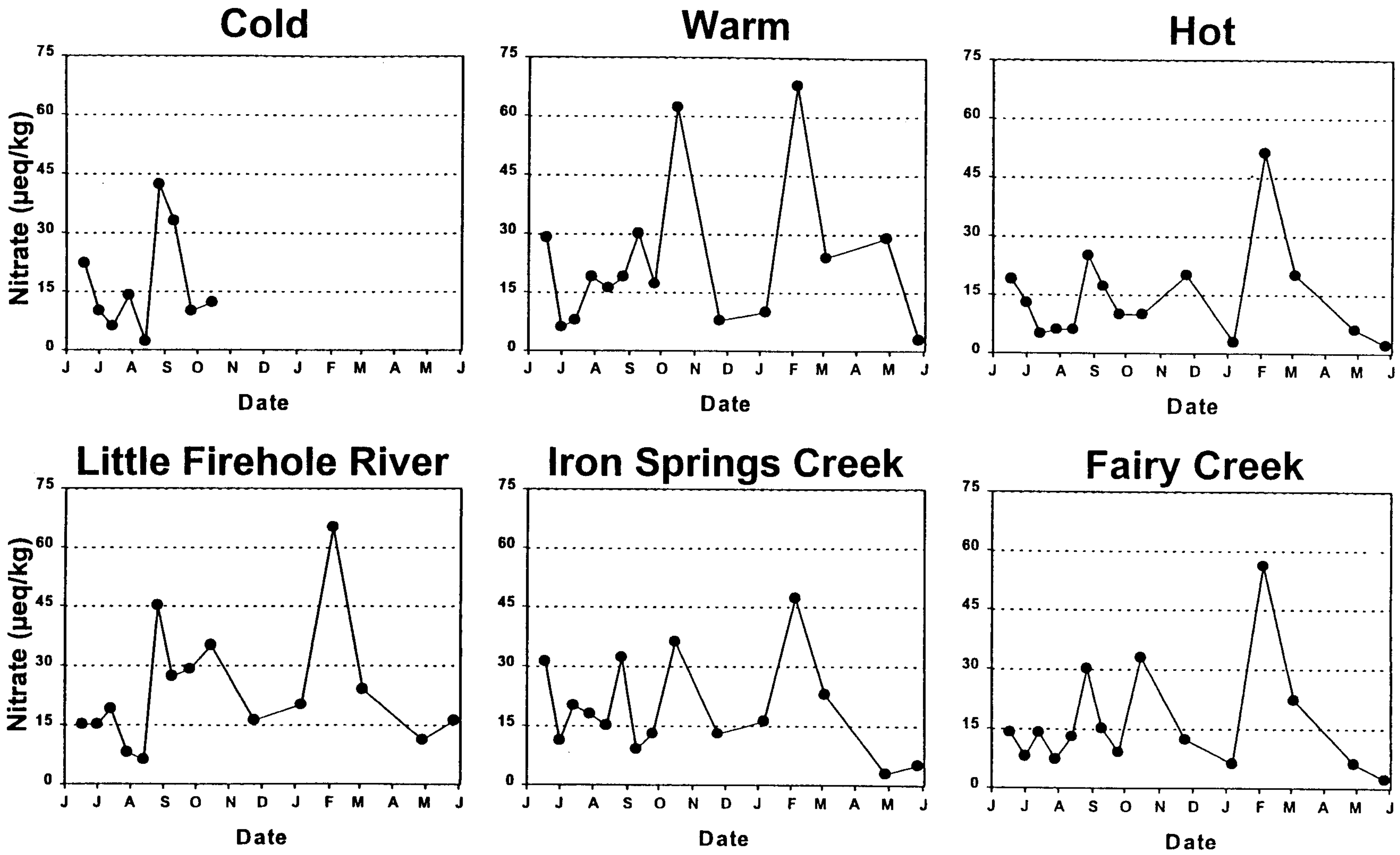


Figure 15. Nitrate (NO_3^-) concentrations measured at the study sites on the Firehole River and tributaries, June 1997 - June 1998.

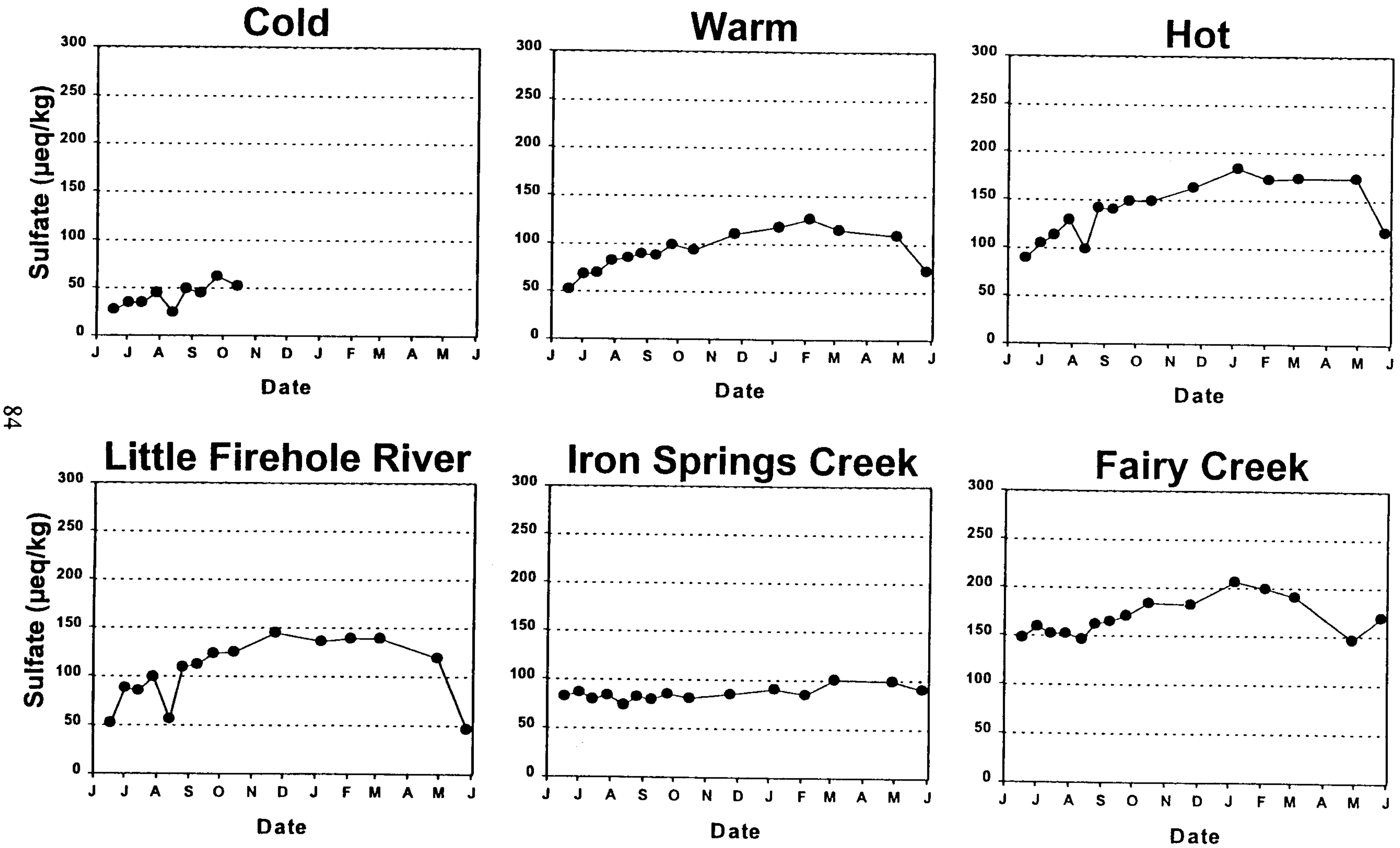


Figure 16. Sulfate (SO_4^{2-}) concentrations measured at the study sites on the Firehole River and tributaries, June 1997 - June 1998.

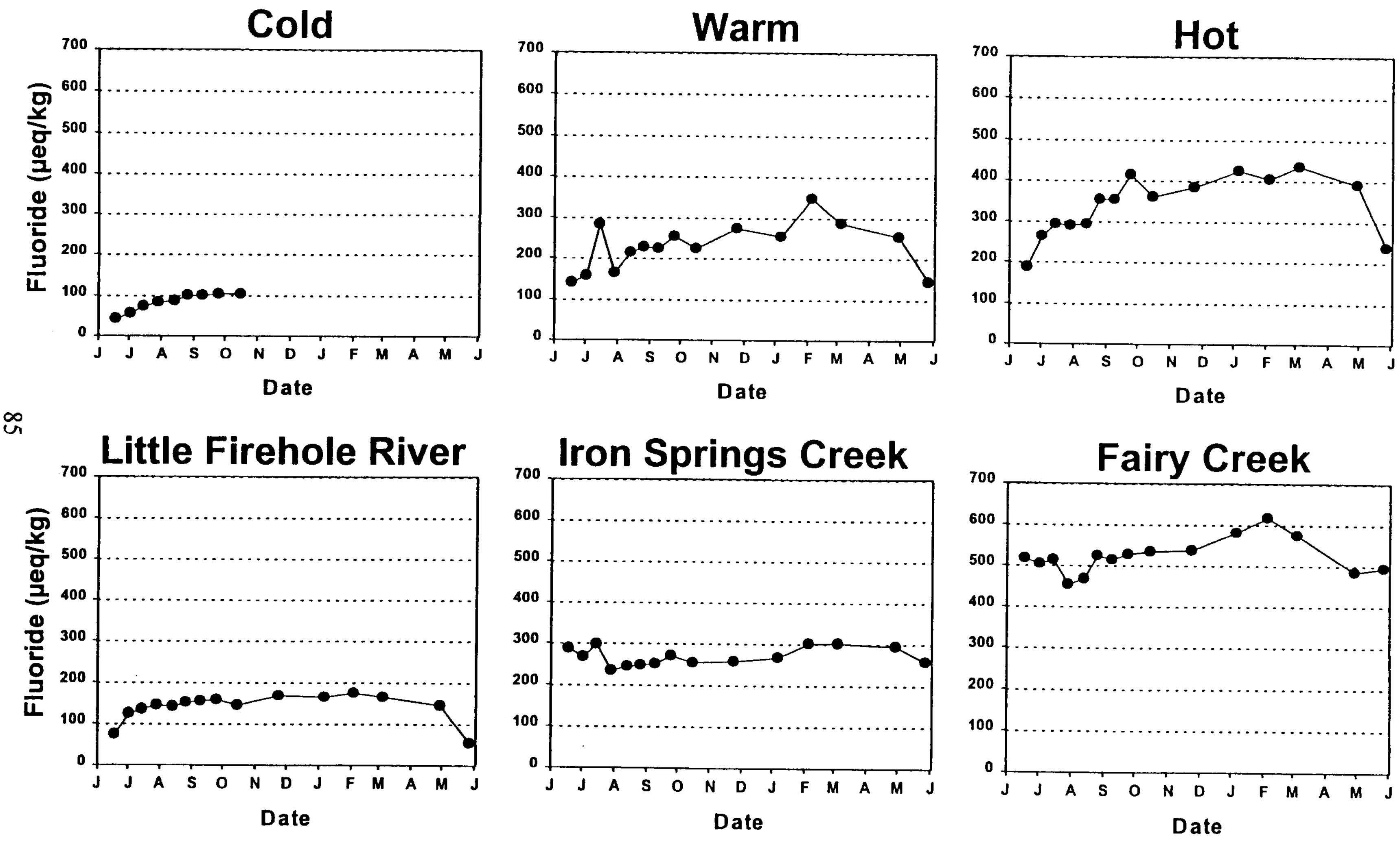


Figure 17. Fluoride (F$^-$) concentrations measured at the study sites on the Firehole River and tributaries, June 1997 - June 1998.

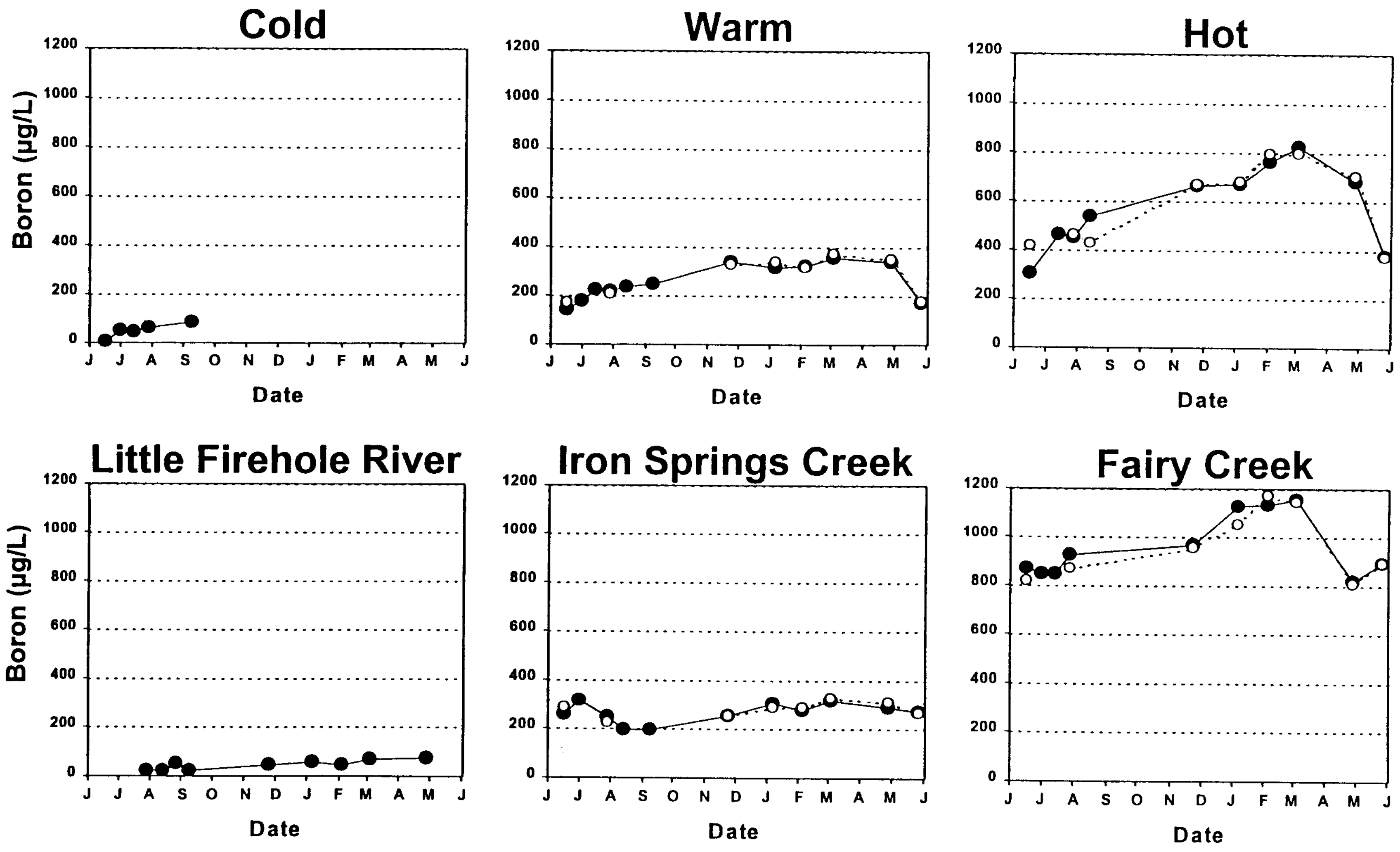


Figure 18. Total (●) and dissolved (○) boron (B) concentrations measured at the study sites on the Firehole River and tributaries, June 1997 - June 1998.

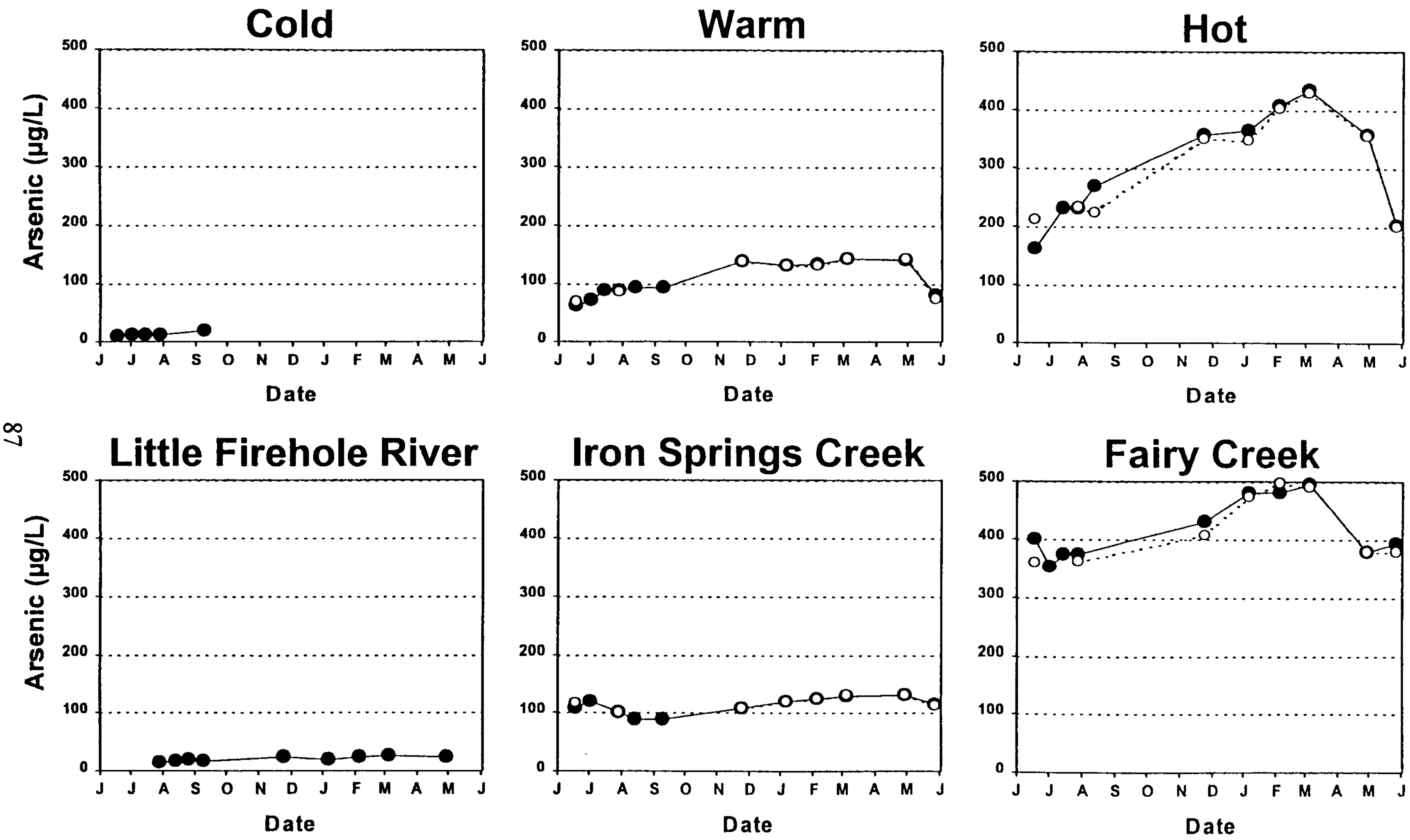


Figure 19. Total (●) and dissolved (○) arsenic (As) concentrations measured at the study sites on the Firehole River and tributaries, June 1997 - June 1998.

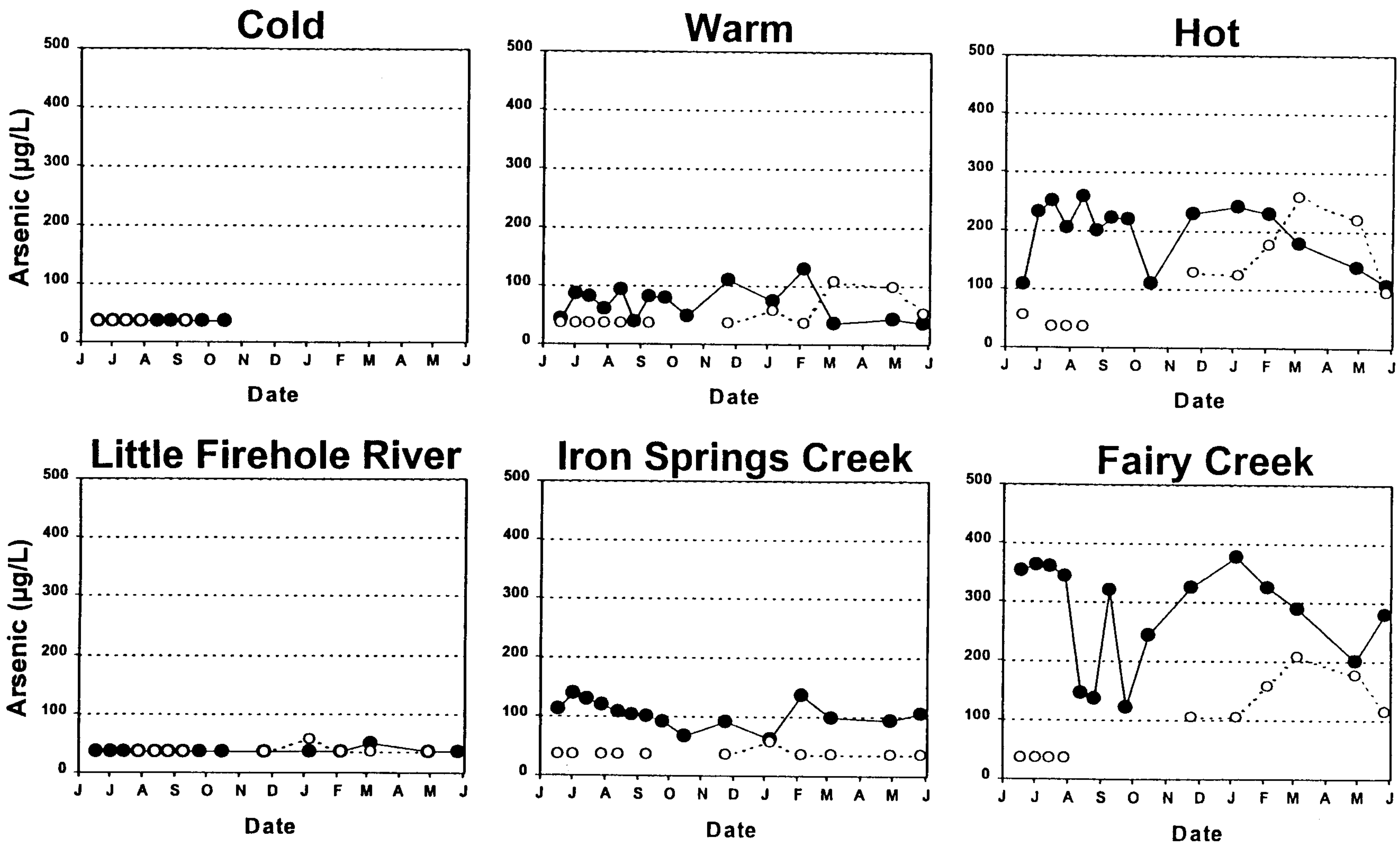


Figure 20. Concentrations of As(III) (○) and As(V) (●) measured at the study sites on the Firehole River and tributaries, June 1997 - June 1998.

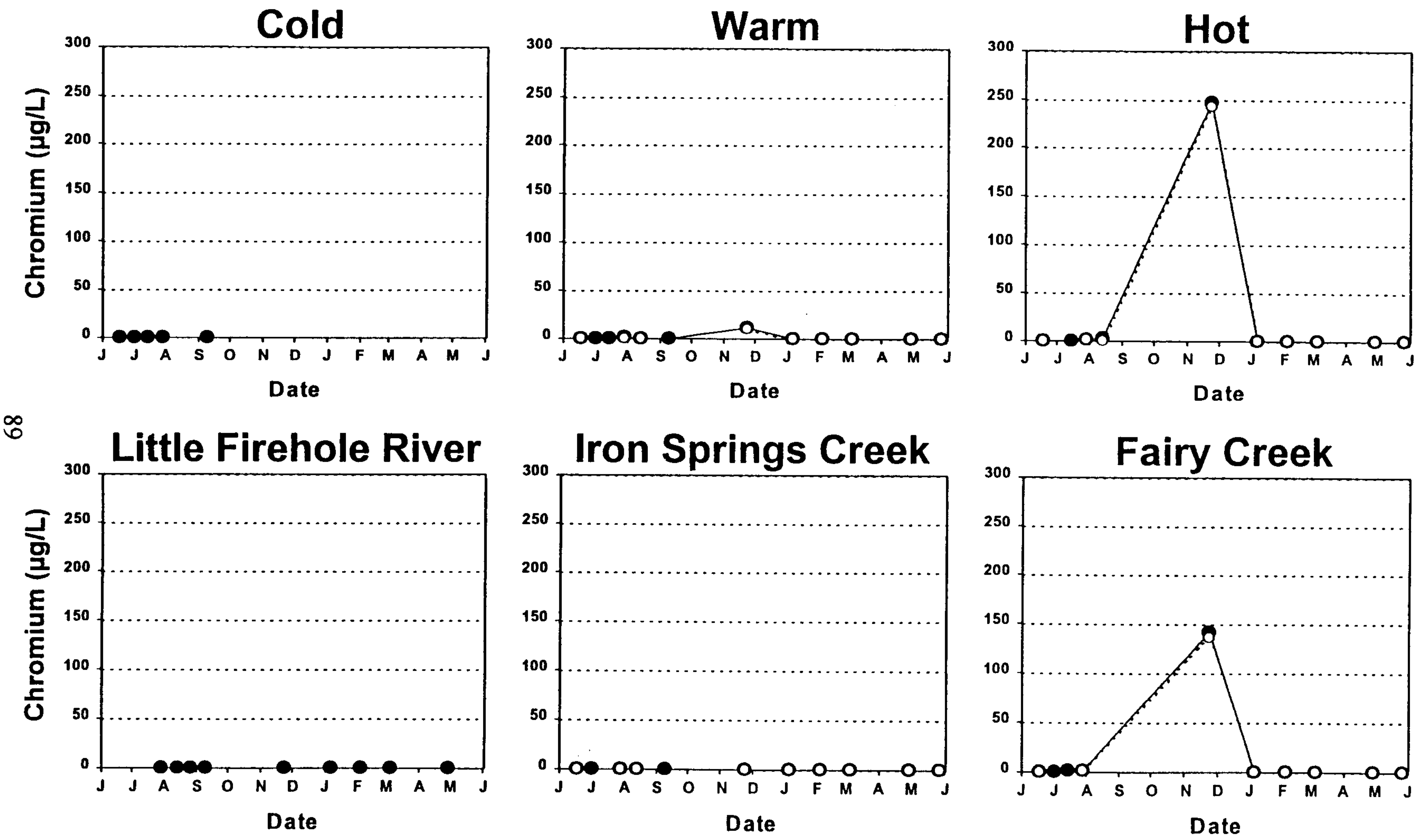


Figure 21. Total (●) and dissolved (O) chromium (Cr) concentrations measured at the study sites on the Firehole River and tributaries, June 1997 - June 1998.

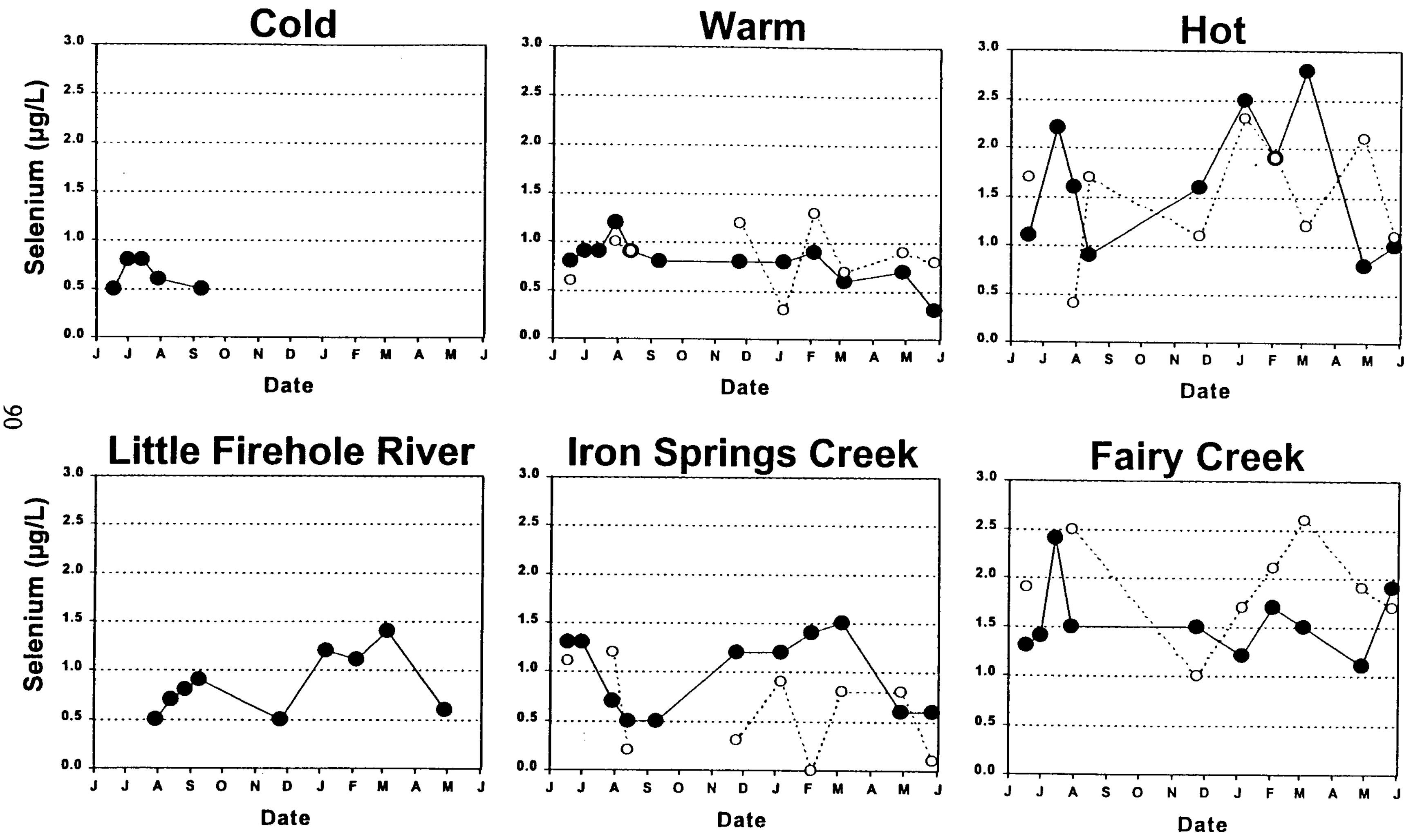


Figure 22. Total (●) and dissolved (○) selenium (Se) concentrations measured at the study sites on the Firehole River and tributaries, June 1997 - June 1998.

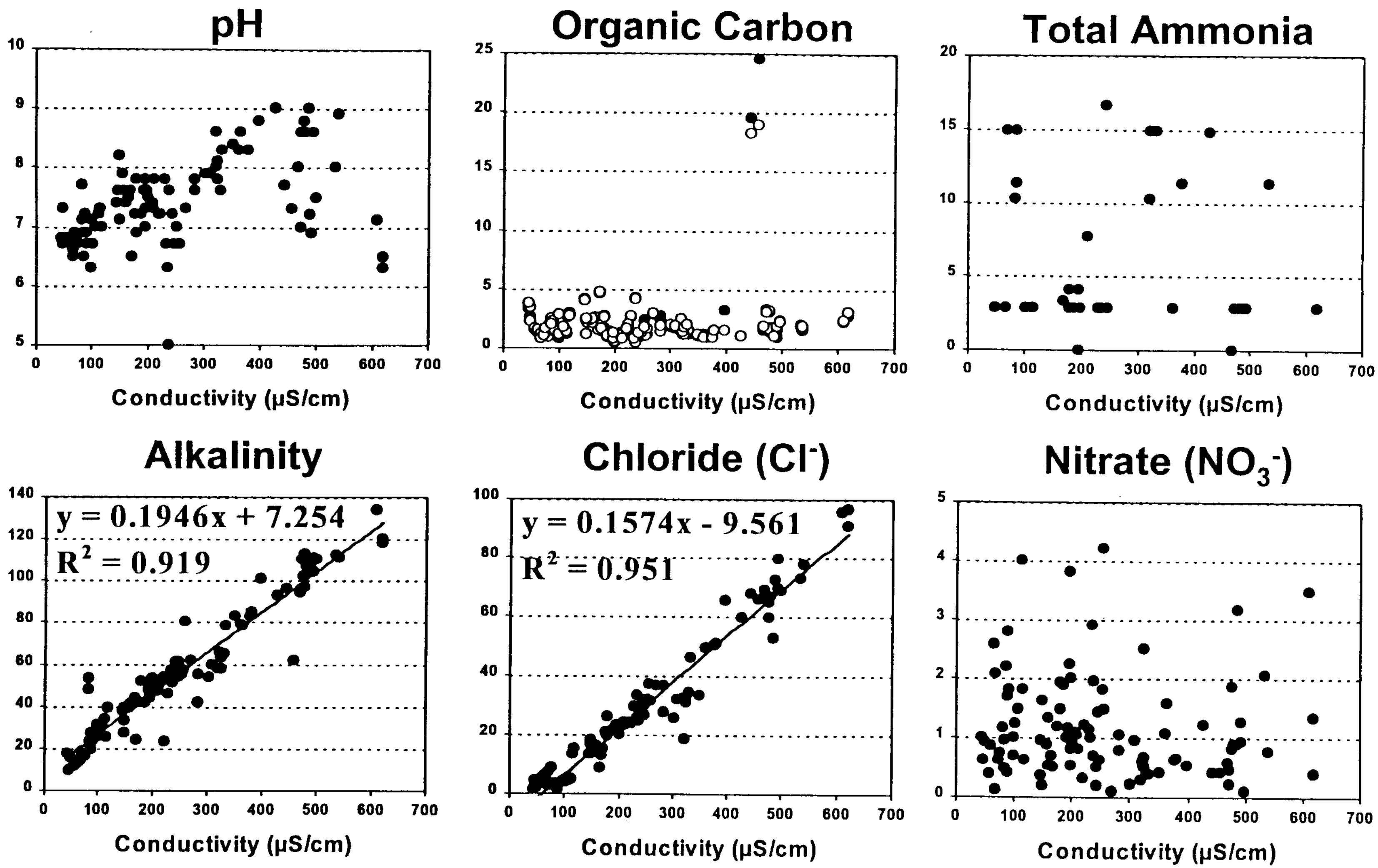


Figure 23. Significant ($P \leq 0.05$) linear regressions of water quality parameters with specific conductivity in the study sites on the Firehole River and tributaries, June 1997 - June 1998. Values are pH (standard units), organic carbon (mg C/L), total ammonia (µg NH_4^+-N/L), alkalinity (mg $CaCO_3$/L), chloride (mg/L), and nitrate (mg/L).

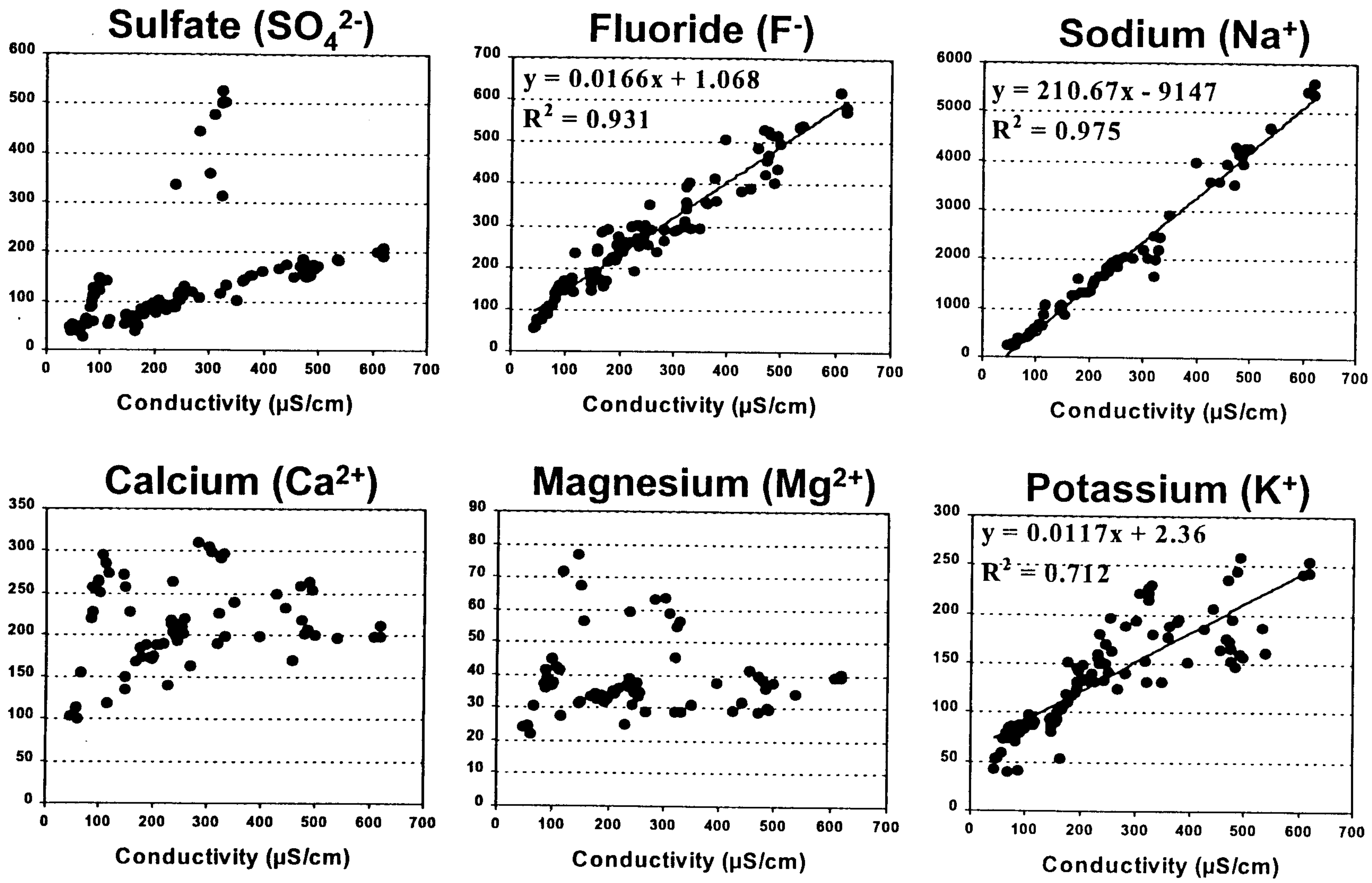


Figure 24. Significant ($P \leq 0.05$) linear regressions of water quality parameters with specific conductivity in the study sites on the Firehole River and tributaries, June 1997 - June 1998. Values are μeq/L.

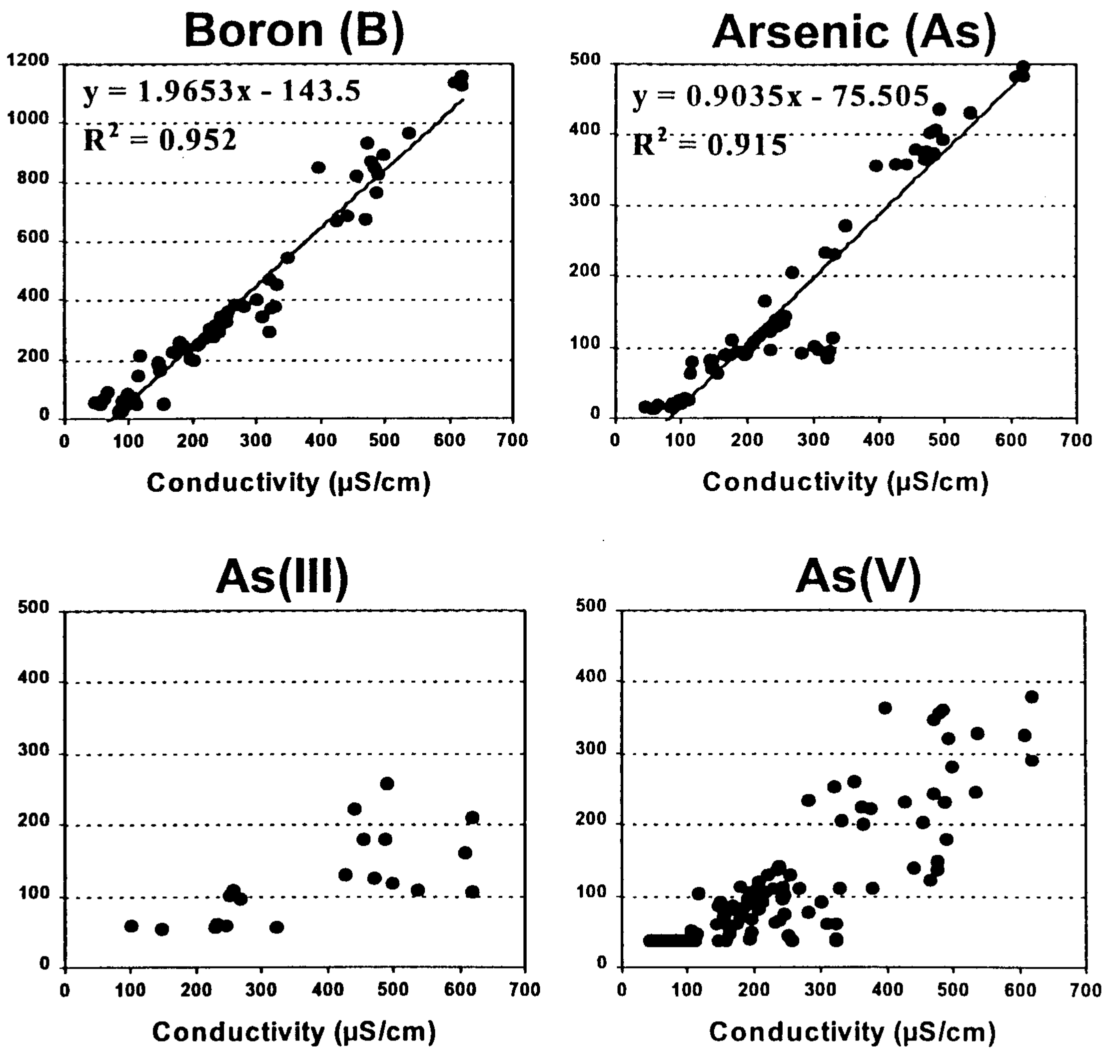


Figure 25. Significant ($P \leq 0.05$) linear regressions of boron, chromium, selenium and arsenic concentrations with specific conductivity in the study sites on the Firehole River and tributaries, June 1997 - June 1998. Values are µg/L.

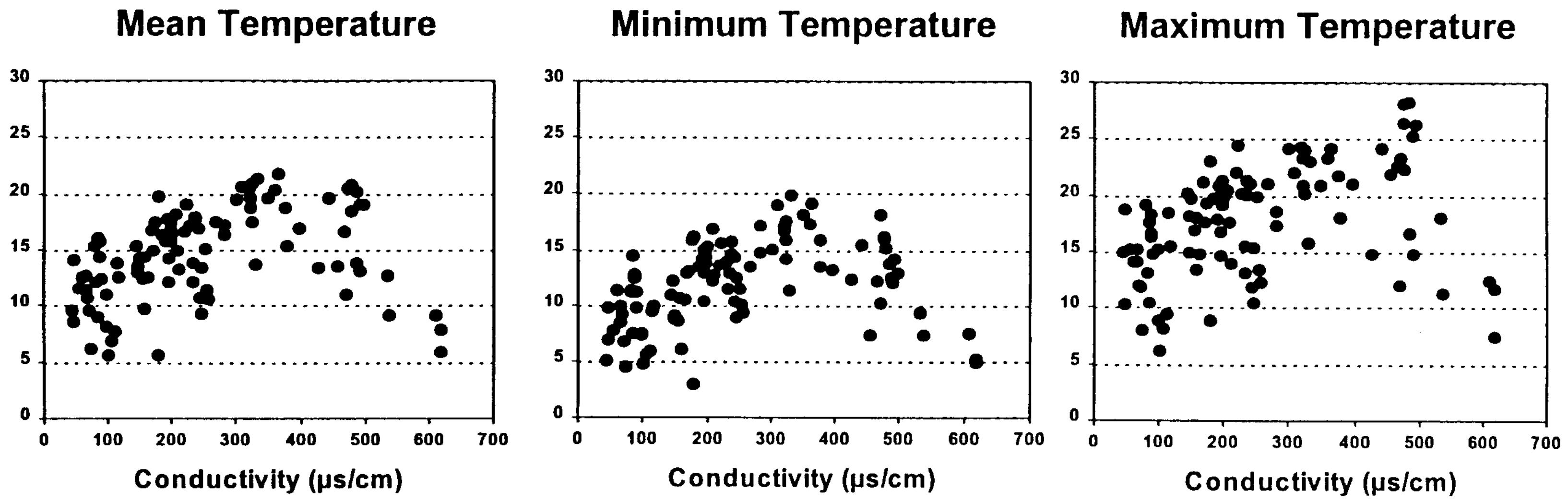


Figure 26. Linear correlation of water temperatures with specific conductivity in the study sites on the Firehole River and tributaries, June 1997 - June 1998. Values are monthly mean temperatures among all sites (°C).

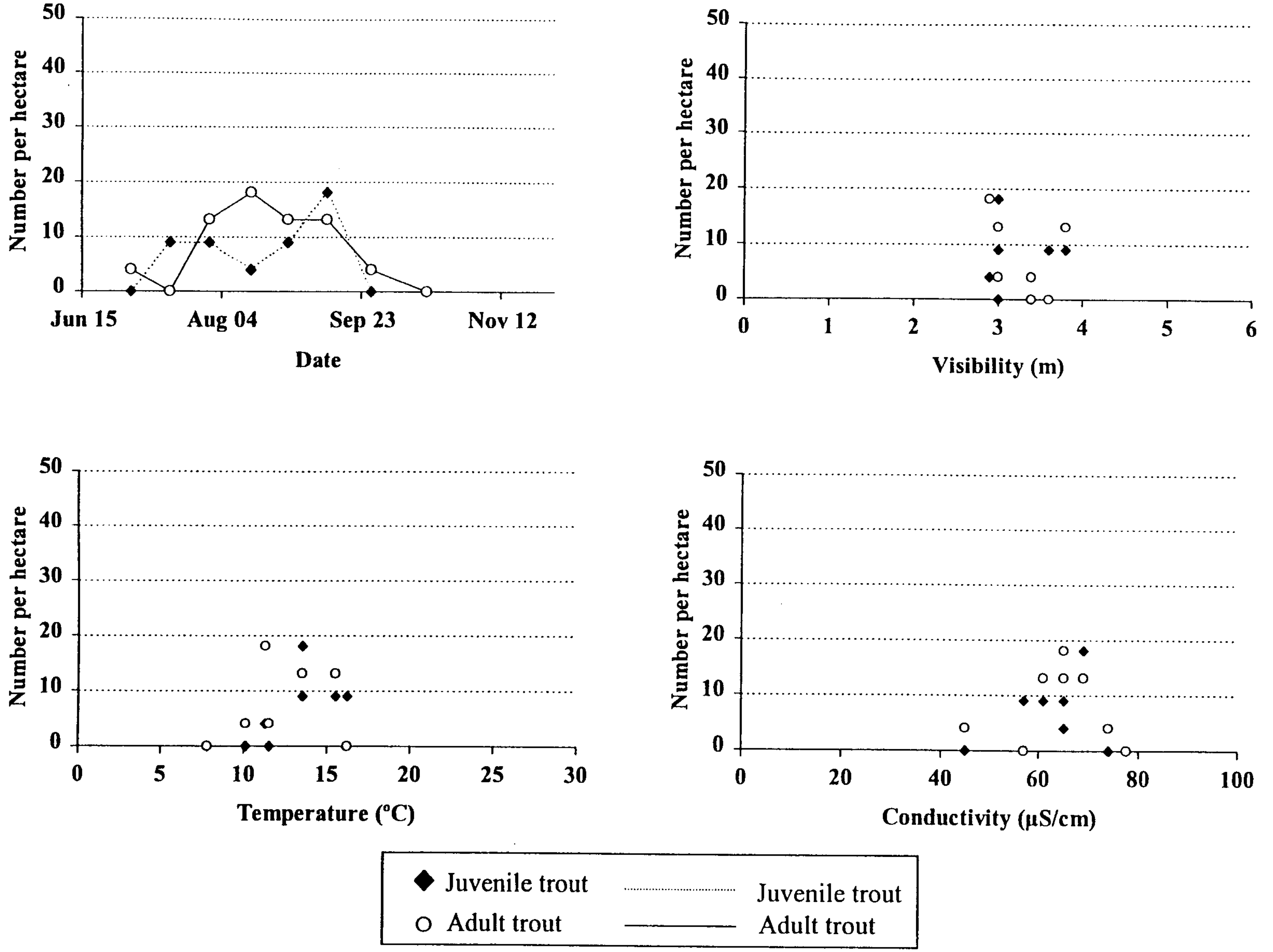


Figure 27. Relations of rainbow trout density and water quality parameters for juvenile and adult fish at the Cold site in the Firehole River, Wyoming, 1997. Equations are given for statistically significant linear regressions between trout density (by age class) and water quality parameters ($P < 0.05$).

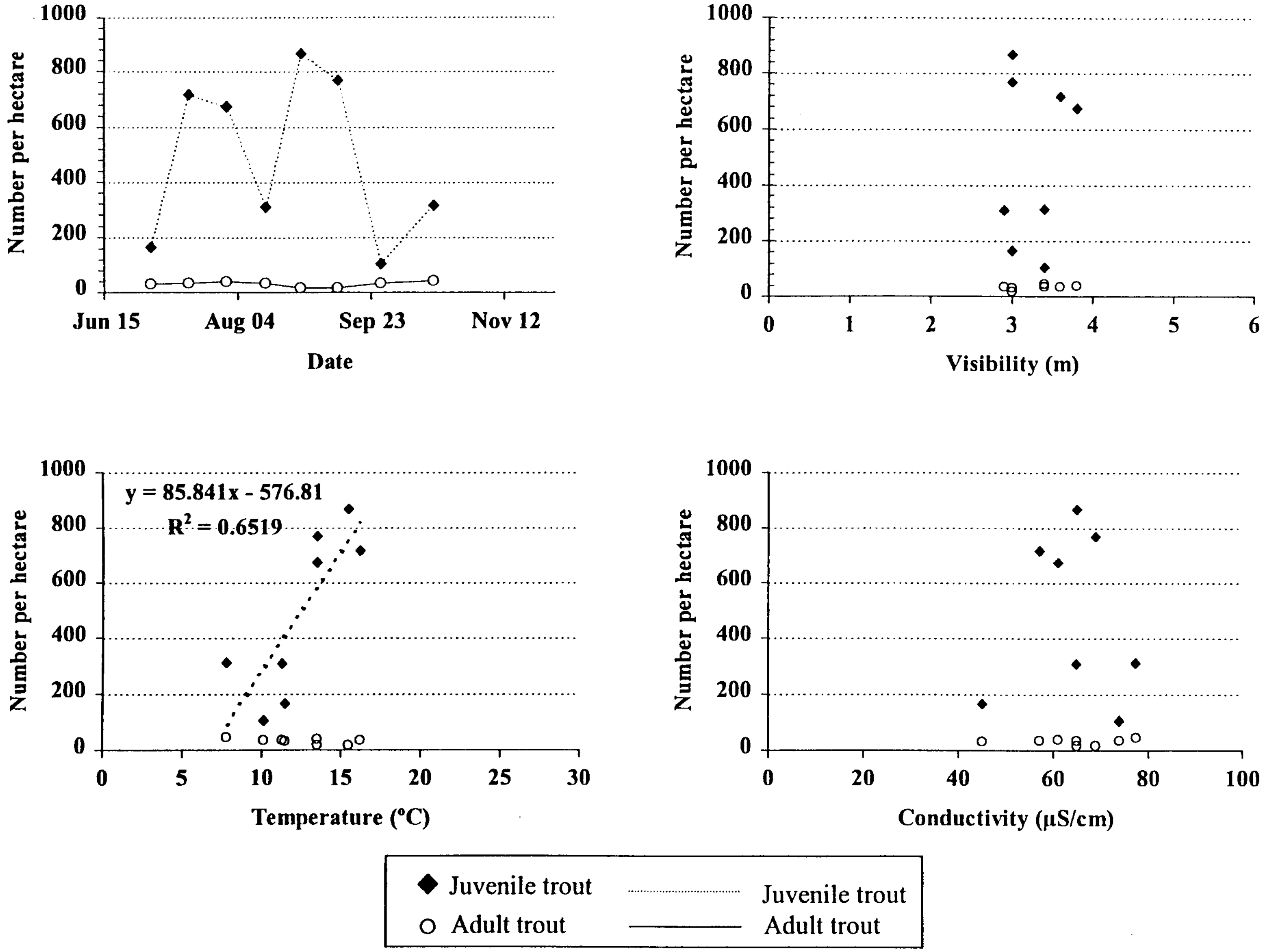


Figure 28. Relations of brown trout density and water quality parameters for juvenile and adult fish in the Cold site in the Firehole River, Wyoming, 1997. Equations are given for statistically significant linear regressions between trout density (by age class) and water quality parameters ($P < 0.05$).

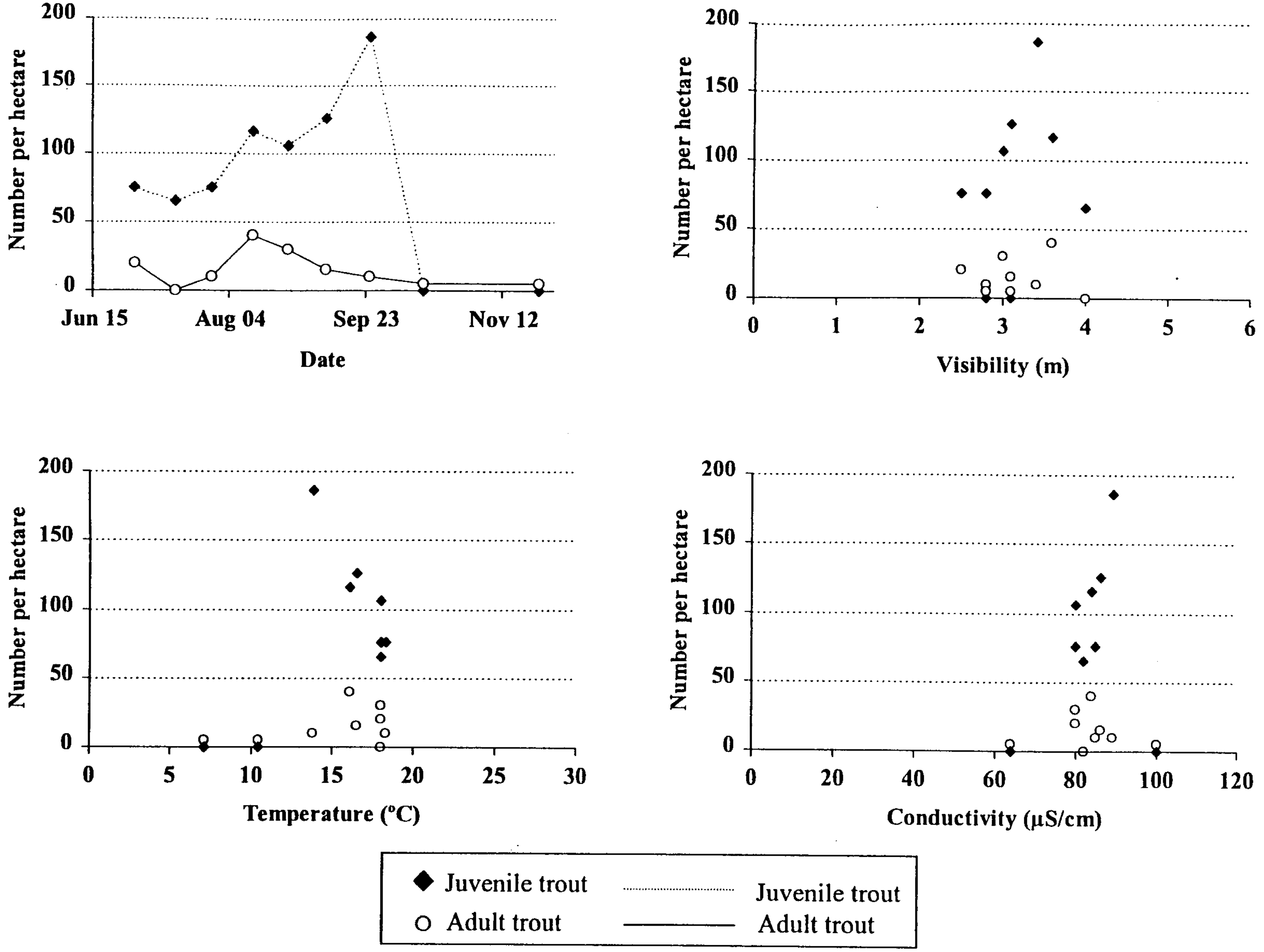


Figure 29. Relations of rainbow trout density and water quality parameters for juvenile and adult fish in the Little Firehole River, Firehole River basin, Wyoming, 1997. Equations are given for statistically significant linear regressions between trout density (by age class) and water quality parameters ($P < 0.05$).

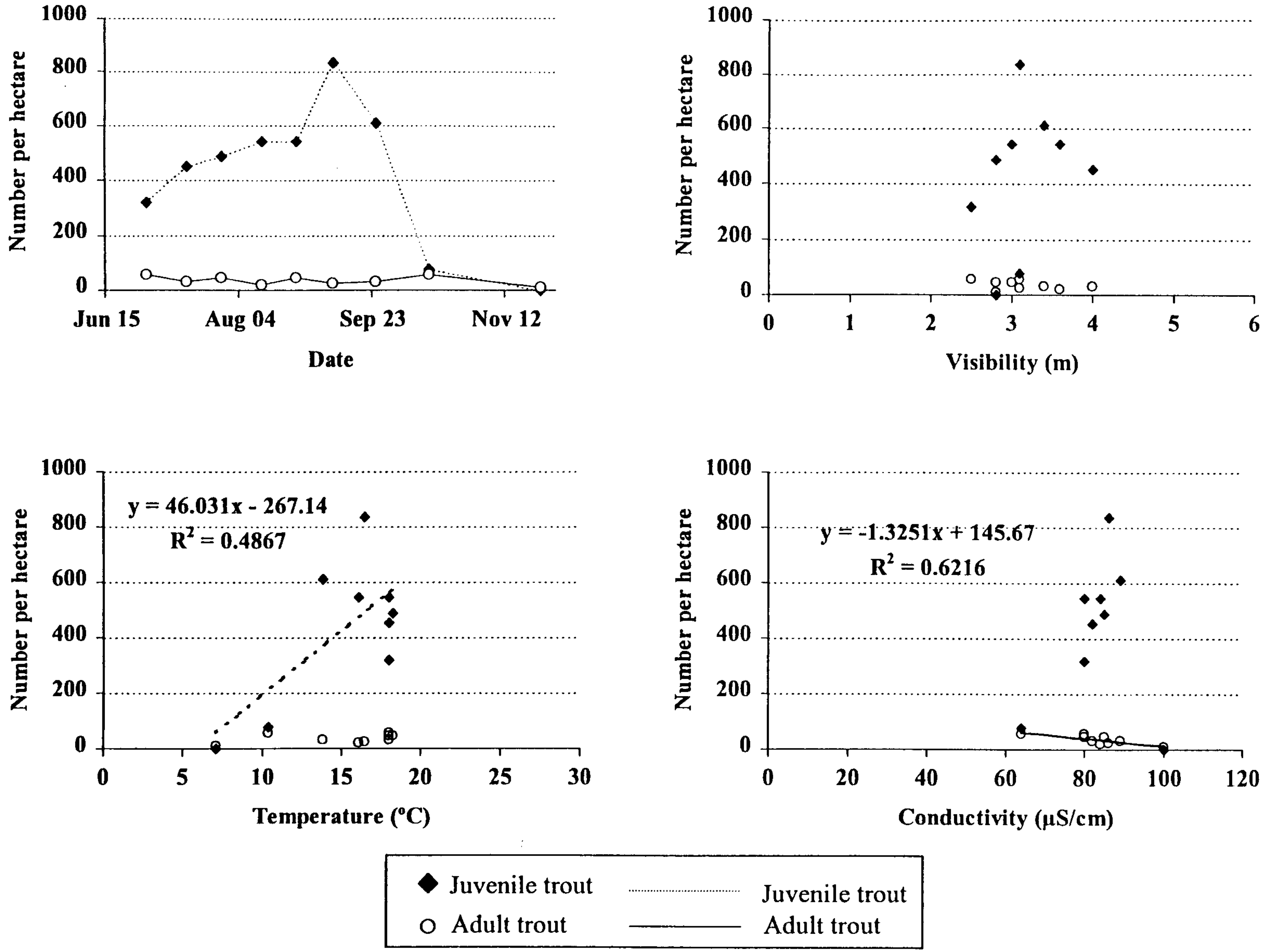


Figure 30. Relations of brown trout density and water quality parameters for juvenile and adult fish in the Little Firehole River site, Firehole River basin, Wyoming, 1997. Equations are given for statistically significant linear regressions between trout density (by age class) and water quality parameters ($P < 0.05$).

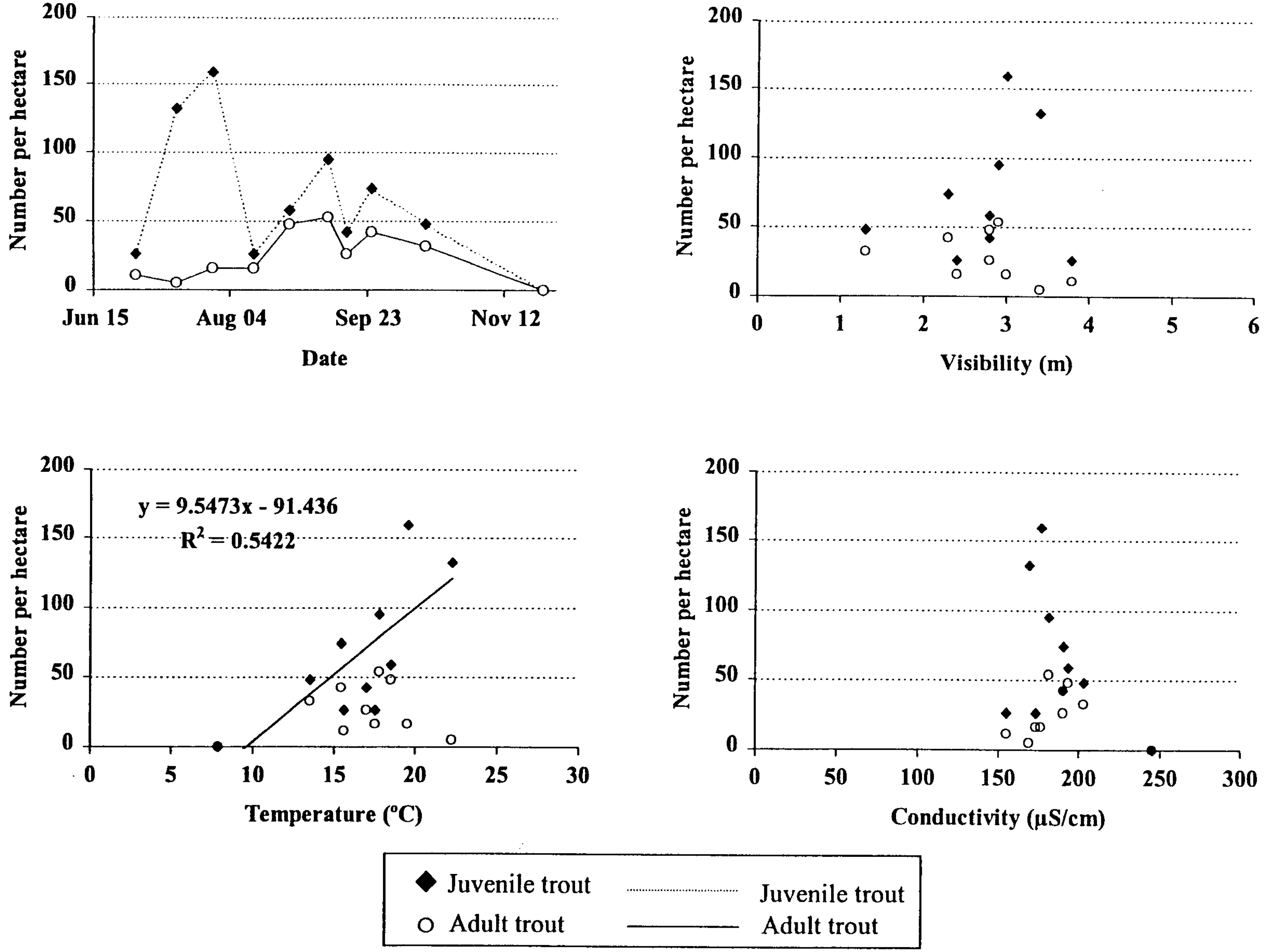


Figure 31. Relations of rainbow trout density and water quality parameters for juvenile and adult fish in the Warm site in the Firehole River, Wyoming, 1997. Equations are given for statistically significant linear regressions between trout density (by age class) and water quality parameters ($P < 0.05$).

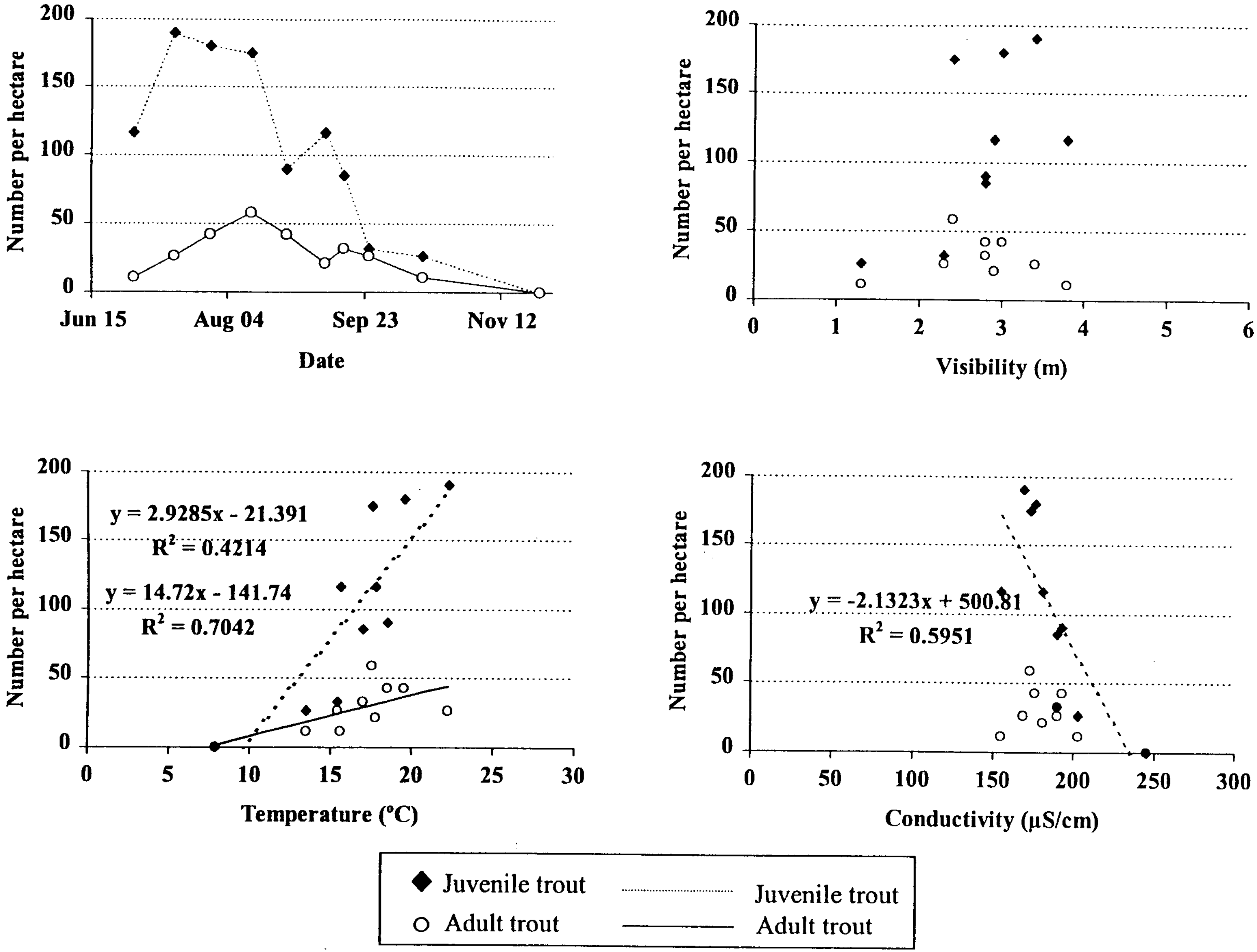


Figure 32. Relations of brown trout density and water quality parameters for juvenile and adult fish in the Warm site in the Firehole River, Wyoming, 1997. Equations are given for statistically significant linear regressions between trout density (by age class) and water quality parameters ($P < 0.05$).

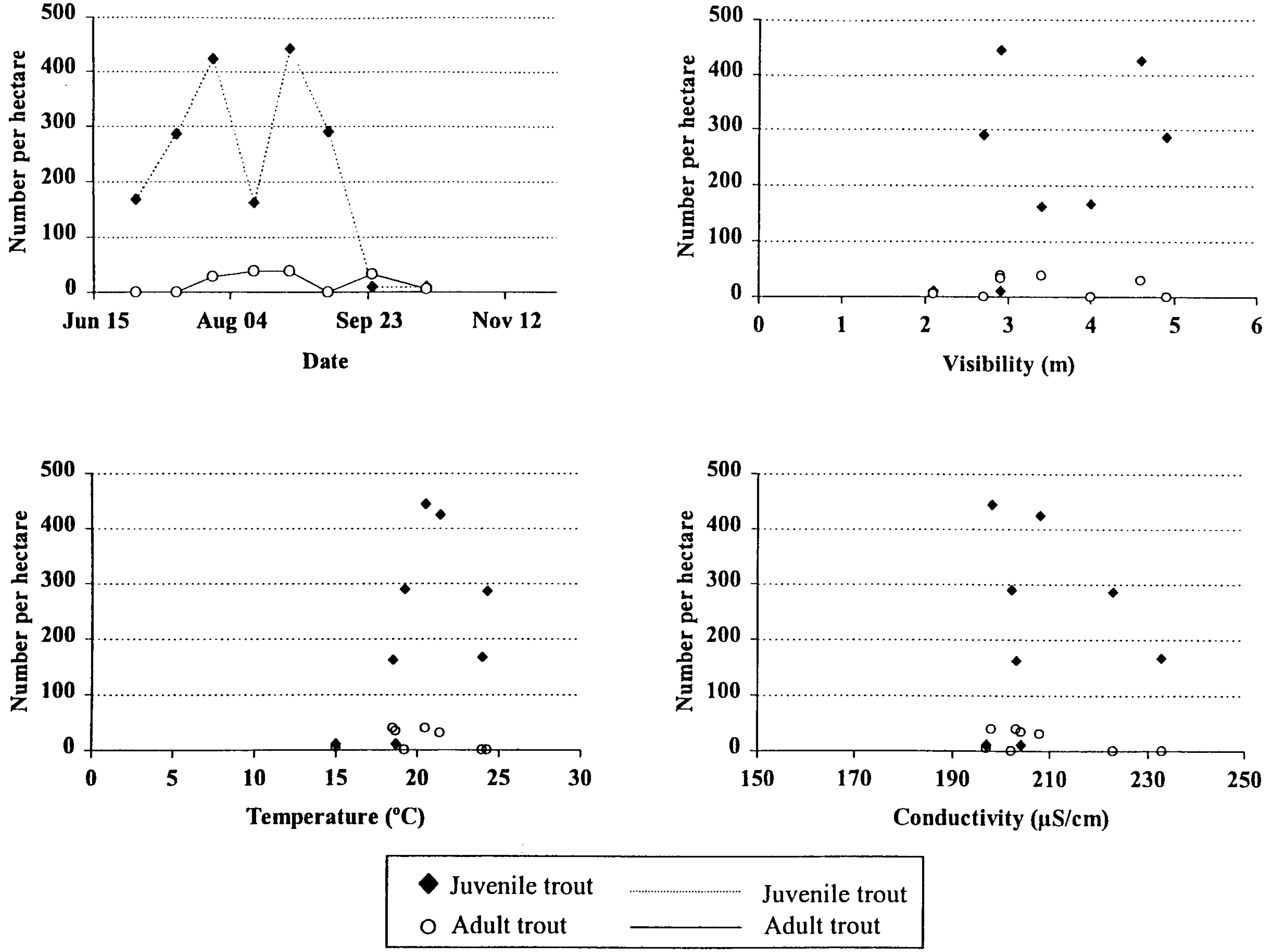


Figure 33. Relations of rainbow trout density and water quality parameters for juvenile and adult fish in Iron Springs Creek, Firehole River basin, Wyoming, 1997. Equations are given for statistically significant linear regressions between trout density (by age class) and water quality parameters ($P < 0.05$).

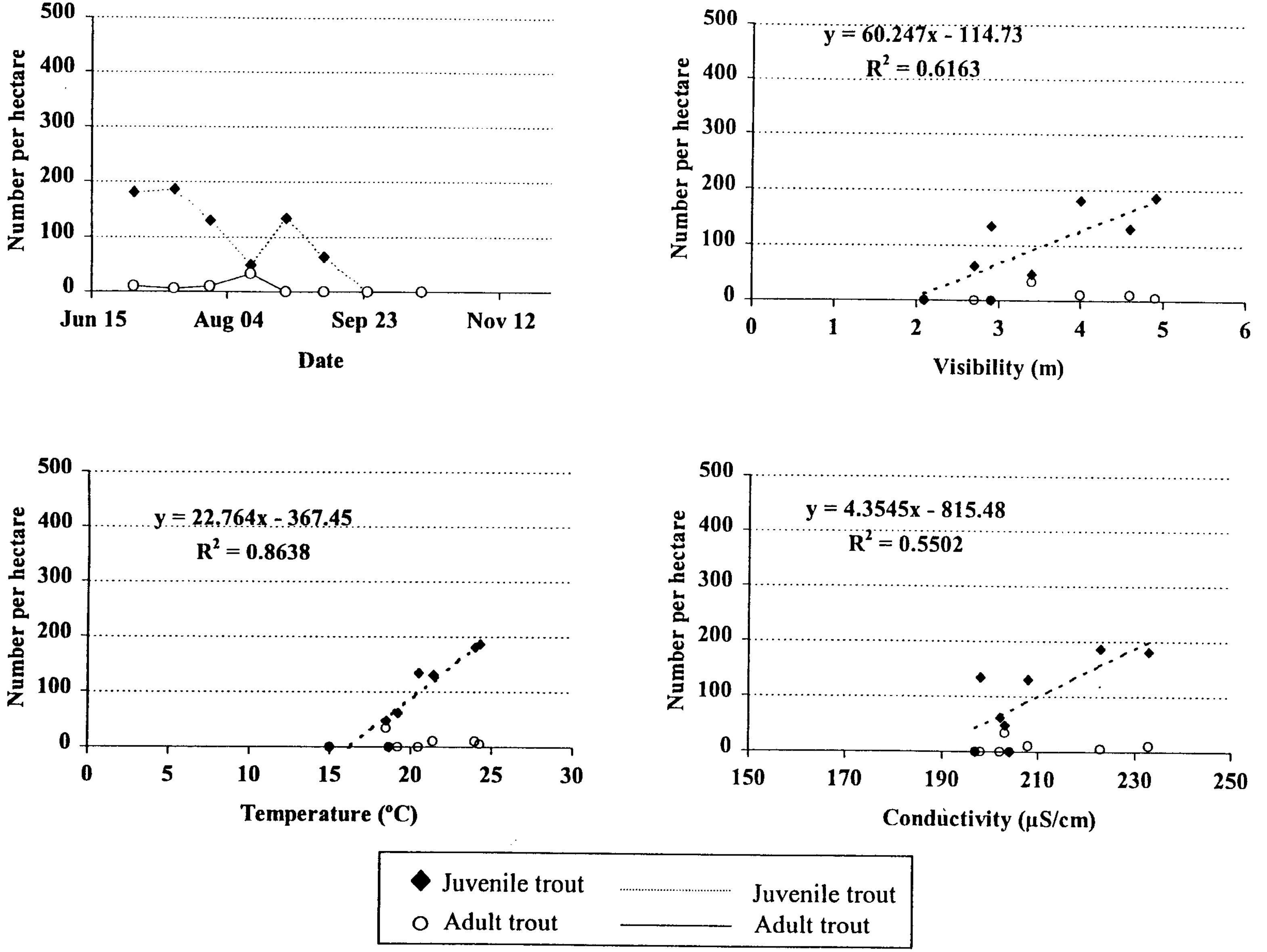


Figure 34. Relations of brown trout density and water quality parameters for juvenile and adult fish in Iron Springs Creek, Firehole River basin, Wyoming, 1997. Equations are given for statistically significant linear regressions between trout density (by age class) and water quality parameters ($P < 0.05$).

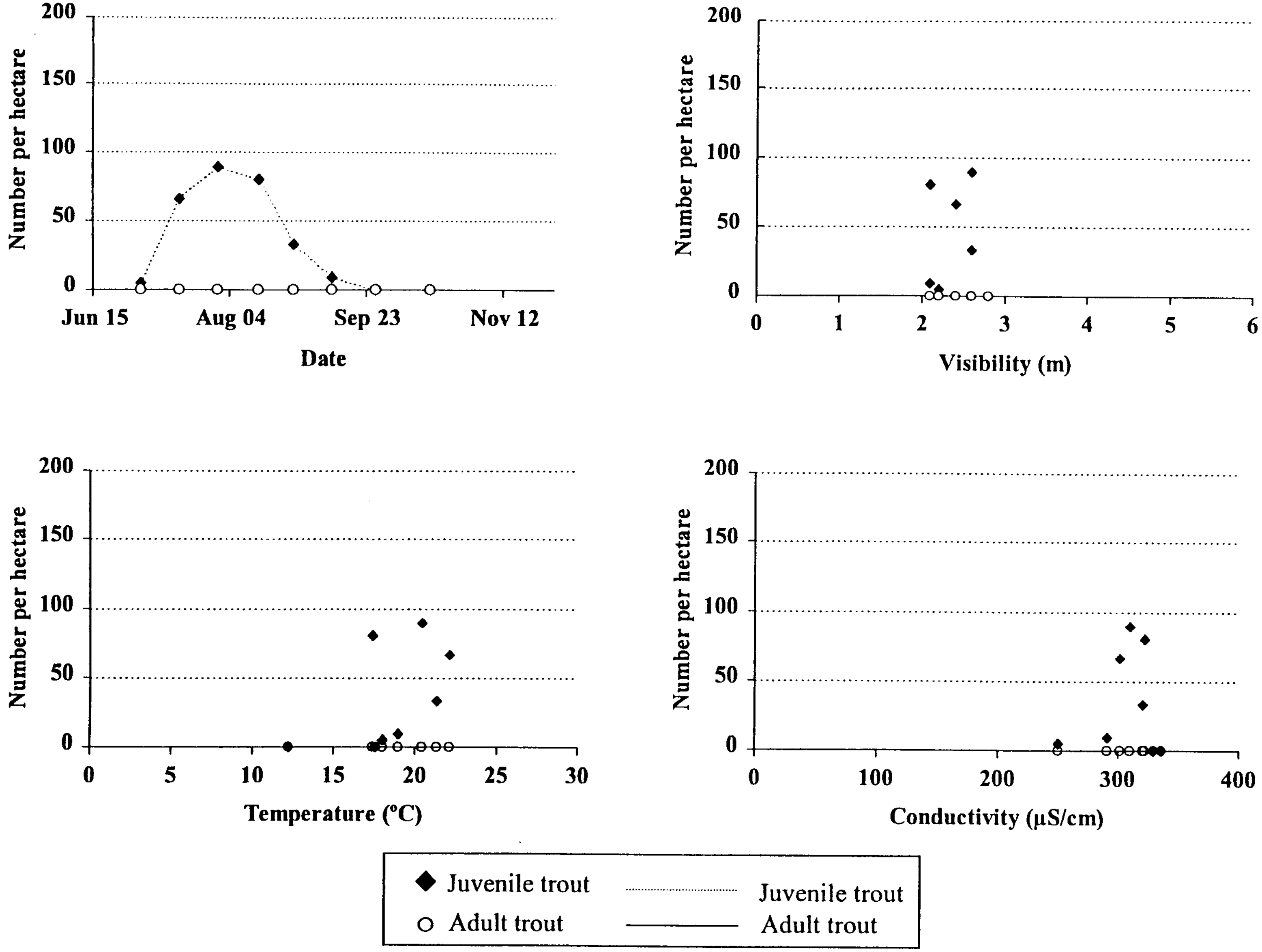


Figure 35. Relations of rainbow trout density and water quality parameters for juvenile and adult fish in Nez Perce Creek, Firehole River basin, Wyoming, 1997. Equations are given for statistically significant linear regresssions between trout density (by age class) and water quality parameters ($P < 0.05$).

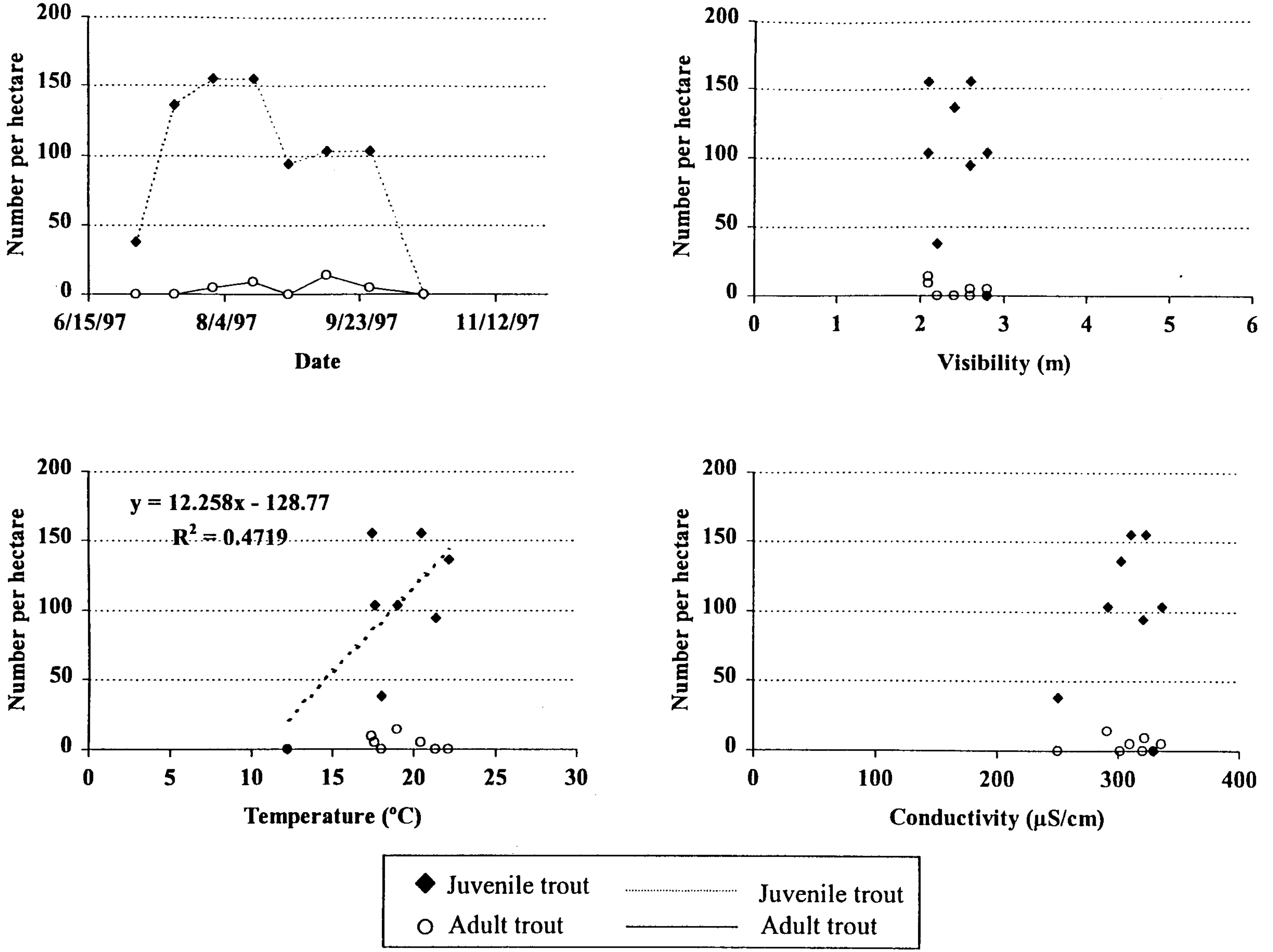


Figure 36. Relations of brown trout density and water quality parameters for juvenile and adult fish in Nez Perce Creek, Firehole River basin, Wyoming, 1997. Equations are given for statistically significant linear regressions between trout density (by age class) and water quality parameters ($P < 0.05$).

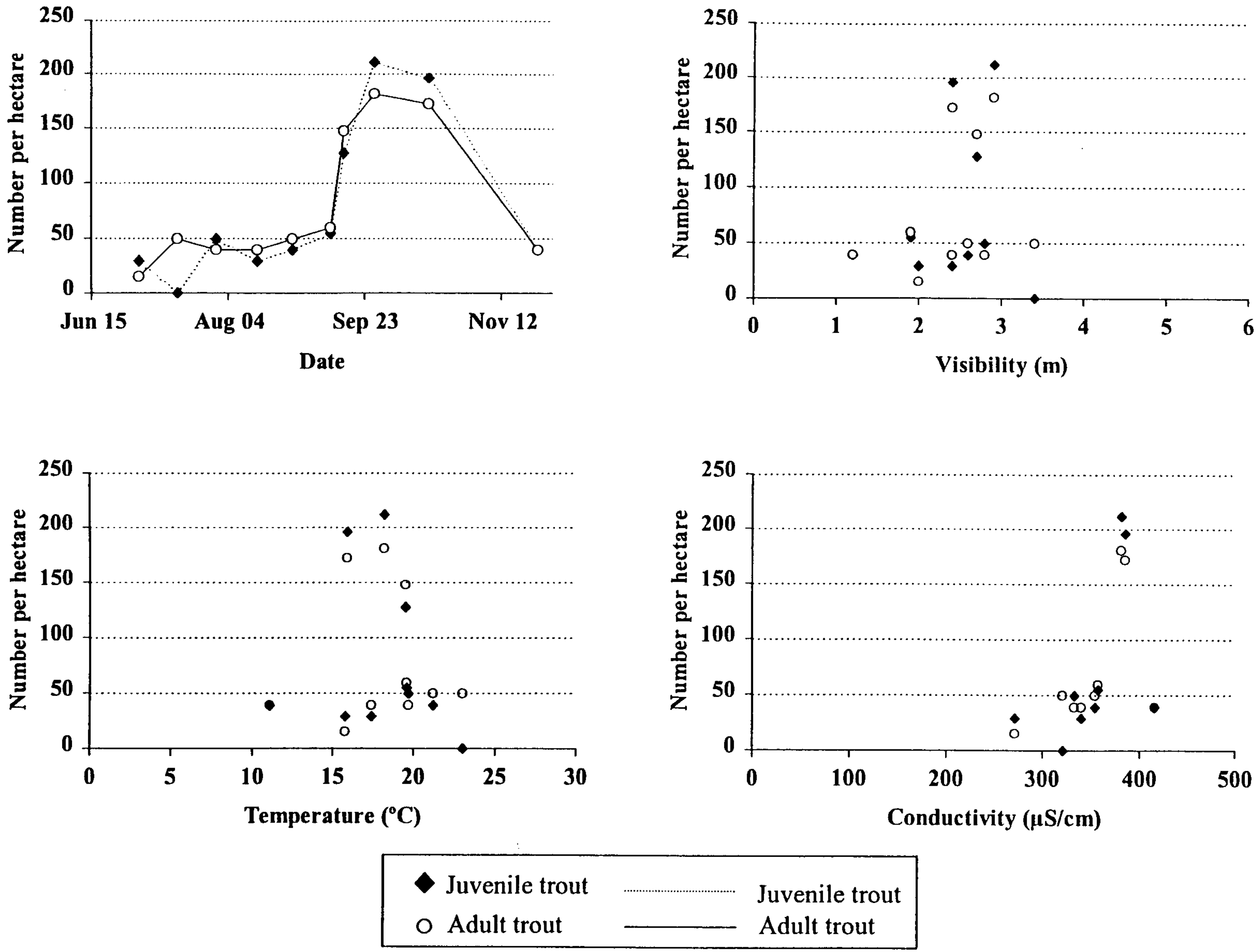


Figure 37. Relations of rainbow trout density and water quality parameters for juvenile and adult fish at the Hot site in the Firehole River, Wyoming, 1997. Equations are given for statistically significant linear regressions between trout density (by age class) and water quality parameters ($P < 0.05$).

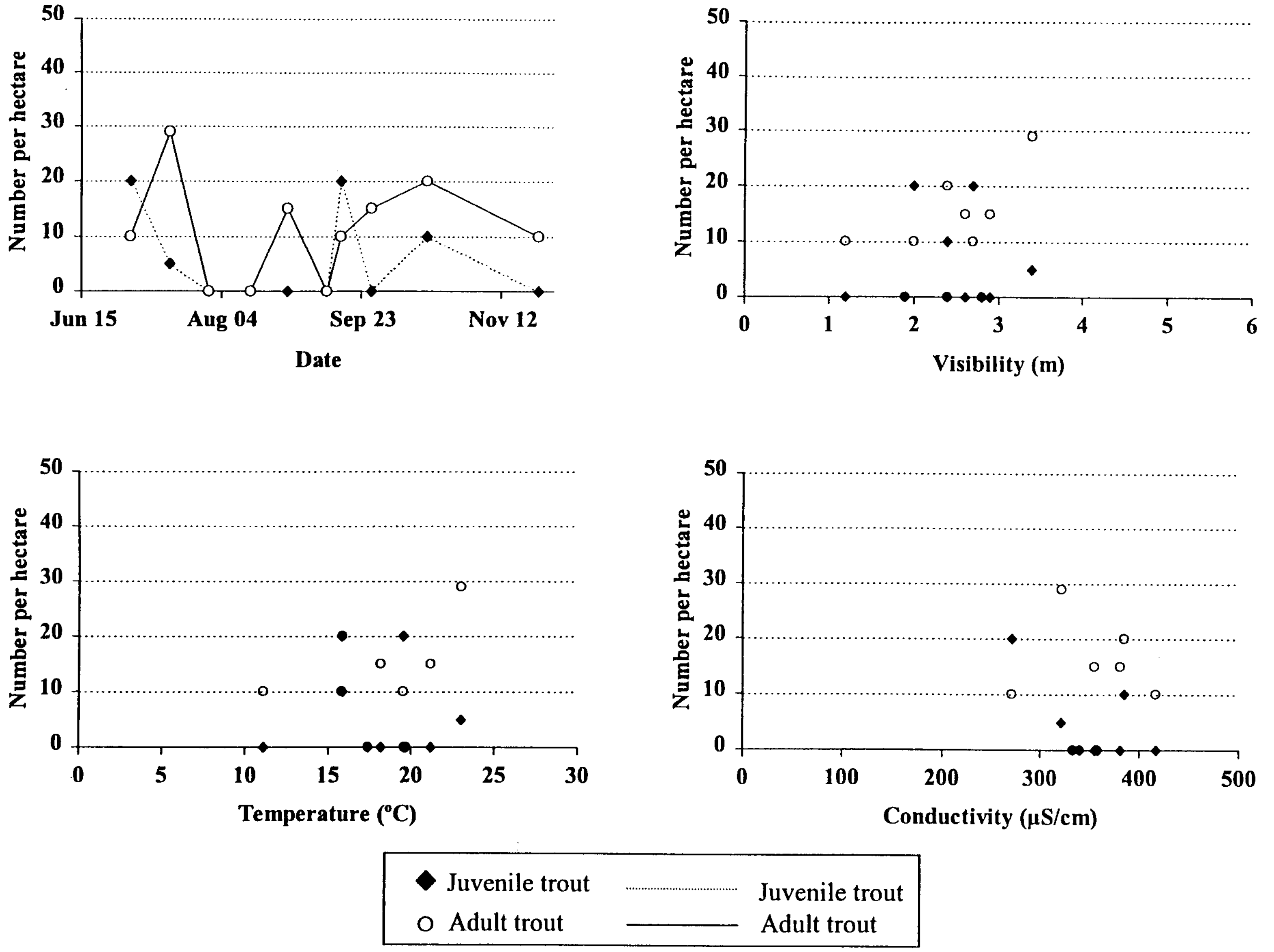


Figure 38. Relations of brown trout density and water quality parameters for juvenile and adult fish at the Hot site in the Firehole River, Wyoming, 1997. Equations are given for statistically significant linear regressions between trout abundance (by age class) and water quality parameters ($P < 0.05$).

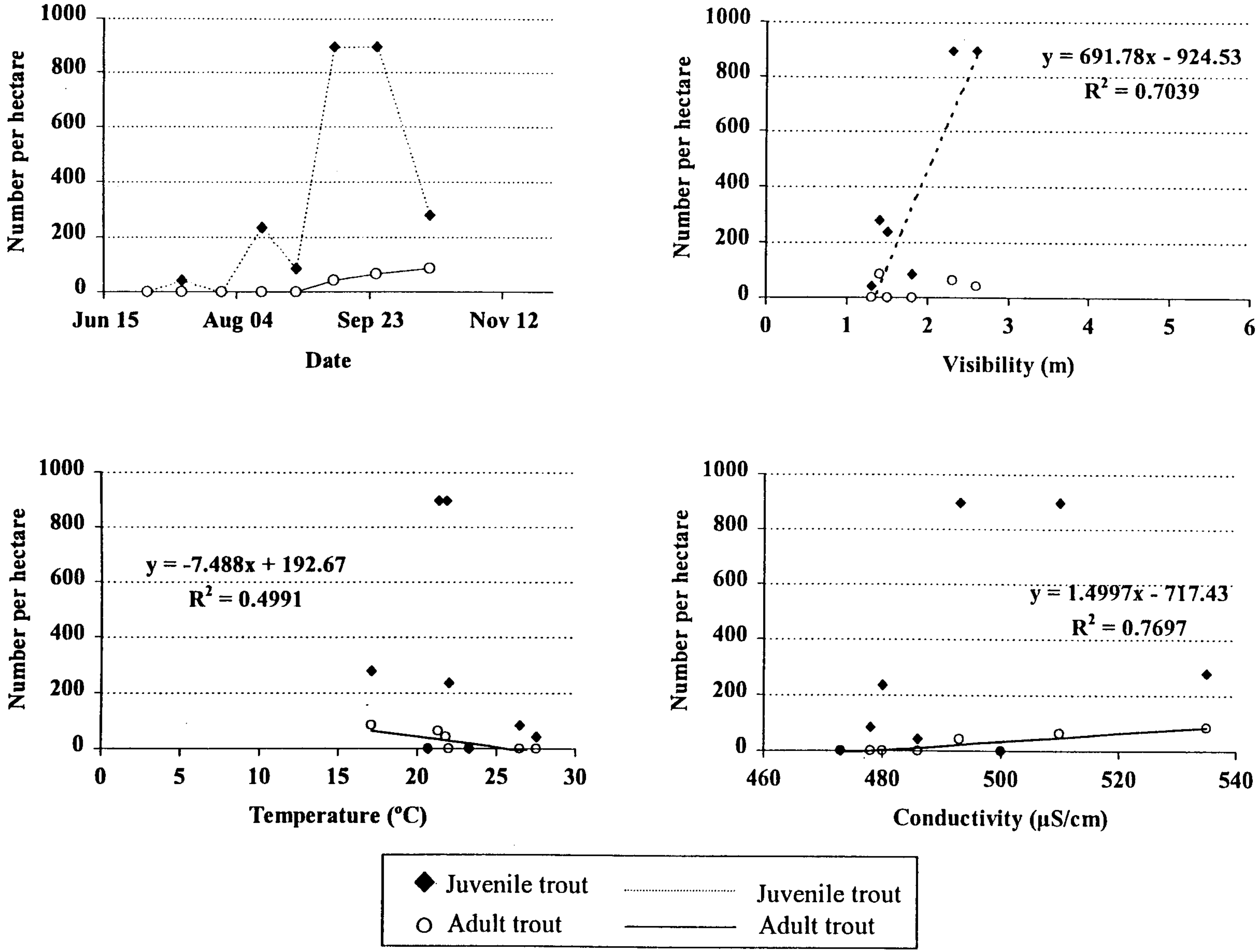


Figure 39. Relations of rainbow trout density and water quality parameters for juvenile and adult fish in Fairy Creek, Firehole River basin, Wyoming, 1997. Equations are given for statistically significant linear regressions between trout density (by age class) and water quality parameters ($P < 0.05$).

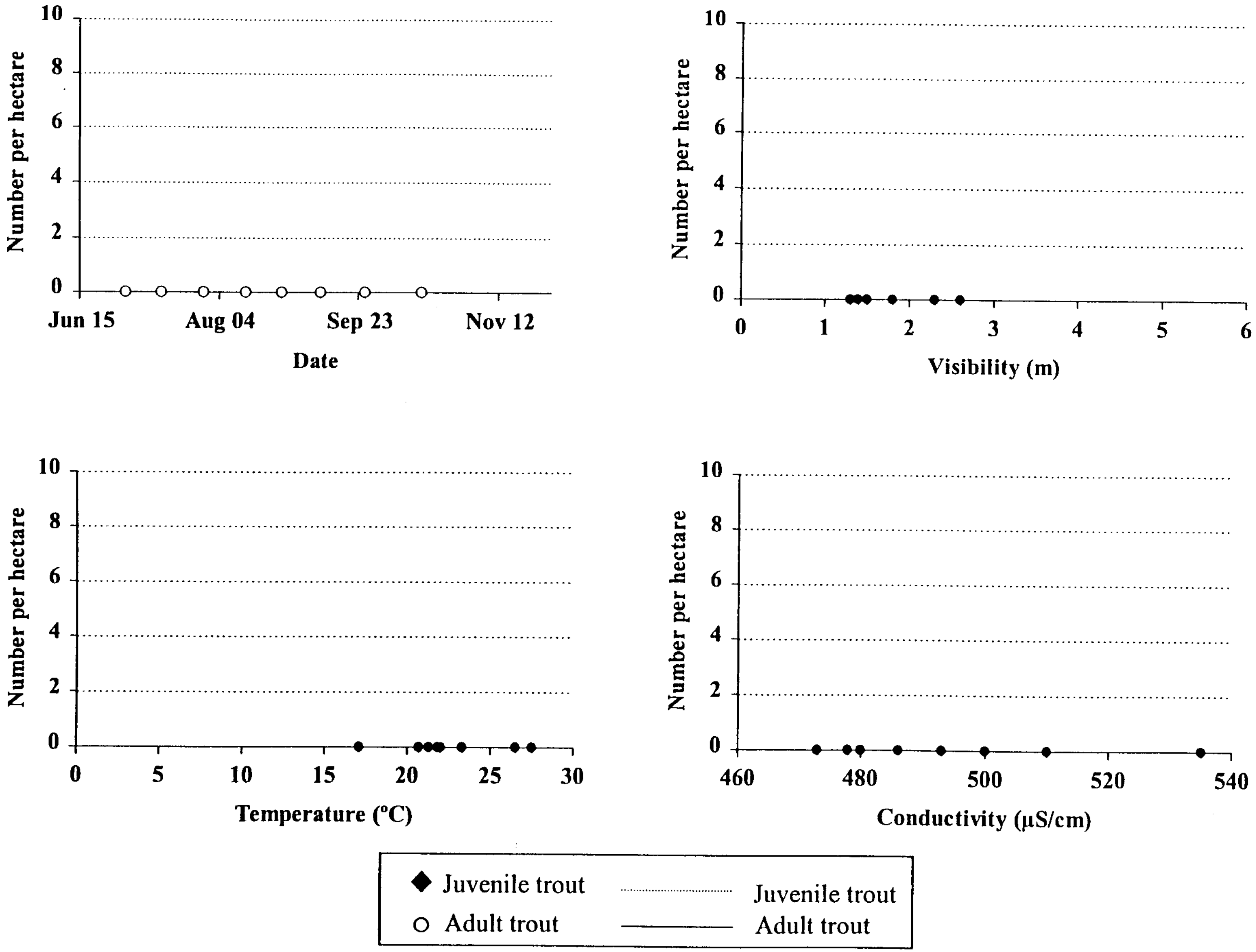


Figure 40. Relations of brown trout density and water quality parameters for juvenile and adult fish in Fairy Creek, Firehole River basin, Wyoming, 1997. Equations are given for statistically significant linear regressions between trout density (by age class) and water quality parameters ($P < 0.05$).

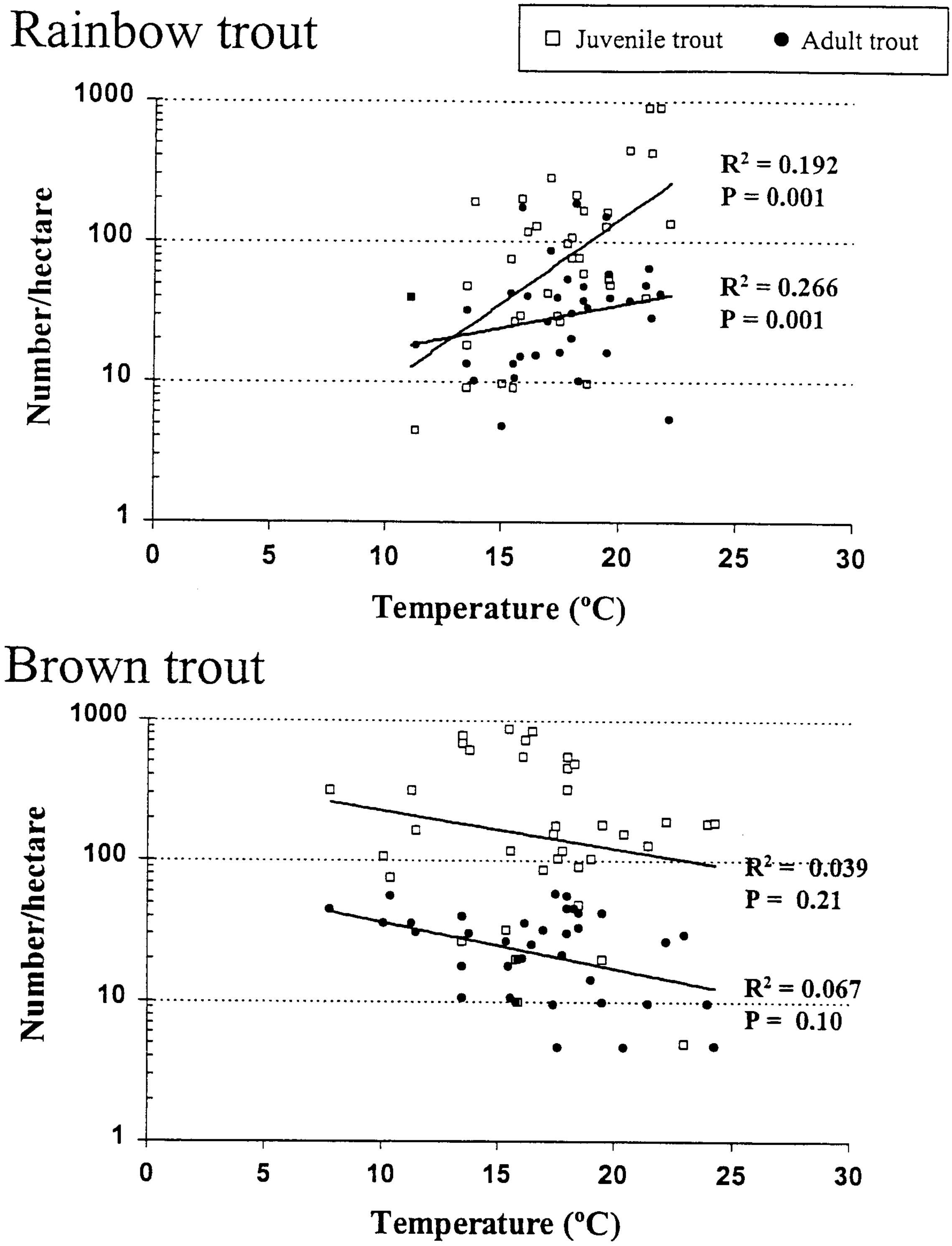
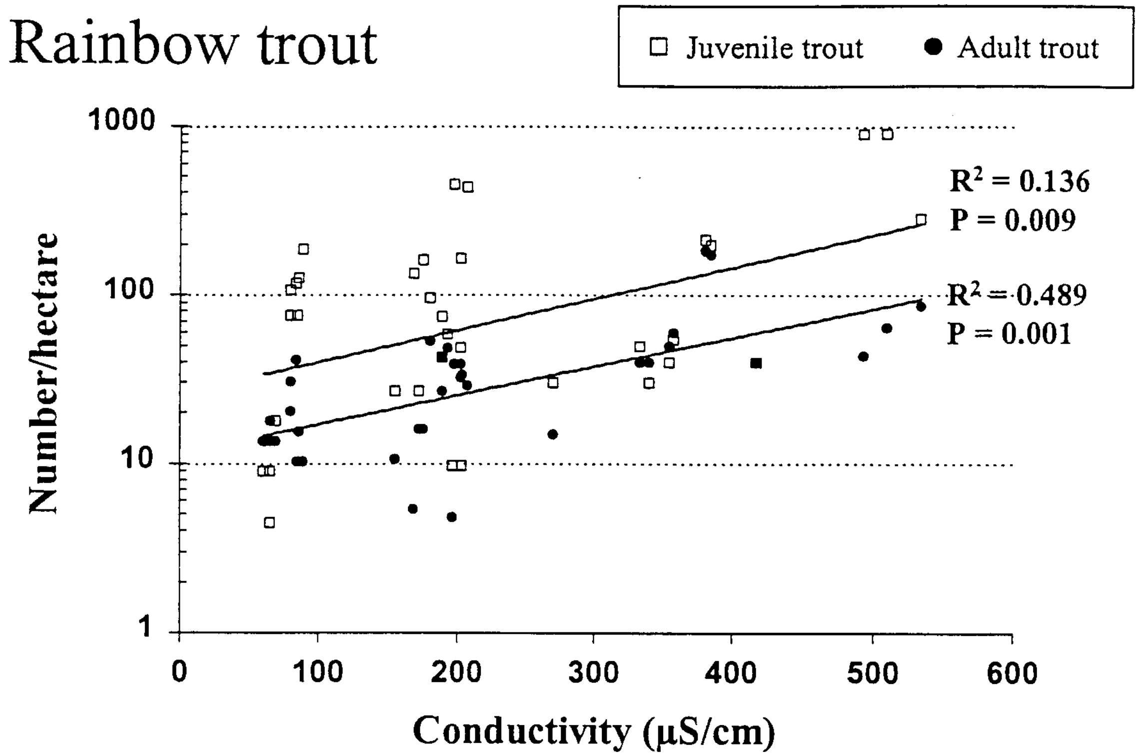


Figure 41. Trout densities (number per hectare; log scale) versus water temperature for population surveys conducted at study sites in the Firehole River and tributaries, Wyoming, 1997.



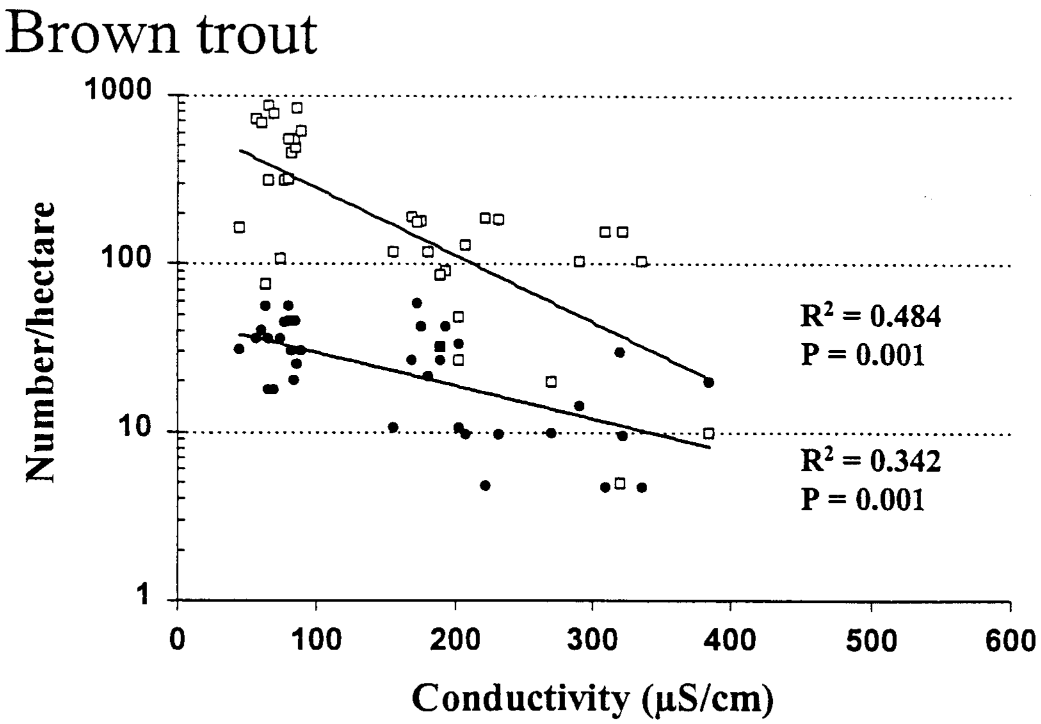


Figure 42. Trout densities (number per hectare; log scale) versus specific conductivity for population surveys conducted at study sites in the Firehole River and tributaries, Wyoming, 1997.

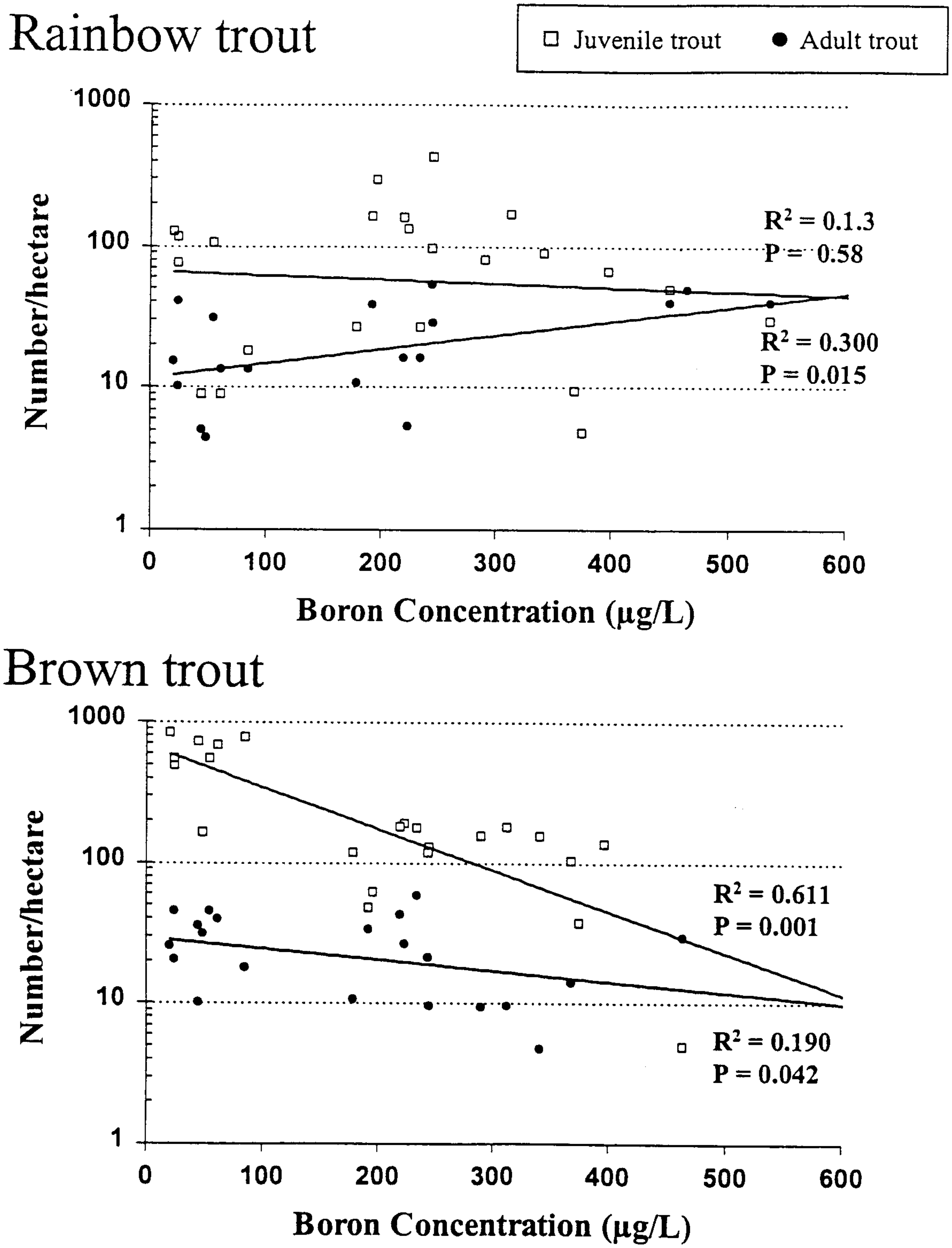


Figure 43. Trout densities (number per hectare; log scale) versus boron concentrations for population surveys conducted at study sites in the Firehole River and tributaries, Wyoming, 1997.

Upper Firehole River

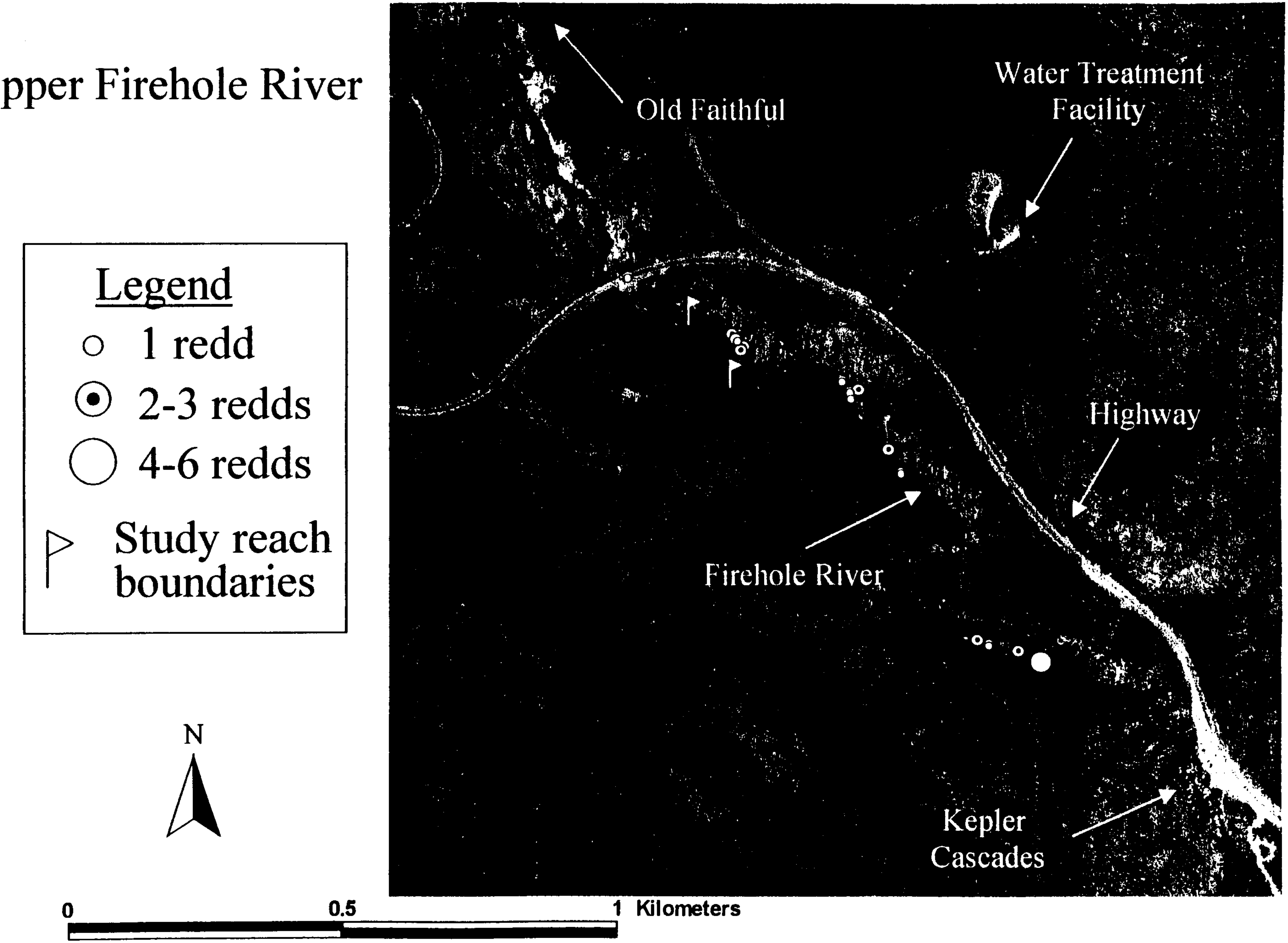


Figure 44. Spawning redds observed in the mainstem of the upper Firehole River, Wyoming. November 1997.

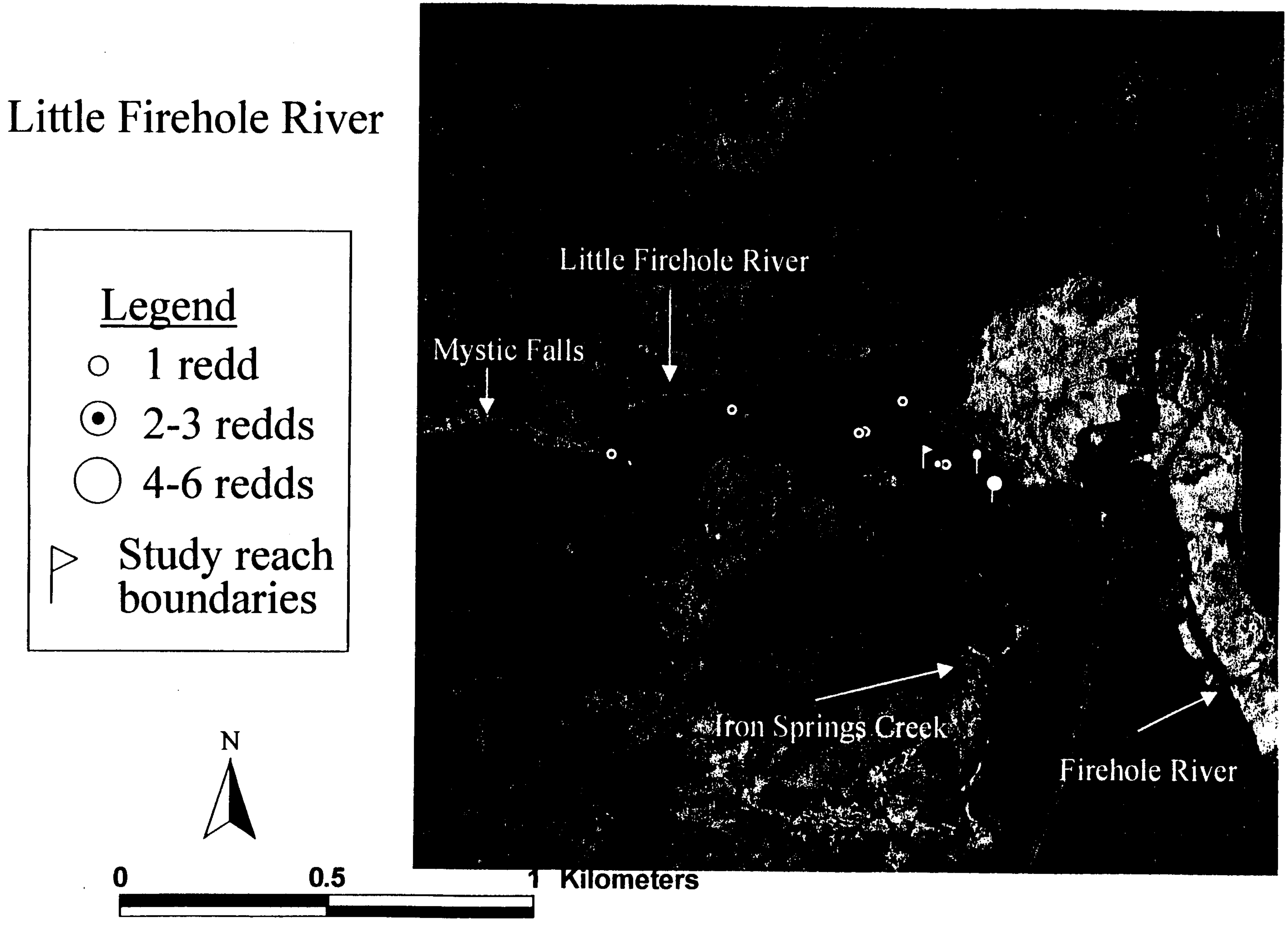


Figure 45. Spawning redds observed in the Little Firehole River, Wyoming. November 1997.

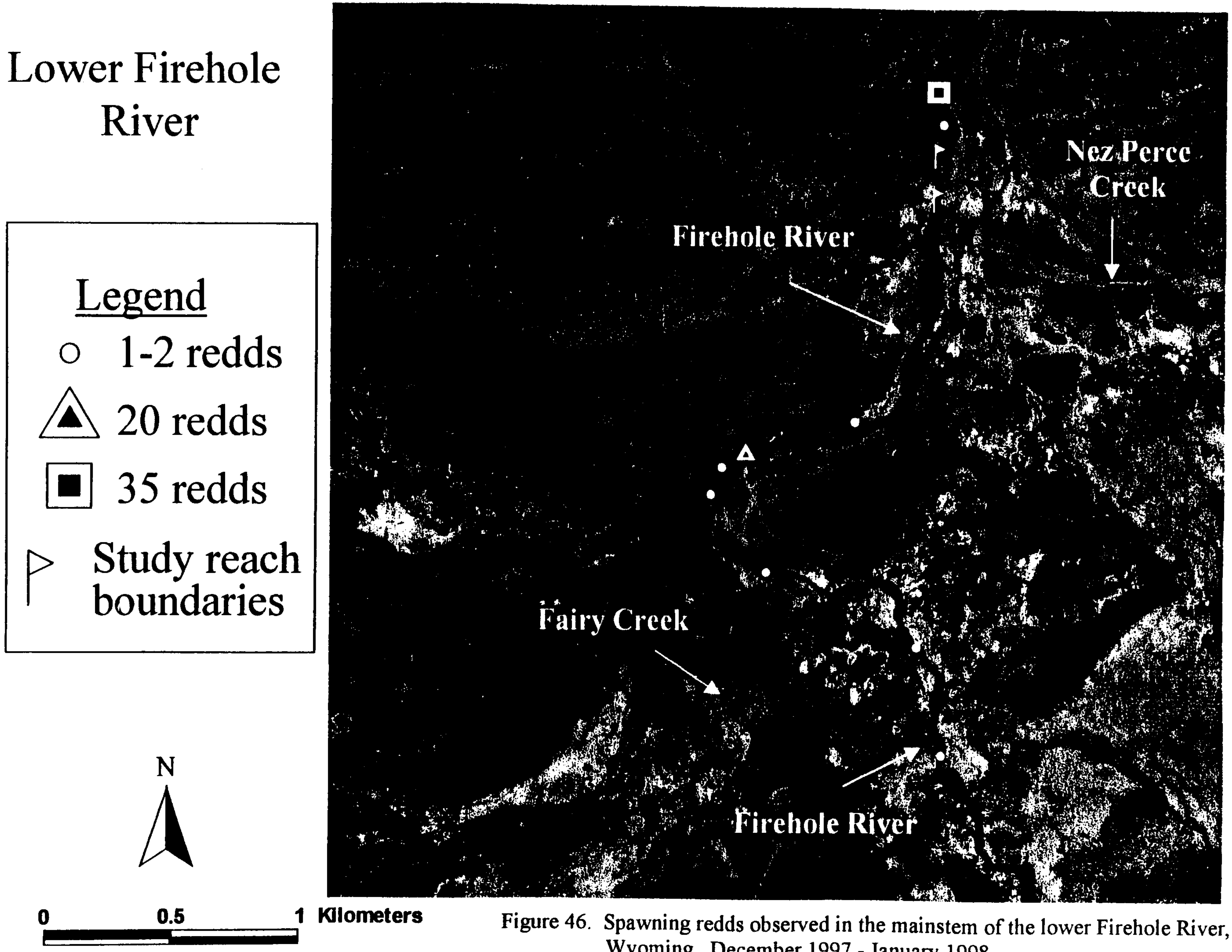


Figure 46. Spawning redds observed in the mainstem of the lower Firehole River, Wyoming. December 1997 - January 1998.

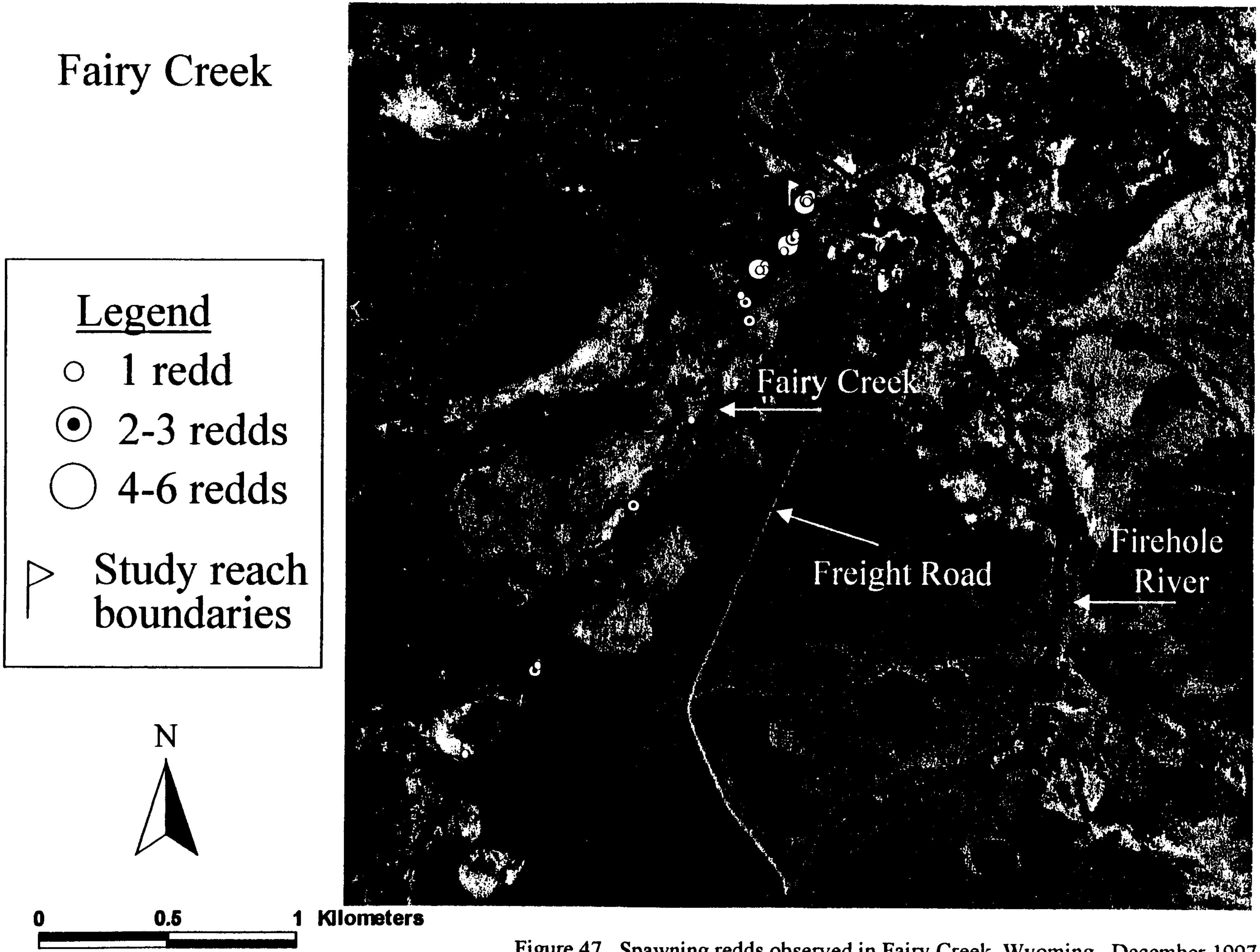


Figure 47. Spawning redds observed in Fairy Creek, Wyoming. December 1997 - February 1998.

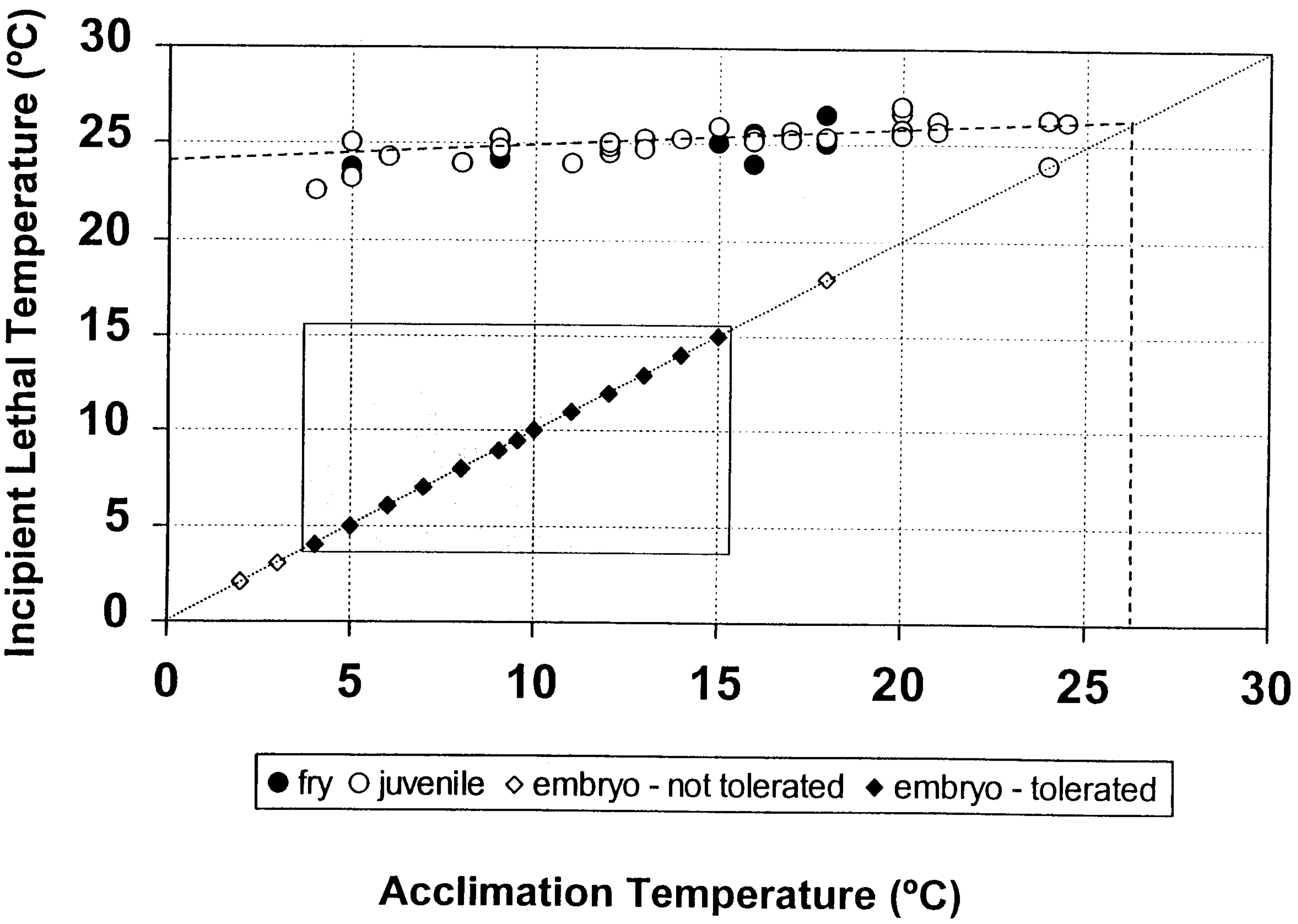


Figure 48. Temperature tolerance range of rainbow trout Oncorhynchus mykiss. Shaded area represents embryonic temperature tolerance range. Large dashed lines indicates temperature tolerance range of post-hatch life stages.

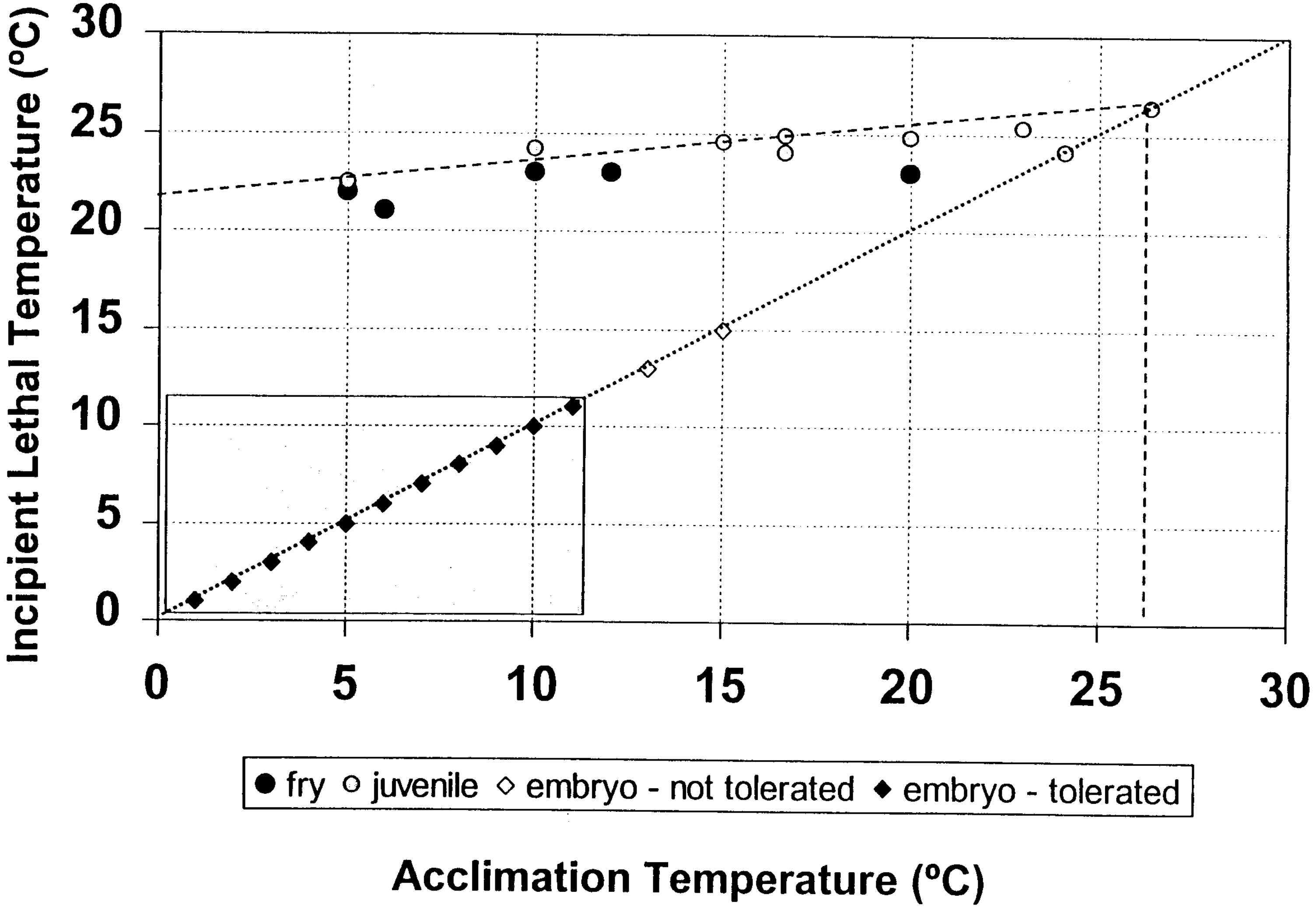


Figure 49. Temperature tolerance range of brown trout Salmo trutta. Shaded area represents the embryonic temperature tolerance range. Large dashed lines indicates temperature tolerance range of post-hatch life stages.

Appendix A. Detailed water chemistry data at study sites in the Firehole River and tributaries, Wyoming, June 1997 to June 1998. LFHR = Little Firehole River, IRON - Iron Springs Creek, FC = Fairy Creek, SC = Sentinel Creek, and NP = Nez Perce Creek. COLD, WARM, HOT = mainstem sites. NS = not sampled. CAB = samples omitted because of cation-anion imbalance

	µS/cm	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Conductivity	COLD	NS	48	57	61	69	66	67	73	76	NS	NS	NS	NS	NS	NS
	FC	480	398	486	473	478	478	493	468	535	539	620	610	620	457	499
	HOT	230	283	321	333	350	365	361	377	379	427	471	488	492	443	269
	IRON	180	238	223	208	202	199	198	198	197	213	233	235	247	243	220
	LFHR	49	84	82	85	88	89	90	92	87	100	102	113	108	99	45
	NP	238	283	302	310	323	325	324	325	330	NS	NS	NS	NS	NS	NS
	SC	146	119	150	171	165	159	156	160	180	NS	NS	NS	NS	NS	NS
	WARM	115	148	169	176	192	195	187	209	197	245	248	255	258	253	149

	pH	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
pH	COLD	NS	6.7	6.8	6.7	6.9	6.6	6.5	6.8	6.7	NS	NS	NS	NS	NS	NS
	FC	8.6	8.8	9.0	8.6	8.6	8.8	8.6	8.0	8.0	8.9	6.5	7.1	6.3	7.3	7.5
	HOT	7.8	7.8	8.6	8.3	8.4	8.6	8.3	8.3	8.3	9.0	7.0	7.2	6.9	7.7	7.3
	IRON	7.8	7.6	7.2	7.3	7.5	7.6	7.3	7.3	7.0	7.8	6.7	6.3		7.2	7.2
	LFHR	7.3	7.1	7.7	6.9	7.2	6.9	6.7	6.9	6.5	7.1	6.7	7.2	7.0	6.3	6.8
	NP	NS	7.6	7.9	7.9	8.0	8.1	7.8	7.8	7.6	NS	NS	NS	NS	NS	NS
	SC	7.4	7.0	8.2	6.5	7.5	7.6	7.9	7.4	6.9	NS	NS	NS	NS	NS	NS
	WARM	7.3	7.6	7.6	7.2	7.6	7.8	7.2	7.4	7.3	NS	6.7	6.7	6.7	7.0	7.1

	m^3/sec	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Discharge	COLD	NS	6.7	4.0	3.3	3.3	2.4	2.9	2.8	2.3	NS	NS	NS	NS	NS	NS
	FC	NS	0.3	0.4	0.4	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4
	HOT	NS	14.6	11.4	12.2	11.1	8.5	10.7	9.6	11.0	8.8	8.5	8.7	9.5	8.5	14.2
	IRON	NS	2.7	2.4	2.7	2.5	3.1	2.6	2.8	2.6	NS	1.9	2.0	2.2	2.1	NS
	LFHR	NS	2.0	1.5	1.6	1.6	1.7	1.5	1.6	1.7	1.3	1.1	1.1	1.1	1.5	3.8
	NP	NS	3.2	2.3	2.2	2.5	1.9	2.0	2.1	2.3	NS	NS	NS	NS	NS	NS
	SC	NS	0.7	0.6	0.6	0.5	0.5	0.5	0.7	0.0	NS	NS	NS	NS	NS	NS
	WARM	NS	12.4	NS	7.3	9.3	8.3	7.7	7.7	7.7	6.8	6.0	5.7	5.6	5.8	NS

	µgNH$_4$-N/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Total Ammonia	COLD	3	75	45	164	15	74	3	43	40	NS	NS	NS	NS	NS	NS
	FC	3	69	256	26	29	83	3	0	11	38	3	89	46	67	48
	HOT	3	62	10	15	50	74	3	84	11	15	3	3	31	67	48
	IRON	3	62	31	26	57	79	3	35	4	8	3	3	58	67	48
	LFHR	3	75	10	15	36	74	40	43	11	29	3	3	82	158	200
	NP	27	114	31	38	15	83	24	43	169	NS	NS	NS	NS	NS	NS
	SC	27	114	38	38	29	87	86	76	4	NS	NS	NS	NS	NS	NS
	WARM	3	56	3	49	50	101	3	43	0	17	3	41	39	105	111

Appendix A. Detailed water chemistry data at study sites in the Firehole River and tributaries, Wyoming, June 1997 to June 1998. LFHR = Little Firehole River, IRON - Iron Springs Creek, FC = Fairy Creek, SC = Sentinel Creek, and NP = Nez Perce Creek. COLD, WARM, HOT = mainstem sites. NS = not sampled. CAB = samples omitted because of cation-anion imbalance

	µeq/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Potassium	COLD	41	52	57	72	39	77	72	84	85	NS	NS	NS	NS	NS	NS
	FC	193	150	145	171	151	164	159	174	185	160	242	241	254	162	156
	HOT	130	139	152	178	130	187	175	191	194	184	235	243	258	205	123
	IRON	149	149	138	147	130	141	130	142	145	132	154	159	168	150	130
	LFHR	52	77	70	77	40	80	78	86	85	82	87	87	96	84	41
	NP	178	187	193	220	130	226	214	221	229	NS	NS	NS	NS	NS	NS
	SC	92	90	79	105	53	92	90	100	109	NS	NS	NS	NS	NS	NS
	WARM	87	93	102	118	119	123	116	132	131	132	148	195	161	140	84

	µeq/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Sodium	COLD	128	225	242	230	CAB	CAB	365	CAB	CAB	NS	NS	NS	NS	NS	NS
	FC	4136	3975	4090	4262	CAB	CAB	CAB	CAB	CAB	4679	5335	5416	5574	3942	4239
	HOT	1652	NS	2462	2437	2878	CAB	CAB	CAB	CAB	3558	3520	3922	4249	3571	2035
	IRON	1591	1834	CAB	1465	1333	CAB	1292	CAB	CAB	1558	1760	1799	1837	1901	1633
	LFHR	CAB	CAB	CAB	389	422	479	461	CAB	CAB	565	508	610	649	575	NS
	NP	1739	2013	2184	2018	1649	CAB	1992	CAB	2173	NS	NS	NS	NS	NS	NS
	SC	940	1049	932	CAB	CAB	CAB	846	CAB	CAB	NS	NS	NS	NS	NS	NS
	WARM	849	1013	1233	1248	1302	CAB	1313	CAB	CAB	1917	1826	1850	1993	1975	1060

	µeq/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Dissolved Sodium	COLD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	FC	4036	NS	NS	4128	NS	NS	NS	NS	NS	4585	5372	5580	5563	3908	4229
	HOT	2242	NS	NS	2415	2275	NS	NS	NS	NS	3594	3598	4033	4245	3665	2031
	IRON	1822	NS	NS	1476	825	NS	NS	NS	NS	1543	1742	1822	1879	1894	1624
	LFHR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	NP	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	SC	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	WARM	1017	NS	NS	1248	544	NS	NS	NS	NS	1951	1860	1850	1984	1959	1053

	µeq/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Calcium	COLD	68	102	112	99	CAB	CAB	154	CAB	CAB	NS	NS	NS	NS	NS	NS
	FC	199	196	205	217	CAB	CAB	CAB	CAB	CAB	195	210	196	197	169	198
	HOT	138	CAB	189	197	237	CAB	CAB	CAB	CAB	248	257	263	253	231	161
	IRON	172	202	CAB	186	173	CAB	170	CAB	CAB	187	216	211	202	196	189
	LFHR	CAB	CAB	CAB	218	226	256	255	CAB	CAB	263	250	284	294	264	NS
	NP	262	309	304	297	225	CAB	291	CAB	295	NS	NS	NS	NS	NS	NS
	SC	270	272	256	CAB	CAB	CAB	227	CAB	CAB	NS	NS	NS	NS	NS	NS
	WARM	118	149	166	184	171	CAB	187	CAB	CAB	191	212	200	218	208	134

Appendix A. Detailed water chemistry data at study sites in the Firehole River and tributaries, Wyoming, June 1997 to June 1998. LFHR = Little Firehole River, IRON - Iron Springs Creek, FC = Fairy Creek, SC = Sentinel Creek, and NP = Nez Perce Creek. COLD, WARM, HOT = mainstem sites. NS = not sampled. CAB = samples omitted because of cation-anion imbalance

	µeq/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Dissolved Calcium	COLD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	FC	188	NS	NS	190	NS	NS	NS	NS	NS	174	185	195	189	164	178
	HOT	185	NS	NS	197	164	NS	NS	NS	NS	236	238	253	250	233	159
	IRON	200	NS	NS	188	100	NS	NS	NS	NS	182	197	201	197	193	176
	LFHR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	NP	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	SC	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	WARM	151	NS	NS	180	NS	NS	NS	NS	NS	184	208	190	203	199	128

	µeq/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Magnesium	COLD	19	24	24	22	CAB	CAB	30	CAB	CAB	NS	NS	NS	NS	NS	NS
	FC	38	37	35	39	CAB	CAB	CAB	CAB	CAB	34	39	39	40	41	37
	HOT	25	CAB	29	28	31	CAB	CAB	CAB	CAB	29	29	30	29	31	28
	IRON	32	39	CAB	35	33	CAB	32	CAB	CAB	34	36	36	34	36	35
	LFHR	CAB	CAB	CAB	37	36	41	39	CAB	CAB	37	38	41	42	44	NS
	NP	59	63	63	59	45	CAB	54	CAB	56	NS	NS	NS	NS	NS	NS
	SC	76	71	67	CAB	CAB	CAB	56	CAB	CAB	NS	NS	NS	NS	NS	NS
	WARM	27	31	33	34	31	CAB	33	CAB	CAB	31	35	33	34	37	31

	µeq/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Dissolved Magnesium	COLD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	FC	38	NS	NS	38	NS	NS	NS	NS	NS	33	41	41	40	41	38
	HOT	30	NS	NS	29	24	NS	NS	NS	NS	30	29	30	30	33	29
	IRON	38	NS	NS	36	20	NS	NS	NS	NS	34	36	37	35	37	35
	LFHR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	NP	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	SC	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	WARM	32	NS	NS	34	NS	NS	NS	NS	NS	32	35	33	34	38	31

	µeq/kg	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Alkalinity	COLD	160	190	220	240	280	260	280	340	320	NS	NS	NS	NS	NS	NS
	FC	2140	2020	2080	2040	2260	1940	2080	1880	2240	2220	2400	2680	2367	1240	2200
	HOT	920	840	1160	1560	1660	1560	1580	1660	1693	1860	2200	2160	2220	1920	1240
	IRON	1040	1140	460	940	1060	1060	960	980	960	1000	1100	1140	1220	1220	1080
	LFHR	300	960	1060	470	540	460	460	500	380	500	580	680	620	620	340
	NP	1020	1100	1080	1200	1320	1160	1260	1300	1300	NS	NS	NS	NS	NS	NS
	SC	760	780	780	480	820	820	800	800	840	NS	NS	NS	NS	NS	NS
	WARM	500	540	880	840	960	880	840	940	900	1220	1080	1140	1600	1100	660

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	µeq/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Chloride	COLD	75	119	124	150	76	162	172	197	234	NS	NS	NS	NS	NS	NS
	FC	1879	1850	1485	1844	1687	1834	1961	1947	2054	2194	2571	2703	2724	1862	1938
	HOT	827	1024	912	1296	934	1389	1390	1421	1427	1687	1894	2050	2246	1907	1027
	IRON	739	736	663	648	555	586	599	590	592	652	719	931	755	812	688
	LFHR	53	90	73	90	40	83	90	92	93	117	112	129	124	118	45
	NP	697	779	718	890	521	874	915	908	964	NS	NS	NS	NS	NS	NS
	SC	375	423	369	423	239	414	423	454	553	NS	NS	NS	NS	NS	NS
	WARM	375	471	360	583	599	629	606	680	654	895	845	1047	887	894	502

	µeq/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Nitrate	COLD	22	10	6	14	2	42	33	10	12	NS	NS	NS	NS	NS	NS
	FC	14	8	14	7	13	30	15	9	33	12	6	56	22	6	2
	HOT	19	13	5	6	6	25	17	10	10	20	3	51	20	6	2
	IRON	31	11	20	18	15	32	9	13	36	13	16	47	23	3	5
	LFHR	15	15	19	8	6	45	27	29	35	16	20	65	24	11	16
	NP	32	17	3	15	10	40	11	8	6	NS	NS	NS	NS	NS	NS
	SC	15	10	26	0	11	21	14	9	24	NS	NS	NS	NS	NS	NS
	WARM	29	6	8	19	16	19	30	17	62	8	10	68	24	29	3

	µeq/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Sulfate	COLD	27	35	35	44	25	48	45	61	52	NS	NS	NS	NS	NS	NS
	FC	147	159	151	152	146	162	165	170	183	181	206	198	190	146	169
	HOT	88	104	113	129	98	141	140	149	149	163	183	172	173	173	117
	IRON	82	86	78	83	73	81	78	84	80	85	90	85	100	98	90
	LFHR	52	87	85	99	56	109	112	123	125	144	136	138	138	119	46
	NP	333	442	358	475	312	500	497	522	500	NS	NS	NS	NS	NS	NS
	SC	51	60	53	49	36	62	60	67	70	NS	NS	NS	NS	NS	NS
	WARM	51	67	69	82	84	88	87	99	93	110	117	126	115	108	71

	µeq/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Fluoride	COLD	44	56	74	83	87	99	101	105	105	NS	NS	NS	NS	NS	NS
	FC	518	505	515	455	468	523	514	527	535	537	581	616	572	484	495
	HOT	188	263	294	291	293	352	354	413	359	383	422	403	435	389	237
	IRON	288	267	297	234	243	248	251	271	253	258	268	299	299	295	258
	LFHR	73	123	135	144	139	149	153	157	145	166	164	173	162	142	53
	NP	248	289	287	290	308	337	355	392	403	NS	NS	NS	NS	NS	NS
	SC	185	233	174	153	169	236	189	241	212	NS	NS	NS	NS	NS	NS
	WARM	141	158	282	165	214	227	223	254	224	272	254	348	288	253	142

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	mg/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
TOC	COLD	3.02	2.58	1.55	1.35	1.12	1.01	0.84	1.31	1.35	NS	NS	NS	NS	NS	NS
	FC	3.08	3.18	1.77	3.27	1.76	1.38	1.51	1.53	1.99	1.56	NS	2.26	2.70	24.50	2.40
	HOT	2.62	2.35	1.52	1.24	1.11	0.94	1.18	1.04	1.59	1.08	NS	1.13	1.00	19.60	2.90
	IRON	1.56	1.29	1.89	1.04	0.74	0.45	0.61	0.76	0.74	0.82	NS	0.99	1.10	1.10	1.30
	LFHR	3.45	2.01	0.93	2.19	1.49	1.28	1.25	1.21	1.54	0.84	NS	1.22	1.50	2.80	3.30
	NP	4.28	2.72	1.76	1.72	1.47	1.22	1.20	1.68	2.02	NS	NS	NS	NS	NS	NS
	SC	4.15	2.97	2.29	4.63	2.63	2.09	NS	2.32	2.75	NS	NS	NS	NS	NS	NS
	WARM	2.70	2.34	1.49	1.40	1.41	0.86	0.95	1.31	0.98	0.98	NS	1.12	1.20	2.40	2.40

	mg/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
DOC	COLD	3.24	2.29	1.61	1.50	1.34	1.14	0.88	1.06	1.68	NS	NS	NS	NS	NS	NS
	FC	3.15	1.56	1.55	3.13	1.73	1.67	1.74	1.90	1.87	1.87	NS	2.38	3.07	18.90	2.30
	HOT	2.75	1.40	2.48	1.50	1.20	1.10	1.00	0.91	1.51	1.10	NS	1.02	1.90	18.20	3.00
	IRON	1.67	0.42	2.00	1.00	1.09	0.64	0.95	1.02	0.84	0.83	NS	0.86	1.30	1.30	1.70
	LFHR	3.39	1.65	0.99	2.47	2.20	1.45	1.81	1.55	1.99	1.18	NS	1.43	1.80	2.80	3.80
	NP	4.17	1.90	1.97	1.95	1.46	1.16	1.42	1.74	1.97	NS	NS	NS	NS	NS	NS
	SC	4.07	2.75	2.19	4.72	2.64	2.09	2.33	2.47	2.63	NS	NS	NS	NS	NS	NS
	WARM	2.59	1.19	1.50	1.70	1.07	0.97	1.04	1.06	1.34	1.14	NS	1.08	1.60	1.80	2.50

	μg/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Arsenic	COLD	9	13	13	12	CAB	CAB	18	CAB	CAB	NS	NS	NS	NS	NS	NS
	FC	400	353	373	375	CAB	CAB	CAB	CAB	CAB	430	481	482	496	378	393
	HOT	162	CAB	232	230	268	CAB	CAB	CAB	CAB	357	364	406	433	357	203
	IRON	108	120	CAB	99	89	CAB	87	CAB	CAB	107	120	125	128	132	114
	LFHR	CAB	CAB	CAB	15	17	18	17	CAB	CAB	23	20	25	26	24	NS
	NP	94	90	100	93	83	CAB	93	CAB	111	NS	NS	NS	NS	NS	NS
	SC	80	78	69	CAB	CAB	CAB	61	CAB	CAB	NS	NS	NS	NS	NS	NS
	WARM	61	72	87	87	93	CAB	92	CAB	CAB	138	130	133	142	141	80

	μg/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Dissolved Arsenic	COLD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	FC	359	NS	NS	362	NS	NS	NS	NS	NS	407	473	498	490	378	379
	HOT	213	NS	NS	234	223	NS	NS	NS	NS	350	348	402	428	354	200
	IRON	117	NS	NS	100	NS	NS	NS	NS	NS	106	119	123	131	130	112
	LFHR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	NP	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	SC	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	WARM	69	NS	NS	86	NS	NS	NS	NS	NS	138	131	130	142	143	75

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	µg/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
As(V)	COLD	<35	<35	<35	<35	<35	<35	<35	<35	<35	NS	NS	NS	NS	NS	NS
	FC	353	361	360	344	145	135	318	121	243	325	377	324	288	201	278
	HOT	108	231	250	204	258	199	221	219	110	229	241	228	178	137	108
	IRON	112	138	128	118	107	103	101	90	66	90	62	135	98	94	104
	LFHR	<35	<35	<35	<35	<35	<35	<35	<35	<35	<35	<35	<35	49	<35	<35
	NP	64	75	90	58	59	<35	38	<35	108	NS	NS	NS	NS	NS	NS
	SC	60	102	90	85	44	58	70	<35	69	NS	NS	NS	NS	NS	NS
	WARM	44	85	80	59	94	38	81	79	48	110	73	128	36	43	<35

	µg/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
As(III)	COLD	<35	<35	<35	<35	CAB	CAB	<35	CAB	CAB	NS	NS	NS	NS	NS	NS
	FC	<35	<35	<35	<35	CAB	CAB	CAB	CAB	CAB	105	104	157	208	177	115
	HOT	54	CAB	<35	<35	<35	CAB	CAB	CAB	CAB	128	123	177	256	220	95
	IRON	<35	<35	CAB	<35	<35	CAB	<35	CAB	CAB	<35	58	<35	<35	<35	<35
	LFHR	CAB	CAB	CAB	<35	<35	<35	<35	CAB	CAB	<35	57	<35	<35	<35	NS
	NP	<35	<35	<35	<35	<35	CAB	54	CAB	<35	NS	NS	NS	NS	NS	NS
	SC	<35	<35	<35	CAB	CAB	CAB	<35	CAB	CAB	NS	NS	NS	NS	NS	NS
	WARM	<35	<35	<35	<35	<35	CAB	<35	CAB	CAB	<35	57	<35	106	98	52

	µg/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Boron	COLD	4	49	45	61	CAB	CAB	85	CAB	CAB	NS	NS	NS	NS	NS	NS
	FC	866	843	845	928	CAB	CAB	CAB	CAB	CAB	963	1123	1130	1152	818	890
	HOT	301	CAB	464	449	535	CAB	CAB	CAB	CAB	665	670	759	821	679	378
	IRON	257	313	CAB	246	192	CAB	197	CAB	CAB	251	305	273	315	287	268
	LFHR	CAB	CAB	CAB	24	24	54	21	CAB	CAB	45	56	48	71	77	NS
	NP	311	375	397	341	291	CAB	369	CAB	374	NS	NS	NS	NS	NS	NS
	SC	188	211	156	CAB	CAB	CAB	47	CAB	CAB	NS	NS	NS	NS	NS	NS
	WARM	143	178	223	220	234	CAB	244	CAB	CAB	340	317	321	355	339	169

	µg/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Dissolved Boron	COLD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	FC	820	NS	NS	868	NS	NS	NS	NS	NS	955	1050	1169	1145	803	891
	HOT	417	NS	NS	465	429	NS	NS	NS	NS	666	682	793	795	705	373
	IRON	288	NS	NS	225	NS	NS	NS	NS	NS	254	283	286	327	306	262
	LFHR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	NP	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	SC	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	WARM	174	NS	NS	204	NS	NS	NS	NS	NS	324	336	316	371	350	177

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	µg/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Chromium	COLD	0	0	0	0	CAB	CAB	0	CAB	CAB	NS	NS	NS	NS	NS	NS
	FC	0	0	1	2	CAB	CAB	CAB	CAB	CAB	141	0	0	0	0	0
	HOT	0	CAB	0	2	3	CAB	CAB	CAB	CAB	247	0	0	0	0	0
	IRON	0	0	CAB	0	0	CAB	0	CAB	CAB	0	0	0	0	0	0
	LFHR	CAB	CAB	CAB	0	0	0	0	CAB	CAB	0	0	0	0	0	
	NP	0	0	4	3	44	CAB	0	CAB	0	NS	NS	NS	NS	NS	NS
	SC	0	0	0	CAB	CAB	CAB	0	CAB	CAB	NS	NS	NS	NS	NS	NS
	WARM	0	0	0	1	0	CAB	0	CAB	CAB	11	0	0	0	0	0

	µg/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Dissolved Chromium	COLD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	FC	0	NS	NS	1		NS	NS	NS	NS	136	0	0	0	0	0
	HOT	0	NS	NS	2	0	NS	NS	NS	NS	243	0	0	0	0	0
	IRON	0	NS	NS	0	0	NS	NS	NS	NS	0	0	0	0	0	0
	LFHR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	NP	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	SC	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	WARM	0	NS	NS	0	0	NS	NS	NS	NS	10	0	0	0	0	0

	µg/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Selenium	COLD	0.5	0.8	0.8	0.6	CAB	CAB	0.5	CAB	CAB	NS	NS	NS	NS	NS	NS
	FC	1.3	1.4	2.4	1.5	CAB	CAB	CAB	CAB	CAB	1.5	1.2	1.7	1.5	1.1	1.9
	HOT	1.1	CAB	2.2	1.6	0.9	CAB	CAB	CAB	CAB	1.6	2.5	1.9	2.8	0.8	1.0
	IRON	1.3	1.3	CAB	0.7	0.5	CAB	0.5	CAB	CAB	1.2	1.2	1.4	1.5	0.6	0.6
	LFHR	CAB	CAB	CAB	0.5	0.7	0.8	0.9	CAB	CAB	0.5	1.2	1.1	1.4	0.6	
	NP	0.5	0.5	1.1	1.8	0.9	CAB	0.6	CAB	1.3	NS	NS	NS	NS	NS	NS
	SC	0.5	1.1	0.9	CAB	CAB	CAB	1.3	CAB	CAB	NS	NS	NS	NS	NS	NS
	WARM	0.8	0.9	0.9	1.2	0.9	CAB	0.8	CAB	CAB	0.8	0.8	0.9	0.6	0.7	0.3

	µg/L	Jun-17-97	Jul-01-97	Jul-14-97	Jul-29-97	Aug-13-97	Aug-26-97	Sep-09-97	Sep-25-97	Oct-15-97	Nov-24-97	Jan-06-98	Feb-04-98	Mar-04-98	Apr-28-98	May-27-98
Dissolved Selenium	COLD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	FC	1.9	NS	NS	2.5	NS	NS	NS	NS	NS	1.0	1.7	2.1	2.6	1.9	1.7
	HOT	1.7	NS	NS	0.4	1.7	NS	NS	NS	NS	1.1	2.3	1.9	1.2	2.1	1.1
	IRON	1.1	NS	NS	1.2	0.2	NS	NS	NS	NS	0.3	0.9	0.0	0.8	0.8	0.1
	LFHR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	NP	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	SC	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	WARM	0.6	NS	NS	1.0	0.9	NS	NS	NS	NS	1.2	0.3	1.3	0.7	0.9	0.8