CONTRACT NO. A932-138
FINAL REPORT
DECEMBER 1994

Aquatic Biota in the Sierra Nevada:

Current Status and Potential Effects of Acid Deposition on Populations

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

AIR RESOURCES BOARD
Research Division

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Final Report

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Prepared for:

California Air Resources Board
Research Division
2020 L Street
Sacramento, California 95814

Prepared by:

Principal Investigators
Thomas M. Jenkins, Jr.
Roland A. Knapp
Kim W. Kratz
and
Scott D. Cooper

Contributing Scientists
John M. Melack
Aaron D. Brown
and
John Stoddard

Marine Science Institute
University of California
Santa Barbara, California 93106

December 1994

Abstract

In the first part of this study we randomly selected 30 sample lakes from the subset of Sierra lakes above approximately 2439 meter (8000 foot) elevation, and qualitatively described the populations of fish and macroinvertebrates present in these lakes (and associated streams) relative to water chemistry. The lakes were selected with EPA's EMAP area-based sampling technique, which projected a total of 1404 lakes > 1 ha in surface area (no actual count was attempted). We described the chemical and biological characteristics of five additional high-elevation lakes, including four that were part of a long-term CARB monitoring program.

Although lakes in our survey were higher in elevation and smaller in surface area than lakes examined in EPA's Western Lakes Survey (WLS), water chemistry results were similar in these two surveys, showing a predominance of low ANC waters with no evidence of chronic changes caused by atmospheric deposition. This similarity is important because the EPA study has been the most comprehensive attempt to characterize the chemical sensitivity of Sierra Nevada waters in general.

A few lakes at the southeastern border of Kings Canyon National Park were apparently acidic from natural basin sources, and had high sulfate and aluminum concentrations. Only 8% of the lakes in the study region had pHs < 6.0.

Of the calculated total of 1404 lakes meeting our selection criteria, we estimated that 881 contained one or two species of salmonid fish, 127 contained only yellow-legged frogs, 284 contained only invertebrates, and 112 contained no fish and almost no invertebrates. Golden trout (*Oncorhynchus mykiss aguabonita*) and rainbow trout (*Oncorhynchus mykiss*) were the most commonly collected fish species, with brook trout (*Salvelinus fontinalis*) ranking third and brown trout (*Salmo trutta*) fourth in frequency of occurrence. A few lakes contained cutthroat trout (*Oncorhynchus clarki*). Nearly all of the present high elevation fish populations were established by humans, and the vast majority (possibly all) of the lakes above 8000 feet in the Sierra Nevada were originally devoid of fish due to natural barriers.

Fish and invertebrates were not collected in the two most acidic lakes (pHs 4.7 and 5.2). Aluminum concentrations tended to be lower where golden trout were present versus absent and pH tended to be higher where brook trout were present versus absent; however, these chemical factors were both correlated with elevation and relationships may have been confounded by patterns of stocking related to elevation. The taxon richness of macroinvertebrates in streams and lakes was positively related to pH, and in lakes it was negatively related to nitrate and elevation. Similarly, pH was higher and nitrate, sulfate, and elevation tended to be lower where common macroinvertebrates (e.g. *Callibaetis*, *Pisidium*) were present compared to where they were absent. It was apparent, however, that all fish and most invertebrate species could live and reproduce in lakes and streams with pHs as low as 6.

In the second part of this study, a dose-response experiment was conducted during snowmelt in channels lying next to the outlet stream (Mine Creek) of a representative high-altitude lake (Spuller Lake). Buried eggs of golden trout were exposed to a gradient of 6 pH levels ranging from 4.8 to 6.6, for a period of 40 hours, and the survivorship of eggs determined nine to ten days later. Survivorship of eggs was high at the

low temperatures (<5° C) encountered during the experiment, and there were no significant impacts of acid inputs on egg survival.

When combined with literature data the results suggest that the eggs of trout species would not be affected by acid inputs until pH was lowered to ≤ 4.5. Literature data also show that later stages, such as sac and swim-up fry, are quite sensitive to high aluminum concentrations and would be negatively affected by pH depressions to 5.0-5.5 if accompanied by high aluminum levels. Trout belonging to the genus *Oncorhynchus* (i.e. golden, rainbow, and cutthroat trout) are more sensitive to acid inputs than trout belonging to the genera *Salvelinus* (brook trout) or *Salmo* (brown trout), and would be the first fish to respond to substantial acid deposition in the High Sierra. Because early life stages of trout are most susceptible to acid inputs, the timing of acid pulses relative to the timing of trout reproduction, egg development and hatching, and emergence of fry from substrates is particularly important in evaluating the effects of acid deposition on trout populations.

Acknowledgments

We thank Connie Millar, U.S.D.A. Pacific Southwest Research Station, for her assistance in gaining permission to conduct the dose-response study in the Harvey Monroe Hall Research Natural Area, John Ellsworth for helping ski equipment into the study site, personnel at the Mt. Whitney Fish Hatchery for their assistance in obtaining golden trout eggs, Cleber Ouverney for his help during the experimental acidification, and Eric Knapp, Thackery Grossman, and Stuart Scofield for their assistance in carrying equipment out from the study site. We also thank Dan Dawson, manager of the Sierra Nevada Aquatic Research Laboratory for his logistical support throughout this study. Ari Martinez, Dennis Schloss, Michael Peterson and Sean Oldham assisted in field collections and chemical analyses. Frank Setaro analyzed chemical samples at UCSB and made useful suggestions regarding chemical techniques.

Dr. Jan van Wagtendonk and Dr. David Graber facilitated the procurement of collecting permits in Yosemite and Sequoia/Kings Canyon National Parks respectively, and provided information concerning fish plants in the study lakes. Dennis Martin of the Inyo National Forest, R.M. Nelson of the Toiyabe National Forest, and Glen Gottschall of the Stanislaus National Forest provided permits for work in their jurisdictions. Darrell Wong of the California Department of Fish and Game allowed us to search their planting records for several of the selected waters.

Disclaimer

The statements and conclusions in this report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source or their use in connection with material herein is not to be construed as either actual or implied endorsement of such products.

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Summary and Conclusions

Purpose and Approach: One purpose of this study was to determine relationships between the water chemistry of high-elevation Sierra Nevada lakes and streams, on one hand, and the numbers and composition of fish and macroinvertebrate assemblages in these lakes, on the other. Ultimately, these data will be used to assess the susceptibility of Sierran waters to damage should water chemistry be altered by atmospheric deposition of chemical pollutants. We randomly selected 30 lakes in the Sierra Nevada at elevations above 2440 meters, and sampled chemistry (ANC, pH, major ions and total aluminum), fish populations, and macroinvertebrate assemblages in the lakes and outlet or inlet streams. The lakes were selected using the EMAP area-based technique developed by the U.S. Environmental Protection Agency for monitoring ecosystem health in U.S. waters. We also sampled water chemistry, fish, and macroinvertebrates in five additional lakes, and associated streams, including four that are part of a long-term CARB monitoring program (Melack et al. 1993).

A second purpose of this study was to acquire information on the effects of varying levels of acid input on the early life history stages of golden trout, the most common fish species encountered in our survey. Before this study was initiated, there was little information on the acid tolerances of golden trout life stages. We conducted a dose-response experiment during snowmelt in flow-through channels constructed next to the outlet stream (Mine Creek) of a representative high-altitude lake (Spuller Lake). Individual channels were dosed with different levels of acid, creating a gradient of pH levels ranging from 4.8 to 6.6, for 40 hours, and survivorship of golden trout eggs was determined nine to ten days after acidification. These data were combined with literature data to predict the effects of different pH levels on trout populations in High Sierra lakes and streams.

Part I: Survey of water chemistry, fish, and macroinvertebrates in High Sierra lakes and associated streams

Lake Chemistry and Physical Attributes: The results of our survey were extrapolated to all Sierra Nevada lakes of the proper size (>1 hectare) and elevation (>8000'), which numbered 1404 according to our EMAP estimates. Our target lakes averaged smaller in surface area than those considered by the EPA Western Lakes Survey (the most comprehensive chemistry study to date), because larger waters at low elevations, included in the EPA survey, were excluded from our survey. The water chemistry of our surveyed lakes was generally similar to water chemistry values reported by the Western Lake Survey (WLS); however, pH and ANC were a bit lower, and nitrate concentrations higher, in the lakes we sampled than in the lakes covered by the WLS. The survey revealed that most high-elevation waters were "poorly buffered" (ANC < 200 μeq/l) and pHs usually fell between 6 and 7. The dominant cations in most lakes were Ca^{++} and Na^{+}, and half of the lakes had $Ca^{++} < 50$ μeq/l. Total aluminum concentrations were less than 1.9 μM (50 μg/l) in most lakes. One cluster of lakes in the southern range were exceptional in that they were acidic (pHs < 5.5), and had high sulfate and aluminum concentrations.

Fish Populations: We estimated that 881 of the 1404 lakes contained one or two species of trout, 126 contained only yellow-legged frogs and 284 contained only invertebrates. An estimated 112 acidic lakes appeared to be almost devoid of animals, although the concentration of these lakes around one geological formation suggests that the estimate would be reduced with more concentrated sampling. Of the lakes with fish, an estimated 498 contained golden trout, 461 contained rainbow trout, 221 contained brook trout, 112 contained brown trout, and 7 contained cutthroat trout. Yellow-legged frogs were projected to live in 155 lakes (29 with trout). Fish were absent from the two acidic lakes (pHs 4.7 and 5.2), despite repeated stocking of one of them. Aluminum concentrations were lower in lakes where golden trout were present than where they were absent and pH was higher in lakes where brook trout were present vs. absent. Both aluminum concentrations and pH, however, were related to elevation, and relationships between the distribution of trout and water chemistry may have been confounded by patterns of stocking related to elevation.

Macroinvertebrates: The invertebrate communities in most of the study lakes and streams were not diverse, and population densities were usually low. Common taxa collected included mayflies (particularly Family Baetidae), odonates (F. Aeshnidae, Coenagrionidae), hemipterans (F. Corixidae, Notonectidae), alder flies (F. Sialidae), caddis larvae (F. Limnephlidae), beetles (F. Dytiscidae), chironomids, snails, and fingernail clams (*Pisidium*). Large or active epibenthic taxa, such as mayfly nymphs (F. Baetidae and Siphlonuridae) and water boatmen (F. Corixidae), were rare or absent in lakes containing trout but were commonly collected in lakes lacking trout. No invertebrates were collected in the two most acidic lakes (pH 4.7 and 5.2), although more intensive and specialized sampling would likely have turned up some species. The number of macroinvertebrate taxa collected in lakes and streams was positively related to pH and negatively related to nitrate and elevation. pH tended to be higher, and nitrate, sulfate and elevation lower in lakes where some common macroinvertebrates (e.g. *Callibaetis*, *Pisidium*) were present compared to lakes where they were absent.

Part II. A field experiment to determine the sensitivity of California golden trout (*Oncorhynchus mykiss aguabonita*) eggs to a simulated acid pulse in the Sierra Nevada, California.

Experimental acidification to pHs as low as 4.8 had no effect on the survival of golden trout eggs. The eggs of spring-spawning species (e.g. golden, rainbow, and cutthroat trout), and the fry of fall-spawning species (brook and brown trout), are present at snowmelt, the time when acid pulses are most likely to occur. Based on our experimental results and literature data, we predict that acid pulses associated with snowmelt will not affect the eggs of spring-spawning species until pH is reduced to ≤ 4.5. Because the swim-up fry stage of trout is especially sensitive to high aluminum concentrations, pH depressions to ca. 5.0 - 5.5, when coupled with high aluminum concentrations and coincident with fry emergence from spawning gravels, could result in declines in trout populations. Coincidence of the presence of swim-up fry and acid/aluminum pulses could occur during summer rain storms, for spring-spawning species, and spring snowmelt, for fall-spawning species. Trout belonging to the genus *Oncorhynchus* (golden, rainbow, and cutthroat trout) are more susceptible to acid inputs than trout belonging to the genera *Salvelinus* (brook trout) or *Salmo* (brown trout). As a consequence, *Oncorhynchus* spp. should show some of the first responses to increased acidification.

Recommendations

1. Although we have a general idea of the life history patterns of common trout species and the timing of potential acid pulses (see Part I), the effects of acid pulses may depend on the precise timing of life history events (fertilization, hatching, emergence). Because early life stages of trout are most sensitive to acid inputs, we need more precise data on the timing of acid pulses relative to the timing of trout reproduction, egg development and hatching, and fry emergence from spawning gravels. Detailed monitoring of High Sierra lakes and streams will indicate specific temporal features of the life cycles of different trout species relative to pulses of acid and aluminum associated with snowmelt and summer rain storms, and allow us to examine correlations between hydrochemical changes and the survival of early trout stages.

2. The literature indicates that elevated aluminum levels associated with acid deposition can have large effects on the survivorship of early life stages of trout. As a consequence, it is necessary to make detailed predictions of aluminum levels in High Sierra streams and lakes under different acid deposition scenarios. Because aluminum levels in waters draining Sierran catchments will depend on the underlying geological characteristics of these basins, there is a need to develop detailed mineralogical maps for all Sierran basins. Data on catchment mineralogy can be combined with geochemical models to provide predictions of aluminum levels under different loadings of acid.

3. It has proven difficult to construct predictive models of trout population responses to different acid and aluminum levels from literature data, because different studies have used different methods, approaches, dosing levels, acclimation periods, background chemistries, and trout stages and strains. In addition, many studies have used combinations of acid and aluminum levels which are unlikely to occur in High Sierra waters. There is a need for additional toxicological experiments, using standard protocols and the background water chemistry, physical conditions, and trout strains typical of High Sierra waters, to develop quantitative models of trout population responses to different acid and aluminum levels. In addition, information acquired from Recommendations (1) and (2) can be combined in designing and conducting informative, realistic dose-response experiments. From information acquired from Recommendation (1) we can concentrate on those sensitive trout stages that are most likely to experience pulses of acid and aluminum. From information acquired from Recommendation (2) we can use those combinations of acid and aluminum levels that are predicted to occur in High Sierra catchments under different acid deposition scenarios. In addition, hydrological and hydrochemical data, and geochemical models, can provide information on the likely durations

and magnitudes of acid/aluminum pulses, which can be used in designing dose-response experiments.

The recent discovery of a series of naturally acidic lakes and streams in the High Sierra (Bradford et al. 1993) provides us with conditions for evaluating the responses of early trout stages to different levels of acid and aluminum under natural conditions. Eggs and fry of different trout species can be held in streams or lakes differing in pH and aluminum concentrations, and correlations between the survivorship of these trout stages and water chemistry can be examined. These bioassays will indicate responses of early trout stages to chronic acidification, and can be compared to trout responses to acid and aluminum pulses in laboratory and field experiments. Amalgamation of the results of field and laboratory experiments, and field bioassays, will allow the development of predictive models of the long and short-term effects of acid inputs on early life history stages of different trout species.

4. Information acquired from Recommendations (1), (2), and (3), and from completed field surveys (e.g. Part I of this report and Bradford et al. 1993), can be combined to make rigorous regional assessments of the effects of different levels of acid input on aquatic resources in the High Sierra. Data on the mineralogy of individual basins, coupled with geochemical models, will allow predictions of hydrochemical conditions during acid pulses (see Part II of this report). Survey data indicate the number of lake/stream systems containing particular species of trout (Part I), and monitoring studies could determine those stages of trout present during periods when acid pulses are most likely. Predictive models of responses of sensitive trout stages to elevated acid and aluminum levels (and durations) likely to be encountered in the High Sierra can be developed from appropriate field and laboratory experiments, and field bioassays. Because early, sensitive stages of some trout species could be present at times of acid increase, we assume that survival of these early stages could constitute an important "bottleneck" in the their life histories. Thus we can potentially assess the probability of trout population declines or extirpation under different acid deposition scenarios.

General Introduction

This report presents the results of a field survey (Part I) and a dose-response experiment (Part II) conducted under Contract A-932-138. Part I describes the water chemistry, trout populations, and macroinvertebrate assemblages present in 30 representative lakes, and associated streams, in the High Sierra. Data on the water chemistry, trout populations, and macroinvertebrate assemblages of five additional lakes, including four which are included in a long-term CARB monitoring program, are also presented. Part II describes the results of a field experiment, conducted in streamside channels during snowmelt, which examined the effects of different acid levels on the survival of golden trout eggs. The experiment described in Part II concentrated on golden trout eggs because golden trout were the fish most commonly encountered during our lake survey, because early life history stages of fish are the stages most susceptible to acid inputs, and because there are very few data on the vulnerability of golden trout to acid additions.

Part I: Survey of water chemistry, fish, and macroinvertebrates in High Sierra lakes and associated streams

INTRODUCTION

The biota of several thousand ponds, lakes and streams at high elevations in the Sierra Nevada could be affected by changes in surface water chemistry resulting from acidic deposition. Experiments and field surveys have demonstrated that reductions in the pH of surface waters can affect fish, invertebrate, and algal communities (Hall et al. 1980; Burton et al. 1985; Hall and Ide 1987; Schindler et al. 1985; review in Baker and Christensen 1991). Increased acidity has been shown to decrease the diversity of aquatic communities, to decrease the abundance of fish and invertebrates, to increase the abundance of periphyton, and to alter invertebrate life histories (Friberg et al. 1980; Okland and Okland 1986; Burton et al. 1985; Lacroix 1985; Hendrey 1976; Altshuller and Linthurst 1984; Hall and Ide 1987).

Stream invertebrates are sensitive to chronic and episodic acidification, although some taxa are more vulnerable than others (Singer 1982). For example, Cooper et al. (1988), Hopkins et al. (1988), and Kratz et al. (1994) monitored benthic invertebrate densities and drift rates during simulated acidic storm runoff in stream channels near Emerald Lake. They found that 8 hr episodic acid additions were sufficient to increase drift rates and decrease the benthic densities of some of the most common aquatic invertebrates in a Sierra stream. Acid additions that lowered pH to 5.2 and 4.6 significantly reduced benthic densities of the mayflies *Baetis* and *Paraleptophlebia*, both important prey of resident trout, and increased the drift rates of other invertebrates. Similar pH depressions during snowmelt should have comparable effects on aquatic invertebrates.

Fish are also susceptible to acidification. Exposure to low pH has been shown to increase fish mortality (Sharpe et al. 1983; Gunn 1989; review in Brown and Sadler 1989; EPRI 1989), decrease fish growth (Mount et al. 1988; Woodward et al. 1989), and decrease fish recruitment by decreasing egg production and embryo survival (Woodward et al. 1989; Trojnar 1977; St. Pierre and Moreau 1986; Mount et al. 1988). All of these effects are likely due to disruption of ion balance mechanisms (McDonald et al. 1989). The threshold of response by fish to lowered pH is species-specific. For example, Johnson et al. (1987) found that mortality increased for a dace and a chub at pH of about 6.0, whereas brook trout (*Salvelinus fontinalis*) were unaffected by pHs as low as 5.1. Similarly, rainbow trout mortality has been found to increase at pH 5.5-6.0, whereas brook trout were unaffected until pH was reduced to 4.5 (Grande et al. 1978).

Sensitivity to pH depressions is probably related to life history stage in all fish species. Adult fish are generally more tolerant of acidity than embryos, larvae, and juveniles (see review in Altshuller and Linthurst 1984; Baker and Schofield 1985; Brown and Sadler 1989). Among early life history stages, small differences in age and the timing of exposure can substantially alter the magnitude of impact on survivorship. For example, some eggs are most sensitive to low pH immediately following fertilization and again during hatching (Runn et al. 1977; Curtis et al. 1989). In the latter case, the immediate effect might be decreased mobility of the hatching larvae, which prevents them from escaping the egg membrane. Some studies have suggested that larvae can be especially sensitive at the end of yolk absorption, when the site of critical ion regulation shifts prior to swim-up (Lacroix et al. 1985; Gunn 1989).

The effects of low pH on fish are also influenced by the concentration of other ions (Brown 1980; Trojnar 1977). For example, moderate to high concentrations of calcium can ameliorate the adverse impact of low pH and high aluminum (Brown and Sadler 1989, Ingersoll et al. 1990), probably by buffering ion regulation mechanisms. In other circumstances, low pH and high calcium can increase mucus production on gill surfaces and disrupt the acid-base balance of the blood, leading to respiratory distress.

Increased mobilization of trace metals, in particular aluminum, at low pHs may have a variety of effects on fish. In laboratory dose-response experiments, rainbow and brown trout exposed to pH 4.4 for 30 hours suffered higher mortality in the presence of dissolved aluminum (Jones et al. 1983). Aluminum can be most toxic to fish in the pH range 5.0-5.5, as a result of chemical speciation changes (Brown and Sadler 1989). Free aluminum ions appear to be extremely toxic to fish, and organic chelators may ameliorate the effects of high aluminum concentrations by binding aluminum ions (Baker and Schofield 1980). This is probably why many fish can tolerate greater acidity in bog waters than in waters acidified by inorganic acids.

High aluminum concentrations often result in mucus clogging of the gills and changes in blood acid-base balance (McCahon et al. 1987; Leivestad 1982), perhaps because aluminum precipitates in the alkaline environment surrounding the gill filaments (Playle and Wood 1990).

Some recent laboratory studies have considered the combined effects of hydrogen, aluminum and calcium ions on early life stages of fish. Although increasingly advanced trout stages are progressively less affected by low pH, the effects of dissolved aluminum tend to increase with age (DeLonay et al. 1993; Woodward et al. 1989; Woodward et al. 1991; Ingersoll et al. 1990). At pH less than 5.0, mortality of eggs of golden trout and brook trout is actually reduced by high aluminum concentrations (DeLonay et al. 1993; Ingersoll et al. 1990;). Calcium apparently protects developing brook trout at levels above 50 μeq/L, although this effect levels off above 100 μeq/L (Ingersoll et al. 1990).

Although we are not aware of studies on fish, there is evidence that sulfate ion >6.4 μeq/L (at neutral pH) can affect the growth of larval amphibians. Because such sulfate concentrations are common in Sierra Nevada catchments, the effects of sulfate and other ions on fish should not be totally discounted.

For fish species spawning in stream riffles and shallow lake margins of alpine habitats, where pulses of acidic snowmelt are least likely to be diluted by standing water, the timing of fertilization, hatching and emergence relative to snowmelt cycles may be a critical determinant of annual recruitment (and hence population size and stability) (Gunn and Keller 1981). Some of the studies mentioned above have addressed specifically the problem of episodic acidification by limiting experimental dosings to a few days and looking at immediate and delayed mortality (DeLonay et al. 1993; Woodward et al. 1989; Woodward et al. 1991).

Effects of episodic acidification on the biota of aquatic systems in the Sierra Nevada will depend primarily on changes in the concentrations of hydrogen, aluminum and calcium ions, and on the locations and developmental stages of aquatic organisms subjected to changes in water chemistry. Fish and aquatic invertebrates may be particularly sensitive to episodic acidification for two reasons. First, melting snow and rain rapidly and dramatically increase stream flows due to the lack of soils in high elevation watersheds. Resulting increases in turbulence and velocity are by themselves serious challenges to invertebrates and fish in streams. During these periods of high flow, invertebrates drift at high rates, and fish almost certainly increase their energy expenditures to remain in place. Even minor weakening of organisms under these circumstances could lead to death or removal from these systems. Second, aquatic organisms are especially vulnerable to acidification during snowmelt. Depending on the exact timing of snowmelt pulses and the species involved, fish could be ripening gametes, spawning, hatching, or emerging from the gravel and starting to feed. Insects are likely to be ovipositing, or in embryonic or early instar larval periods, during snowmelt.

If we are to detect early damage to fish and invertebrate populations from episodic acidification, we should determine the distributions of sensitive indicator organisms relative to waters of specified chemistry. Stream invertebrates, and especially insects, would be most valuable as indicators because aquatic insects are ubiquitous and sensitive to low pH. In addition, streams are likely to be the waters most affected by episodes of pH depression. As for trout, it would be most valuable to determine the number of populations of each species relative to the likelihood that their habitats will acidify under various regimes of acid deposition. It also would be useful to determine the extent and importance of natural reproduction, relative to stocking, in maintaining trout populations in the High Sierra under present circumstances.

The objectives of this part of our study are: (1) to estimate the number and status of populations of sensitive invertebrate and fish species in lakes and associated streams above 8000 feet (2439 m) in the Sierra Nevada and (2) to relate the distributions of these organisms to water chemistry. This study provides baseline information for detecting changes in the distribution of organisms. It will also facilitate selection of indicator species that can be used for early detection of changes in aquatic systems caused by acid deposition.

METHODS

1. *Lake Selection*--The lakes sampled in this study were selected by Dr. John Stoddard of our team, in conjunction with EPA personnel and the Environmental Monitoring and Assessment Program (EMAP, Paulsen et al. 1991). The selection procedure is described below:

In EMAP the United States has been divided into about 12600 635 km^2 hexagons; their centers form a triangular grid with 27 km sides. Forty km^2 (1/16 scale) hexagons with the same centers as the primary hexagons are considered large enough to describe most ecological resources, and were used here. In this study, the density of 40 km^2 hexagons over the Sierra Nevada was enhanced three-fold by centering extra hexagons at the mid-points of lines between each primary grid point (raising the scale to 3/16). This ensured that enough lakes were sampled to characterize those of interest. We chose only hexagons with centers at or above 8000 feet (2439 m) elevation because lower waters are less likely to be at risk from acidification. Of the total population of 42 hexagons at adequate elevation, 30 (71%) were selected randomly as study areas. Within each hexagon, one target lake with a surface area of one hectare or larger was selected randomly from all lakes within that hexagon (Fig. 1.1).

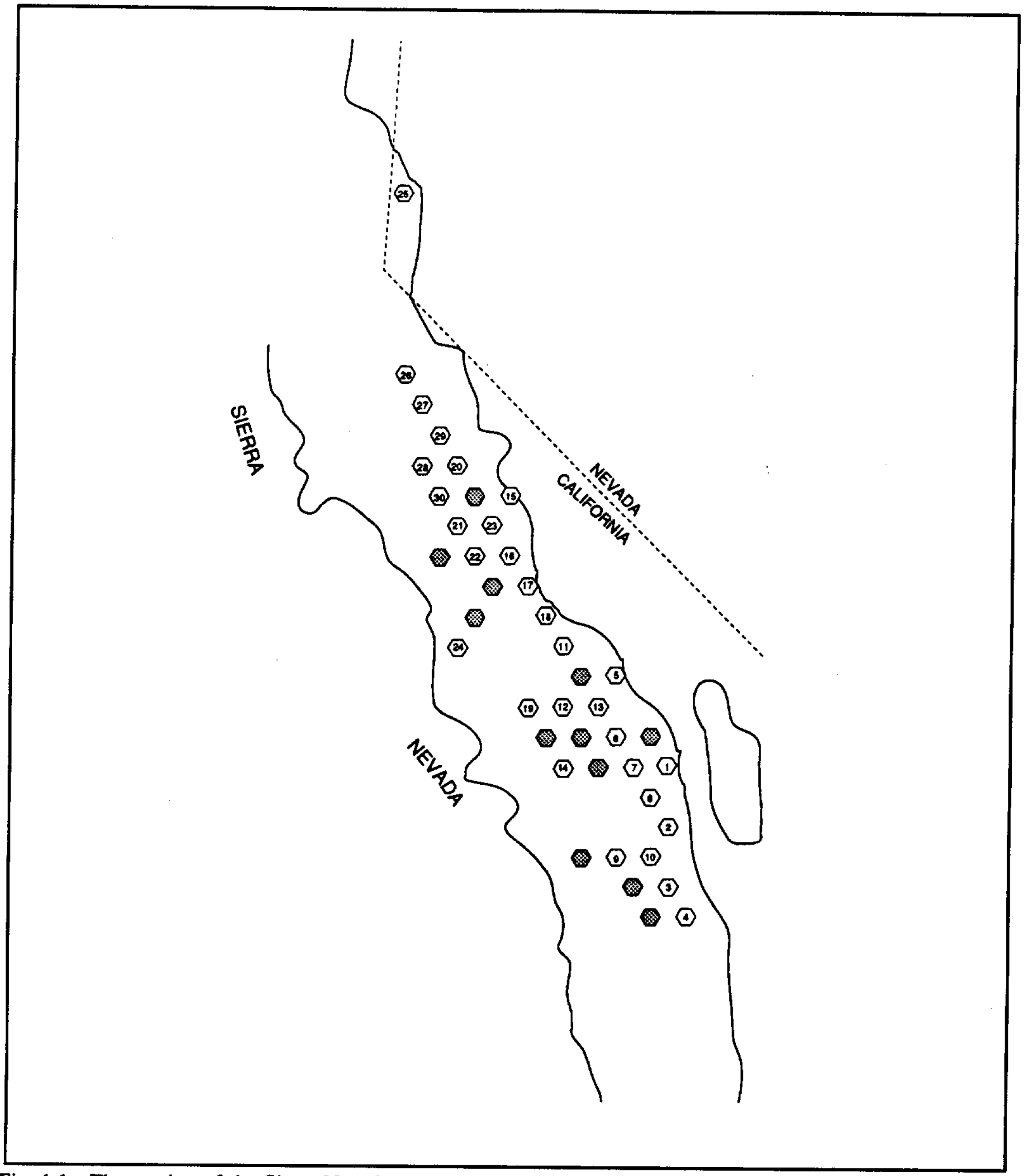

Fig. 1.1. The portion of the Sierra Nevada containing lakes above 8000' (2439 m) elevation, showing all of the hexagons within the proper altitude range. The number within each sampled hexagon corresponds to the number of the lake sampled within that hexagon.

Table 1.1 shows the lakes resulting from this selection process. Although many lakes were quite remote, we hiked to and successfully sampled all of them. One of the lakes (#18) was slightly below 8000', although the hexagon center was above this elevation. Two lakes appeared to be slightly smaller than one hectare, possibly due to differences in our measurement techniques.

Table 1.1. Information concerning lakes sampled in this study. Lakes in quotation marks were unnamed on maps, so we applied our own names for these lakes.

Lake Number	Lake Name	Latitude	Longitude	1:24 000 Scale Topo Map	Elev(m)	Area(ha)
1	Birch	37°4'16"	118°25'20"	Split Mtn	3292	10.1
2	"Diamond"	36°50'28"	118°23'05"	Mt. Clarence King	3460	2.1
3	"Quartz"	36°35'29"	118°20'11"	Mt. Whitney	3460	2.9
4	High	36°29'20"	118°13'57"	Cirque Peak	3501	3.3
5	Catherine	37°24'43"	118°42'31"	Mt. Morgan	3537	4.4
6	"Dead Ass"	37°09'27"	118°40'29"	Mt. Darwin	3535	16.2
7	"Knapsack"	37°04'16"	118°32'33"	North Palisade	3389	3.1
8	"Ickes"	36°55'46"	118°27'10"	Mt. Pinchot	3520	2.2
9	"Fun"	36°40'32"	118°38'19"	Mt. Silliman	2963	1.8
10	East	36°43'14"	118°26'32"	Mt. Brewer	2886	12.7
11	Ram	37°32'42"	118°55'13"	Blood Mtn	3294	8.5
12	Hooper	37°18'05"	118°54'30"	Florence Lake	3231	2.7
13	Merriam	37°17'45"	118°47'30"	Mt. Hilgard	3333	13.6
14	Marsh	37°04'16"	118°32'33"	Courtright Reservoir	2878	2.3
15	Tamarack	38°07'34"	119°18'52"	Twin Lakes	2936	6.3
16	L. Gaylor	37°54'40"	119°16'03"	Tioga Pass	3135	9.9
17	Sullivan	37°44'34"	119°10'00"	Mt. Ritter	2994	8.2
18	Sotcher	37°37'36"	119°04'49"	Mammoth Mtn	2340	8.9
19	L. Twin	37°17'31"	119°09'09"	Kaiser Peak	2623	2.4
20	L. Long	38°13'35"	119°34'03"	Tower Peak	2621	5.4
21	Murdock	38°00'10"	119°30'15"	Piute Mtn	2904	2.4
22	L. Cathedral	37°50'42"	119°25'27"	Tenaya Lake	2832	9.9
23	M. McCabe	37°59'29"	119°20'01"	Tioga Pass	3120	4.5
24	Iron	37°29'29"	119°29'48"	Little Shuteye Peak	2506	5.7
25	Tamarack	39°19'02"	119°54'13"	Mt. Rose	2683	1.3
26	Summit	38°36'19"	119°52'07"	Ebbetts Pass	2451	3.7
27	Asa	38°30'12"	119°46'06"	Ebbetts Pass	2610	0.7
28	Ridge	38°13'35"	119°44'30"	Emigrant Lake	2811	6.9
29	Wolf Creek	38°21'23"	119°37'08"	Pickel Meadow	3085	2.4
30	"White Bear"	38°06'13"	119°37'02"	Piute Mtn	2732	1.2
	Crystal	37°35'36	119°01'05"	Crystal Crag	2951	5.0
	Lost	38°51'37"	120°05'48"	Fallen Leaf Lake	2475	0.7
	Ruby	37°24'50"	118°46'15"	Mt. Abbot	3426	12.6
	Spuller	37₀56'55"	119°17'02"	Tioga Pass	3121	2.2
	"45"	38°56'12	118°25'07"	Mt. Pinchot	3500	6.6

For calculating target population characteristics from the characteristics of each sample lake, we multiplied each sample value by a distincive "weighting" factor based on our method of selecting lakes. Each of the 30 hexagons was considered a separate stratum in the design, and together they represented 0.13 (3/16 x 30/42) of the area above 8000' elevation. Each lake therefore represents a certain number of lakes in the target population (all lakes with elevations > 8000 feet), with the weight for each lake calculated as the number of lakes in its hexagon, divided by the proportion of hexes used (30/42), divided by the proportion of area over 8000 feet covered by all of the hexes (3/16).

We sampled five additional lakes for water chemistry, fish populations, and invertebrate assemblages. Four of these lakes, Lost, Spuller, Ruby, and Crystal, have been sampled for water chemistry and zooplankton as part of a long-term CARB monitoring program (Melack et al. 1993). The fifth lake, Lake 45, is one of the most acidic lakes in the Sierra Nevada (pH = 4.7) and was included for comparative purposes. Data from these extra lakes were not used in extrapolating our results to the entire population of lakes in the study region. They were sampled primarily to check the representativeness of lakes included in long-term monitoring programs, or, in the case of the acidic lake, because it was near a sample lake with low pH and was known to be chemically unusual.

2. *Sampling Procedures For Fish and Invertebrates*--Fish in lakes were sampled using a "Swedish Experimental" gill net, which was 43.5 m long, 1.5 m deep, and consisted of 6 panels with mesh sizes of 2.5, 3.1, 3.7, 4.3, 4.9, 5.5, and 6.2 cm. The net was anchored on shore with the smallest mesh in the shallowest water, and deployed along the bottom at an angle perpendicular to the shoreline. Where possible, angling was also used to increase catch rate and possibly catch species not taken with the net. Ample fish to determine species composition were usually taken in daytime or within 2-3 hours after dark but, in some instances, the net was set over night and checked periodically with an underwater light. Fish in the first 50 meters of a lake outlet (or inlet in the case of Lake 11, which had a diffuse outlet) were sampled with a Smith-Root Type 11-A battery-powered electrofishing unit. Fish captured in lakes and streams were held in mesh bags until a sample was complete, then they were identified, weighed, measured and returned to the water.

Macroinvertebrates in the littoral zone of lakes were sampled by sweeping shallow areas next to the shore with a D net (mesh size = 1 mm). Two workers more or less arbitrarily chose a point along shore and collected in opposite directions for 15 minutes. Stream insects were collected from a range of habitats (e.g. pools and riffles) by taking 3 kick samples in each stream with a standard aquatic "D" net (radius of curved portion about 15 cm, mesh size = 1 mm). For each sample, a D net was pushed against the stream bottom, an area upstream of the net equal to the area of the net opening was disturbed, and dislodged invertebrates were carried into the net by currents. Invertebrates were preserved in 70% alcohol, then identified to genus or lower, except chironomid larvae which were identified to family, under dissecting microscopes at UCSB.

Study of ampibians was specifically excluded from this study, because they were covered in a parallel investigation. Mention of their presence is based on incidental but reliable visual observations.

3. *Chemical Sampling Procedures*--We sampled surface water near lake outlets and assumed that the chemical composition of this water was representative of both lake and stream chemistry. To assess mixing at the time of sampling, we measured temperature and oxygen profiles at the deepest point in lakes, using a YSI Model 58 portable meter with a polarographic electrode and thermister. Chemical samples were collected near the lake outlets in new linear polyethylene bottles rinsed 5 times with distilled water (DIW) and soaked in DIW for at least 5 days.

For each lake, we took one unfiltered sample for pH, ANC and conductivity. This sample was refrigerated in snow if it could not be processed in a few hours. pH was measured in the lab on an Orion SA250 meter using a Ross 8104 probe. The meter was calibrated against commercial buffers at pH 4.00 and 7.00. Calibration was checked with freshly diluted solutions of 10^{-4} and 10^{-5} M HCl, and calibration was repeated if readings differed more than 0.09 pH units from nominal in either solution. ANC was determined by Gran titration with a microburet and the Orion meter. Specific conductance was measured with a Fisher digital conductivity meter.

Samples for major ions (one from each lake) were drawn into a syringe rinsed 5 times in lake water, then forced into a sample bottle through a 1μm glass fiber filter. Aluminum samples were similarly forced through a 0.1μm nucleopore filter and acidified with Ultrex nitric acid. These samples were transported to the Melack laboratory at UCSB for analysis on a Dionex IC (anions), an atomic absorption spectrometer (cations), or a graphite-furnace atomic absorption spectrometer (aluminum). QA/QC quidelines for laboratory analyses are presented in Setaro and Melack (1989). In order to evaluate the overall precision of field and laboratory techniques, we collected duplicate field samples in 10% (3) of the sample lakes, selected at random. The results can be found in Appendix C.

Because low concentrations of labile (inorganic) monomeric aluminum are expected at the pH's we encountered (Driscoll et al. 1980; Baker and Schofield 1982), we only measured this form of aluminum in three representative lakes using fractionation procedures (Barnes 1975; Driscoll 1984). Duplicate aliquots were drawn through 0.45μm filters, and the polymeric forms of aluminum were differentially removed by a brief reaction with 8-hydroxyquinoline (HQ) terminated by extraction in methyl isobutyl ketone (MIBK). One of the duplicates was then forced through an ion exchange column (Amberlite) to remove the non-labile (organic) monomeric species. The resulting extracts were analyzed in the normal manner (graphite furnace AAS), and the difference between duplicates was considered to be inorganic monomeric aluminum. This fraction was compared with total aluminum from samples collected simultaneously, and acidified blanks subjected to the same fractionation procedures.

RESULTS

Lake Characteristics--Because we concentrated on lakes likely to be low in solutes, the distribution of elevations and lake areas differed between our survey and the Western Lakes Survey, which is our most extensive source of information on Sierra Nevada water chemistry (Figs. 1.2, 1.3). Low elevation lakes were not included in our survey, which incidentally eliminated most of the largest lakes in the Sierra. Our target population was estimated to be 1404 lakes, whereas the WLS population was 2119 lakes.

Lake Chemistry--Distributions of chemical values in our target lakes were affected by outliers (Fig. 1.4), but median values were similar to those from the Western Lake Survey (Table 1.2). Median pH, however, was substantially lower (6.08 vs. 6.93), and nitrate was higher (2.2 vs. 0.4 μeq/L) in our study compared to the WLS. Median acid neutralizing capacity (ANC) was slightly lower in our target lakes versus lakes in the WLS (51.2 vs. 60 μeq/L), but the cumulative frequency distributions were nearly identical (Fig. 1.5). Median sulfate values are nearly the same in this and the Western Lake Survey (7.5 vs. 7.0 μeq/L) but the cumulative frequency curves diverge due to a small number of high values in our lakes (Fig. 1.5).

Melack and Stoddard (1991) explain broad differences in the chemistry of Sierra Nevada lakes on the basis of basin geology, and their generalizations apparently apply to the lakes in this study. According to their scheme, most of our sample lakes were chemically consistent with weathering of the plagioclase feldspars (calcium and sodium aluminum silicates) and to a lesser extent orthoclase feldspars (potassium aluminum silicates) from igneous intrusive ("granitic") rocks in catchments. As they predict for lakes of low conductivity, the ratio of ANC to the combined concentrations of calcium and sodium ions was near 1:1 over a broad range of ion strengths (Fig. 1.6).

Lakes with calcium and sodium as the dominant cations are termed "Category A" lakes in Table 1.3. Twenty-four lakes from the survey and the 4 lakes from the CARB long-term monitoring program fall within this group. Three category A lakes (5, 29 and 20) deviate from predicted patterns of water chemistry in igneous intrusive basins, insofar as they contain almost as much magnesium as sodium. Unlike the other lakes, these three lakes lie in basins containing dark metavolcanic rocks which may contribute magnesium to receiving waters.

Category B and C lakes, which fit the second pattern discussed by Melack and Stoddard (1991), were high in calcium and sulfate. Melack and Stoddard (1991) suggested that various combinations of iron pyrite, calcium sulfate and calcium carbonate in basins might explain the chemistry found in these lakes. They suggested that moderate ANC should be present in this type of lake, such as we found in Lake 15, the one Category B lake. The basin of Lake 15 appeared to contain large amounts of volcanic and metavolcanic rocks.

"C" lakes were high in sulfate and calcium like the Category B lake, but they were also low in pH with unusually low ANC relative to their ion strengths. These lakes are in basins containing roof pendant metamorphics, and appear to be restricted to an area about 10 km in diameter at the eastern edge of Kings Canyon National Park. In Lakes 8 and 45, ANC was near or below zero, pH was acidic, and sulfate was high, but calcium was higher and nitrate lower than would be expected in lakes acidified by atmospheric deposition (Driscoll et al. 1991). Lake 2 is less extreme in its sulfate and ANC levels than Lakes 8 and 45, and appears to be a dilute example of Category C lakes. It would fall into Category A based only on its sum of base cations (SBC). Lake 2 was also the only lake still covered by ice at the time of sampling, which might have influenced its composition.

Category D lakes fit the third pattern described by Melack and Stoddard (1991). These lakes are high in magnesium, potassium, calcium and sodium, and are low in sulfate. All four Category D lakes are located in areas dominated by volcanic soils. Three of the four lakes in this category had especially high pH as well, although Lake 25 (Tamarack Lake) near Lake Tahoe was an exception. Lake 25 is very marshy and drains a large boggy area which was apparently a former lake basin. Its drainage may contribute organic acids to Lake 25, thereby lowering pH.

Concentrations of total aluminum (from acidified samples) were below 1.9 μM (50 μg/L) in most of the sample lakes, although Al reached 63 μg/L in Lake 25 from Category D and Lake 8 of Catetgory C and 792 μg/L in Lake 45 from Category C. Much of the aluminum in Lake 25 probably existed in organically-bound forms characteristic of mildly acidic bog lakes, but the low pH of Category C lakes probably insured that most aluminum in these lakes was in inorganic monomeric forms.

Inorganic aluminum in the 3 lakes we sampled for fractionation was about the same as that found in the DIW blanks, and varied from approximately 3 to 14 percent of the total aluminum present (Table 1.4).

Lake and Stream Biology--According to our estimates, only 8.5% of the target lakes had pH below 6 (an approximate threshold for biological effects), but most showed ANC in the range (< 200 μeq/L) sensitive to acidic inputs and one-half had low levels of calcium (< 50 μeq/L) (Table 1.5). Total aluminum values were usually low (< 1.9 μM) and our fractionation results (Table 1.4) suggest that most was in biologically inactive forms. Acidic waters, however, such as Lakes 8 and 45, may have had high levels of inorganic monomeric aluminum (Bradford et al. 1993).

Biological sampling in the present study focused on fish and benthic and littoral zone invertebrates, in lakes and associated streams. Fish in Sierra Nevada waters sensitive to acidification are nearly all introduced and non-native, so their importance to humans, with a few important exceptions, is primarily recreational. Only 6 species of fish have been successfully introduced to the waters of the study region. These are brown, brook, rainbow, golden, and cutthroat trout, and Owens tui chub.

European brown trout (*Salmo trutta*) spawn in the autumn, only in streams, but can live in lakes as adults. Their eggs hatch from January to approximately March, and young fish emerge from the gravel and begin feeding sometime in the spring. They are relatively rare at high elevations.

Brook trout (*Salvelinus fontinalis*) from eastern North America also spawn in the fall, but they reproduce successfully in some lakes as well as in streams (Melack et al. 1989). In the Emerald Lake basin, Sequoia National Park, where they have been studied most intensively, brook trout hatch from January to June and begin feeding from April to July. This is one of the most common fish found in lakes of the Sierra Nevada.

Three types of *Oncorhynchus* are present in acid-sensitive Sierra lakes and streams. Several strains commonly called "rainbow" trout we have termed *Oncorhynchus mykiss*. The California golden trout is now called *O. mykiss aguabonita*. Cutthroat trout in the high Sierra are mostly *O. clarki henshawi* (Lahontan cutthroat trout), although other subspecies have been introduced (e.g. *O. clarki pleuriticus*). None of these three taxa are native to the high-elevation lakes targeted in this study. They all spawn in streams in the "spring", but at high elevations this may occur in June, July, or even August. Their embryos develop far more rapidly than those of fall spawners owing to higher water temperatures during egg development, and young emerge and begin feeding in mid-summer. No instances of successful lake reproduction in *Oncorhynchus* have been documented to our knowledge.

The endangered Owens tui chub (*Gila bicolor snyderi*), a cyprinid native to the eastern Sierra, was accidentally introduced to one of our sample lakes some years ago. It spawns on the vegetation of lakes in May or June, but little else is known of its life history.

Only brook, golden and rainbow trout were common in the sample lakes, with respectively 11, 9 and 10 populations. Twelve of the 30 lakes contained one species of trout, 11 contained two species, and 7 contained no fish (Table 1.6).

Using the weighting procedures described in the Methods, we extrapolated our results to the entire population of lakes above 8000' in the study region. Using the EMAP protocols, we estimated that golden trout are the most widely dispersed fish in the High Sierra, occurring in 36% of the lakes above 8000'. By the same calculations, rainbow trout occur in 33% of the lakes, brook trout in 16%, brown trout in 8%, and cutthroat trout in only 0.5% of the target waters. The tui-chub *Gila* was estimated to inhabit only 7 of the 1404 target lakes. Calculations for the yellow-legged frog place them in 11% of the lakes. Table 1.7 summarizes our projections for trout.

Almost a third of the lakes (28%) contained no vertebrates, and we collected no animals from the acidic lakes (pH < 5.5, 8% of total). Nevertheless, our data show that the commonly introduced species of fish (brook, golden and rainbow trout) can live in lakes with pH near 6 and calcium well under 50 μeq/L; consequently, their absence from many lakes with invertebrate communities is probably a result of historical stocking patterns or other factors (e.g. shallowness which may result in winter anoxia, or absence of suitable conditions for reproduction) (Table 1.8; Appendix A). We do not have enough information to comment on the chemical tolerances of the rarer fish species.

A closer examination of correlations between trout distributions and water chemistry indicated that golden trout distributions were weakly associated with conditions found at high elevations, such as lower pH and ANC (Fig. 1.7). Although the negative relationship between golden trout abundance and aluminum concentration is statistically significant, all but the highest aluminum values are below those firmly established as toxic to trout (Part II; Table 1.9).

Rainbow trout presence was negatively related to elevation, due to the low average elevation of lakes currently stocked with rainbow trout. There was no relationship between *reproducing* populations of rainbow trout and elevation, or any other factors (Fig. 1.8, Table 1.10).

Lakes where brook trout reproduce have a significantly higher pH than lakes where they are absent (Table 1.11), but the scatter graph (Fig. 1.9) shows that brook trout reproduce successfully at least to pH 6. The tendency of governmental agencies to stock golden and rainbow trout rather than brook trout at the highest elevations (which tend to have the lowest pHs) can probably explain this relationship (see Elevation in Fig. 1.9).

When we combine all species of trout with yellow-legged frogs, it appears that only a few lakes do not support aquatic vertebrate populations (Fig. 1.10, Table 1.12). Because so few lakes lack vertebrates of any kind, Lake 8 has an inordinate effect in lowering the average pH of fishless lakes.

Detailed data on oxygen and temperature profiles, and the abundances, size distributions, and stocking records of trout populations are presented in Appendix A.

Macroinvertebrate densities and species richness were generally low across the sampled lakes and streams (Appendix B). No macroinvertebrates were collected in the two acidic lakes (Lakes 8 and 45, pH'< 5.8). Because fish have beeen consistently shown to have large effects on lake macroinvertebrate assemblages (Bendell and McNicol 1987, Evans 1989, Bradford et al. 1993), we first checked to see if the distributions of common macroinvertebrate taxa were related to fish distributions. The mayfly *Callibaetis* was collected more frequently in non-acidic lakes lacking than containing fish (71% vs. 19%, p= 0.016, Fisher's exact test), and water boatmen (corixids) occurred more frequently in lakes where fish were rare or absent than where fish were abundant (54% vs. 14%, P = 0.033, Fisher's exact test). The distributions of other taxa, however, were not related to fish presence, and taxon richness did not vary significantly between lakes containing and lacking fish (t-test, p= 0.822). Consequently, when we examined the relationships between water chemistry and the distributions of common macroinvertebrate taxa (occurring in $\geq$ 9 lakes) we analyzed the data separately (fish vs. fishless lakes) only for those taxa which were affected by fish presence (*Callibaetis*, corixids). For other taxa, we examined correlations between their occurrence and water chemistry across all lakes.

In lakes, taxon richness was positively related to pH and negatively related to nitrate and elevation. In streams, taxon richness was related only to pH. (Figs. 1.11 and 1.12).

In an attempt to find which species of invertebrates were most sensitve to water chemistry, we examined correlations between the most common invertebrate species and various chemical factors and elevation. The mayfly *Callibaetis* was found in only 5 of the 22 lakes containing fish, but were present where pH, calcium, and ANC were relatively high and nitrate relatively low. The relationship with elevation was not significant. *Callibaetis* was found in 5 of 8 fishless lakes and was associated with higher pH and aluminum and relatively lower sulfate, nitrate and elevation (Fig. 1.13). Corixid bugs were present in 6 of 22 lakes containing fish and 3 of 8 lacking fish. When water boatmen were present with fish, aluminum tended to be higher and sulfate and elevation lower compared to lakes where the bugs were absent (Fig. 1.14).

The clam *Pisidium* was also present in a moderate number of lakes. Sulfate, nitrate and elevations were lower in lakes where they were present versus absent, and aluminum was higher (Fig. 1.15). Midges of the family Chironomidae are highly diverse in their food habits, life histories, and habitat preferences, so they might be expected to live in habitats with a wide variety of physical and chemical characteristics. Nevertheless, they occurred in lakes with relatively low nitrate and sulfate concentrations (Fig. 1.16). Damselflies nymphs (family Aeshnidae) were associated with lower elevations and sulfate levels (Fig. 1.17). Limnephilid caddisfly larvae seemed to show no particular pattern with respect to the chemical parameters we measured (Fig. 1.18). Dytiscid beetles were likewise distributed broadly with respect to lake chemistry, but their habitats averaged lower in calcium than lakes where they were absent (Fig. 1.19).

Outlet habitats varied so much in physical conditions that relationships between chemical variables and individual taxonomic groups are difficult to evaluate. No relationships between chemical variables and presence of the mayfly *Baetis* were apparent (Fig. 1.20), and *Pisidium* distributions appeared to be related (negatively) only to elevation (Fig. 1.21) Neither did chironomid larvae in streams show obvious tolerance problems (Fig. 1.22),

The complete list of species collected is presented in Appendix B. In lakes with fish, *Hyalella* (an amphipod crustacean), *Callibaetis*, and possibly 3 species of Lymnaeid gastropod appeared not to be associated with lower pHs; in lakes without fish, *Callibaetis*, chironomid larvae, *Pisidium* and other, rarer taxa were not found in lakes with pH of about 6 or lower. No invertebrates were collected from Lake 8 at pH 5.23, although one insect larva was fleetingly observed during intensive search of shoreline rocks. In outlet streams, *Baetis*, *Pisidium* and perhaps *Rhyacophila* showed the same tendency to be absent at pHs of 6 or lower, although chironomids and to a lesser extent limnephilids were found in virtually all streams.

Table 1.2. Comparison of median values for some chemical measurements from this study and from the Western Lake Survey (Landers et al. 1987).

	N	pH	ANC	Ca^{2+}	Na^{+}	Mg^{2+}	SBC	Cl^{-}	NO^{3-}	SO_4^{2-}	Elev
			(μeq/L)	(μeq/L)	(μeq/L)	μeq/L	(μeq/L)	(μeq/L)	(μeq/L)	(μeq/L)	(m)
WLS (Pop)	2119	6.93	60	43	19	6	76	2	0.4	7	3008
Present Study	1404	6.08	51.2	54.9	16.5	4.5	92.5	3.1	2.2	7.5	3292

Table 1.3. Values for chemical variables in 30 sample lakes, 4 lakes from the CARB Long-term Studies of Lakes and Watersheds survey, and an extra lake (45) in the vicinity of lake number 8. Lakes are ranked by their Sum-of-Basic-Cations (except for Lake 2). Horizontal lines divide chemical groups (categories A-D) based on sulfate, ANC, and the relationship between [Ca^{2+} + Na^{+}] and ANC.

LAKE	COND µS/cm	pH	ANC µeq/L	Ca^{2+} µeq/L	Na^{+} µeq/L	Mg^{2+} µeq/L	K^{+} µeq/L	Al µM	SBC µeq/L	Cl^{-} µeq/L	NO_3^{-} µeq/L	SO_4^{2-} µeq/L	CAT
Lost	3.1	6.13	29.3	19.0	8.0	5.0	2.0	0.80	34.0	1.2	0.1	3.2	A
22	3.1	6.38	25.4	16.0	11.4	3.8	4.7	0.65	35.9	2.8	11.6	2.9	
24	4.7	6.00	20.6	15.2	19.6	1.8	4.0	1.05	40.6	3.9	13.7	14.4	
21	4.4	6.32	35.6	12.7	24.1	2.2	3.6	1.25	42.6	4.6	0.6	4.9	
13	4.6	6.02	34.6	28.5	11.5	2.1	3.0	0.49	45.1	2.8	2.5	5.3	
28	3.9	6.10	44.2	21.4	15.5	5.2	3.4	0.33	45.5	2.5	0.3	4.1	
7	6.1	6.11	43.4	27.0	12.2	3.9	4.7	0.82	47.8	1.8	0.4	7.5	
30	5.2	6.34	18.7	31.9	13.4	4.3	5.3	0.84	54.9	4.2	0.1	2.3	
14	7.6	5.98	47.7	21.2	20.5	7.4	8.3	1.34	57.4	4.9	0.1	1.7	
11	7.2	6.04	51.5	31.9	17.1	3.7	5.3	0.28	58.0	2.1	0.2	9.1	
12	8.2	6.11	53.5	28.8	18.2	5.3	6.5	0.47	58.8	2.4	2.2	7.4	
Ruby	8.4	6.56	39.1	45.0	10.0	5.0	3.0	0.14	63.0	1.6	0.1	10.4	
Spull	6.2	6.40	55.5	38.9	22.1	4.0	5.1	-	70.1	5.1	0.7	9.8	
Crys	7.9	6.68	64.7	40.0	17.0	12.0	7.0	0.75	76.0	3.1	12.0	6.3	
19	10.9	6.17	85.1	49.0	20.6	9.4	5.9	1.82	84.9	3.5	0.1	3.5	
4	9.4	6.29	88.5	37.2	40.4	6.1	5.9	0.45	89.6	3.8	0.0	6.2	
23	9.7	6.67	80.2	56.0	32.4	1.8	3.8	1.00	94.0	3.4	0.2	11.5	
6	12.7	6.04	88.6	71.3	16.4	4.7	6.6	0.46	99.0	3.2	2.9	8.5	
9	12.1	6.11	100.5	54.4	30.6	11.4	10.2	1.30	106.6	3.7	2.2	7.1	
17	11.8	6.66	98.6	77.3	20.2	5.6	7.5	0.31	110.6	3.6	0.2	8.1	
3	18.1	6.36	128.1	102.0	15.5	5.1	4.4	0.81	127.0	1.1	4.3	7.2	
16	13.0	6.69	69.2	81.9	34.2	7.7	13.7	0.64	137.5	11.5	30.4	21.0	
5	17.9	6.87	109.0	106.9	14.7	14.5	15.0	0.65	151.1	1.8	0.1	41.8	
29	13.5	6.65	149.3	82.9	39.6	32.3	8.7	0.88	163.5	2.2	0.1	3.8	
10	22.7	6.20	134.3	130.0	42.0	4.1	5.2	1.29	181.3	5.7	4.6	49.0	
20	20.8	6.68	175.9	110.6	31.2	34.0	10.9	1.47	186.7	5.4	0.1	0.9	
1	20.1	6.40	129.7	151.4	25.6	8.0	10.9	0.46	195.9	4.0	4.6	44.5	
15	50.1	6.97	203.5	279.1	60.9	38.9	9.2	0.59	388.1	0.0	0.1	208.0	B
2	25.0	6.00	76.4	155.0	15.0	9.8	13.0	0.59	192.8	6.0	12.0	125.0	C
8	33.0	5.225	3.9	135.0	25.0	42.0	14.0	2.32	216.0	4.0	16.5	215.0	
45	80.0	4.70	-1.6	227.0	30.0	130.0	9.2	29.33	396.2	4.1	11.1	540.0	
26	46.6	9.56	355.0	178.2	86.8	103.2	22.8	0.89	391.0	3.4	0.9	4.0	D
25	58.9	6.42	517.0	224.0	108.0	135.0	46.0	2.31	513.0	6.1	0.2	1.0	
27	61.5	8.34	548.2	248.6	92.0	148.0	45.8	0.54	534.4	4.9	0.0	0.9	
18	90.3	7.49	817.4	383.8	339.0	96.2	34.0	0.45	853.0	10.8	52.4	20.3	

Table 1.4. Results of HQ/MIBK/Amberlite fractionation of aluminum samples from 3 representative lakes. Values in ppb.

	7 Oct 1991				8 Oct 1991		9 Oct 1991			
	Crystal		Blanks		Gaylor		Cathedral		Blanks	
REPLICATE	1	2	1	2	1	2	1	2	1	2
Total Aluminum	72	72	-	-	33	33	32	32	-	-
Total Monomeric	4.5	3.6	3.0	4.2	9.8	3.2	2.0	0.0	0.0	1.8
Inorg Monomeric(IM)	4.5	2.0	2.5	3.9	7.4	1.8	2.0	0.0	0.0	1.8
MEANS(IM)		3.3		3.2		4.6		1.0		0.9

Table 1.5. The numbers and proportions of survey lakes estimated to contain indicated levels of chemical properties.

	pH		ANC (µeq/L)			Ca^{2+} (µeq/L)		Total Aluminum (µM)	
	<6.0	<7.0	<50	<100	<200	<50	<100	<1.0	<2.0
NUMBER	119	1337	627	1082	1315	687	941	986	1277
PERCENT	8.5	95.2	44.7	77.1	93.6	49.0	67.0	70.2	91.0

Table 1.6. Status and relative abundance of aquatic vertebrates in the 30 sample lakes, 4 long-term monitoring lakes, and lake 45 (near lake 8). Status: 1=sustained by natural reproduction; 2=sustained by reproduction and supplemented with stocked fish; 3=stocked with hatchery fish--no reproduction. Abundance : A= abundant, C= common, R= rare. Abbreviations: *Sf= Salvelinus fontinalis* (brook trout); *Oa= Oncorhynchus mykiss aguabonita* (golden trout); *Om=Oncorhynchus mykiss* (rainbow trout); *Oc= Oncorhynchus clarki* (cutthroat trout); *St= Salmo trutta* (brown trout); *Gs= Gila bicolor snyderi* (Owens chub); *Rm= Rana muscosa* (yellow-legged frog).

	STATUS							ABUNDANCE						
LAKE	*Sf*	*Oa*	*Om*	*Oc*	*St*	*Gs*	*Rm*	*Sf*	*Oa*	*Om*	*Oc*	*St*	*Gs*	*Rm*
1	-	-	-	2	-	-	-	-	-	-	A	-	-	-
2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	-	1	1	-	-	-	1	-	R	R	-	-	-	R
4	-	2	-	-	-	-	-	-	A	-	-	-	-	-
5	1	3	-	-	-	-	-	A	R	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	1	-	-	-	-	-	-	A
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	1	-	1	-	-	-	-	C	-	A	-	-
11	-	1	-	-	-	-	-	-	A	-	-	-	-	-
12	-	2	1	-	-	-	-	-	A	R	-	-	-	-
13	-	1	-	-	-	-	-	-	A	-	-	-	-	-
14	3	3	-	-	-	-	-	R	R	-	-	-	-	-
15	1	2	-	-	-	-	-	R	C	-	-	-	-	-
16	1	-	-	-	-	-	-	C	-	-	-	-	-	-
17	1	-	-	-	-	-	-	A	-	-	-	-	-	-
18	-	-	3	-	2	1	-	-	-	C	-	C	C	-
19	1	-	3	-	-	-	-	R	-	R[1]	-	-	-	-
20	-	-	3	-	-	-	-	-	-	A	-	-	-	-
21	-	-	-	-	-	-	-	-	-	-	-	-	-	-
22	1	-	2	-	-	-	-	A	-	C	-	-	-	-
23	-	-	2	-	-	-	-	-	-	C	-	-	-	-
24	1	-	3	-	-	-	-	A	-	A	-	-	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26	3	-	-	-	-	-	-	R	-	-	-	-	-	-
27	2	-	-	-	-	-	-	A	-	-	-	-	-	-
28	-	2	1	-	-	-	-	-	A	A	-	-	-	-
29	1	-	-	-	-	-	-	A	-	-	-	-	-	-
30	-	-	-	-	-	-	1	-	-	-	-	-	-	C
Ruby	1	-	-	-	-	-	-	A	-	-	-	-	-	-
Crystal	-	2	-	-	-	-	-	-	C	-	-	-	-	-
Lost	1	3	-	-	-	-	-	A	-	-	-	-	-	-
Spuller	1	-	-	-	-	-	-	A	-	-	-	-	-	-
45	-	-	-	-	-	-	-	-	-	-	-	-	-	-

[1] Rainbow trout are stocked periodically, but we saw no evidence that they were present.

Table 1.7. The projected numbers and proportions of lakes above 8000' in the study region containing different species of trout.

	S. fontinalis	*O. aguabonita*	*O. mykiss*	*O. clarki*	*S. trutta*
Populations in Sample	11	9	10	1	2
Estimated No. Populations	223	500	463	7	112
% Lakes Occupied	16	36	33	0.5	8

Table 1.8. Some chemical and biological characteristics of lakes inhabited by 5 salmonids fish species and the yellow-legged frog (*Rana muscosa*). Characteristics of the 6 lakes without aquatic vertebrates are included for comparison. Status 1=sustained by natural reproduction; 2=sustained by reproduction and supplemented with stocked fish; 3=stocked with hatchery fish--no reproduction.

SPECIES		ANC	pH	Ca^{++}	Status	Other Species	Est. No. Lakes	Cum %
No Vertebrates	-	3.9	5.23	135.0	-	-	112	28
		35.6	6.32	12.7	-	Invertebrates	45	40
		76.4	6.00	155.0	-	Invertebrates	45	51
		88.6	6.04	71.3	-	Invertebrates	172	94
		100.5	6.11	54.4	-	Invertebrates	7	96
		517.0	6.42	224.0	-	Invertebrates	15	100
						Total	396	
Oncorhynchus mykiss aguabonita	Reprod	34.6	6.02	28.5	1	-	157	33
		44.2	6.10	102.0	1	O.m.	119	59
		51.5	6.04	31.9	1	-	83	76
		53.5	6.11	28.8	2	O.m.	52	87
		88.5	6.29	37.2	2	-	22	92
		128.0	6.36	102.0	1	R.m., O.m.	29	98
		203.5	6.97	279.1	2	S.f.	7	100
						Total	469	
	Stocked							
		47.7	5.98	21.2	3	S.f.	7	24
		109.0	6.87	106.9	3	S.f.	22	100
						Total	29	
						Species Total	498	
Oncorhynchus mykiss	Reprod	25.4	6.38	16.0	2	S.f.	22	6
		44.2	6.10	21.4	1	O.a.	119	40
		53.5	6.11	28.8	1	O.a.	52	55
		80.2	6.67	56.0	2	-	22	61
		128.1	6.36	102.0	1	O.a., R.m.	29	70
		134.3	6.20	130.0	1	S.t.	105	100
						Total	349	
	Stocked	20.6	6.00	15.2	3	S.f.	38	34
		85.1	6.17	49.0	3	S.f.	15	48
		175.9	6.68	110.6	3	-	52	94
		817.4	7.49	383.8	3	S.t., G.s.	7	100
						Total	112	
						Species Total	461	
Oncorhynchus clarki	Reprod	129.7	6.40	151.4	2	-	7	100
						Species Total	7	
Salmo trutta	Reprod	134.3	6.20	130.0	1	O.m.	105	94
		817.4	7.49	383.8	2	O.m., G.s	7	100
						Species Total	112	

Table 1.8 (concluded). Some chemical and biological characteristics of lakes inhabited by 5 salmonids fish species and the yellow-legged frog (*Rana muscosa*). Characteristics of the 6 lakes without aquatic vertebrates are included for comparison.

SPECIES		ANC	pH	Ca^{++}	Status	Other Species	Est. No. Lakes	Cum %
Salvelinus fontinalis	Reprod	20.6	6.00	15.2	1	O.m.	38	20
		25.4	6.38	16.0	1	O.m.	22	32
		69.2	6.69	81.9	1	-	7	36
		85.1	6.17	49.0	1	O.m	15	44
		98.6	6.66	77.3	1	-	38	65
		109.0	6.87	106.9	1	O.a.	22	77
		149.3	6.65	82.9	1	-	7	80
		203.5	6.97	279.1	1	O.a.	7	84
		548.2	8.34	248.6	2	-	29	100
						Total	185	
	Stocked	47.7	5.98	21.2	3	O.a.	7	19
		355.0	9.56	178.2	3	-	29	100
						Total	36	
						Species Total	159	
Rana muscosa	Reprod	18.7	6.34	31.9	1	-	52	33
		43.4	6.11	27.0	1	-	74	81
		128.1	6.36	102.0	1	O.a,O.m.	29	100
						Species Total	155	

Table 1.9. Summary statistics comparing the chemistry of lakes where golden trout (*Oncorhynchus mykiss aguabonita*) were and were not present. Also presented are probabilities from Kruskal-Wallis one-way non-parametric ANOVAs (absent vs. reproducing vs. stocked; a/r/s) or Mann-Whitney U tests (a/r only) that samples are from the same population. Significant differences are in bold type.

		Golden Trout		
		Absent	Reproducing	Stocked
pH	Mean(SE)	6.593(0.20)	6.270(0.13)	6.425(0.45)
	prob(a/r/s)	0.542		
	prob(a/r)	0.243		
Calcium	Mean(SE)	109.15(20.2)	75.56(35.5)	64.05(42.9)
	prob(a/r/s)	0.472		
	prob(a/r)	0.265		
ANC	Mean(SE)	170.14(46.3)	86.271(23.0	78.350(30.7)
	prob(a/r/s)	0.826		
	prob(a/r)	0.542		
Nitrate	Mean(SE)	7.324(4.3)	1.371(0.63)	0.100(0.00)
	prob(a/r/s)	0.173		
	prob(a/r)	0.311		
Sulfate	Mean(SE)	26.481(11.2)	35.329(28.8)	21.750(20.1)
	prob(a/r/s)	0.944		
	prob(a/r)	0.770		
Aluminum	Mean(SE)	1.016(0.126)	0.489(0.066)	0.995(0.345)
	prob(a/r/s)	**0.023**		
	prob(a/r)	**0.009**		
Elevation	Mean(SE)	2937(78.8)	3224(97.9)	3208(329.5)
	prob(a/r/s)	0.164		
	prob(a/r)	0.080		

Table 1.10. Summary statistics comparing the chemistry of lakes where rainbow trout (*Oncorhynchus mykiss*) were and were not present. Also presented are probabilities from Kruskal-Wallis one-way non-parametric ANOVAs (a/r/s) or Mann-Whitney U tests (a/r only) that samples are from the same population. Significant differences are in bold type.

		Rainbow Trout		
		Absent	Reproducing	Stocked
pH	Mean(SE)	6.552(0.208)	6.303(0.088)	6.585(0.335)
	prob(a/r/s)	0.935		
	prob(a/r)	0.903		
Calcium	Mean(SE)	101.82(18.1)	59.03(19.2)	139.65(83.7)
	prob(a/r/s)	0.521		
	prob(a/r)	0.223		
ANC	Mean(SE)	138.45(34.7)	77.62(18.4)	274.75(183.7)
	prob(a/r/s)	0.704		
	prob(a/r)	0.626		
Nitrate	Mean(SE)	3.705(1.71)	3.867(1.727)	16.575(12.4)
	prob(a/r/s)	0.427		
	prob(a/r)	0.188		
Sulfate	Mean(SE)	36.285(14.8)	16.683(7.17)	9.775(4.57)
	prob(a/r/s)	0.874		
	prob(a/r)	0.951		
Aluminum	Mean(SE)	0.871(0.13)	0.758(0.144)	1.198(0.259)
	prob(a/r/s)	0.49		
	prob(a/r)	0.976		
Elevation	Mean(SE)	3112(75.6)	3057(106.0)	2523(66.7)
	prob(a/r/s)	**0.014**		
	prob(a/r)	0.523		

Table 1.11. Summary statistics comparing the chemistry of lakes where brook trout (*Salvelinus fontinalis*) were and were not present. Also presented are probabilities from Kruskal-Wallis one-way non-parametric ANOVAs (a/r/s) or Mann-Whitney U tests (a/r only) that samples are from the same population. Significant differences are in bold type.

		Brook Trout		
		Absent	Reproducing	Stocked
pH	Mean(SE)	6.259(0.098)	6.748(0.225)	7.770(1.790)
	prob(a/r/s)	0.125		
	prob(a/r)	**0.030**		
Calcium	Mean(SE)	94.363(21.0)	106.322(31.6)	99.7(78.5)
	prob(a/r/s)	0.969		
	prob(a/r)	0.787		
ANC	Mean(SE)	138.0(45.4)	145.433(53.8)	201.35(153.7)
	prob(a/r/s)	0.765		
	prob(a/r)	0.539		
Nitrate	Mean(SE)	5.595(2.79)	6.256(3.52)	0.500(0.400)
	prob(a/r/s)	0.429		
	prob(a/r)	0.287		
Sulfate	Mean(SE)	28.25(12.3)	33.82(22.2)	2.85(1.15)
	prob(a/r/s)	0.318		
	prob(a/r)	0.883		
Aluminum	Mean(SE)	0.915(0.14)	0.792(0.146)	1.115(0.225)
	prob(a/r/s)	0.459		
	prob(a/r)	0.961		
Elevation	Mean(SE)	3109(80.0)	2918(106.9)	2665(213.5)
	prob(a/r/s)	0.157		
	prob(a/r)	0.21		

Table 1.12. Summary statistics comparing the chemistry of lakes where aquatic vertebrates were and were not present. Also presented are probabilities from Mann-Whitney U tests that samples are from the same population. Significant differences are in bold type.

		Vertebrates	
		Absent	Present
pH	Mean(SE)	6.019(0.172)	6.628(0.167)
	prob	**0.055**	
Calcium	Mean(SE)	108.73(31.5)	95.70(19.28)
	prob	0.568	
ANC	Mean(SE)	137.0(77.4)	146.3(37.8)
	prob	0.641	
Nitrate	Mean(SE)	5.733(2.79)	5.383(2.47)
	prob	0.143	
Sulfate	Mean(SE)	60.25(36.6)	20.225(8.64)
	prob	0.534	
Aluminum	Mean(SE)	1.372(0.329)	0.772(0.081)
	prob	0.097	
Elevation	Mean(SE)	3178(151.7)	2983(72.0)
	prob	0.204	

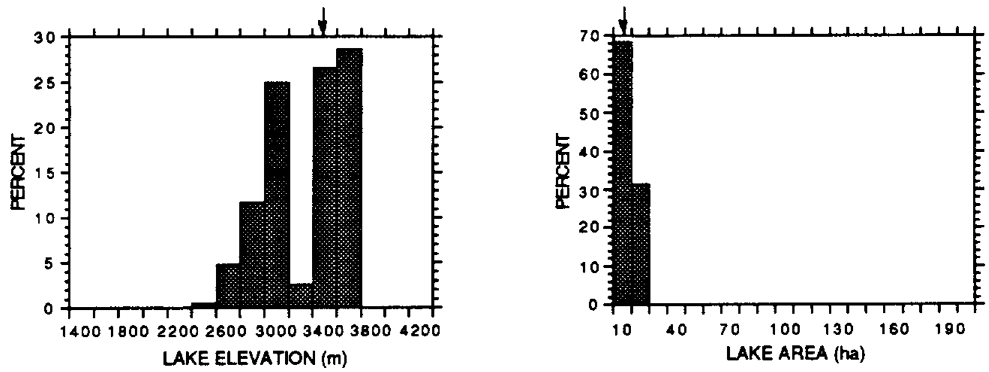

Figure 1.2. Frequency distribution of elevations and surface areas of the estimated 1404 target lakes in the study region. Arrows indicate median values based on EMAP "weighting" factors.

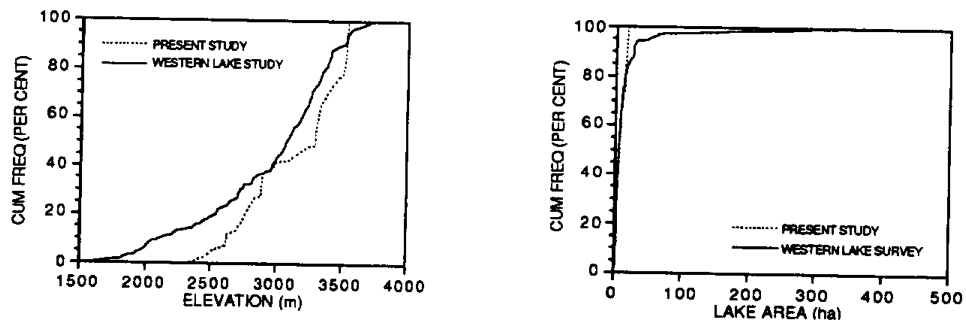

Figure 1.3. Cumulative frequency distributions of lake elevations and surface areas in the target populations of this study and the Western Lakes Survey

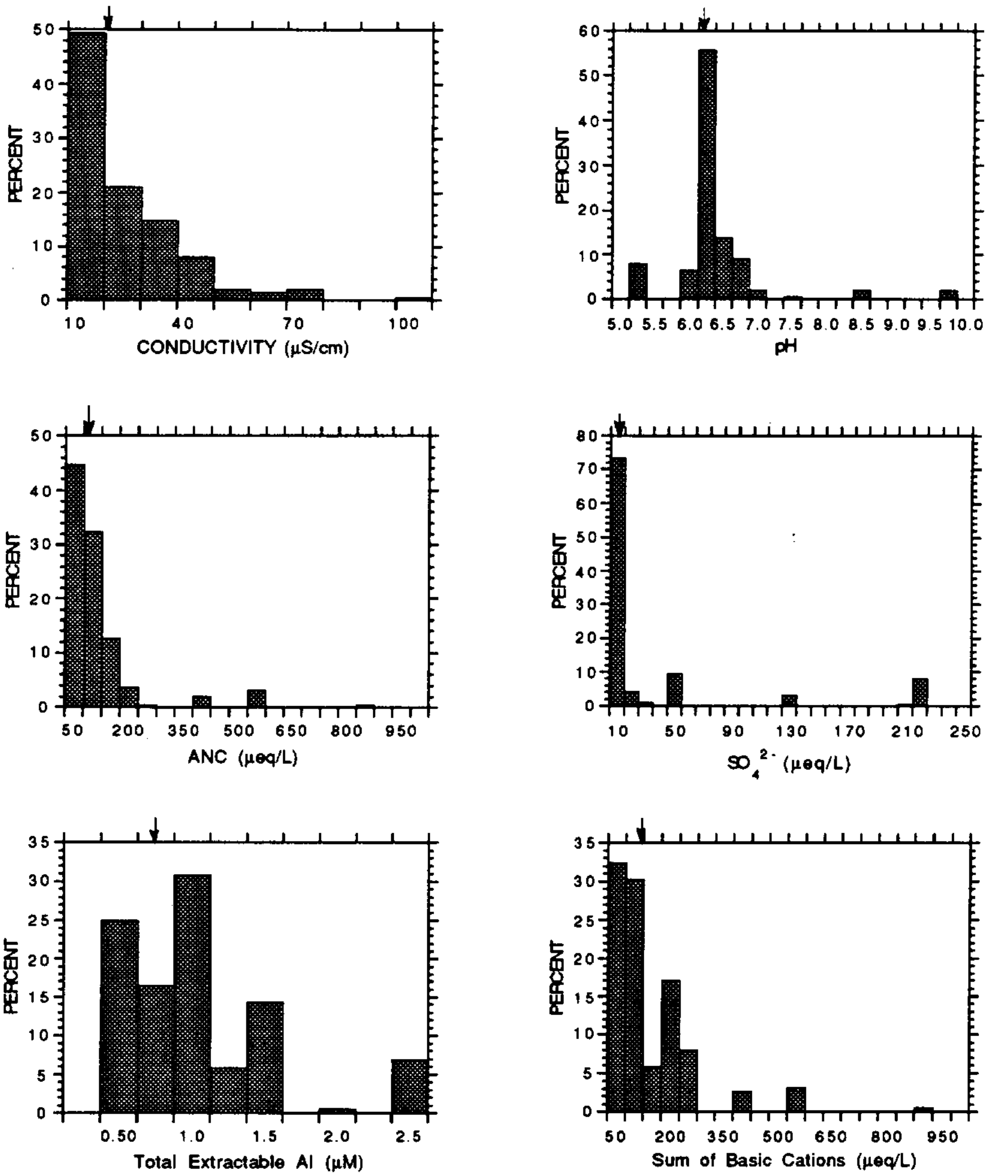

Figure 1.4. Frequency distributions for some chemical characteristics of the target population of lakes in this study. Arrows indicate median values.

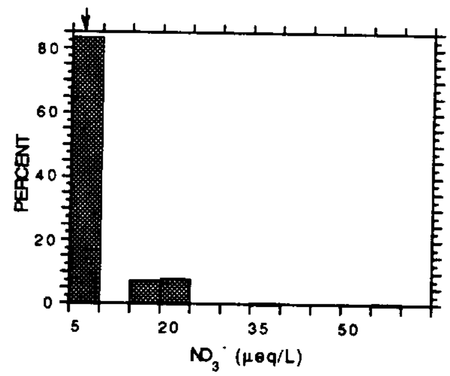

Figure 1.4 (concluded). Frequency distributions for some chemical characteristics of the target population of lakes in this study. Arrows indicate median values.

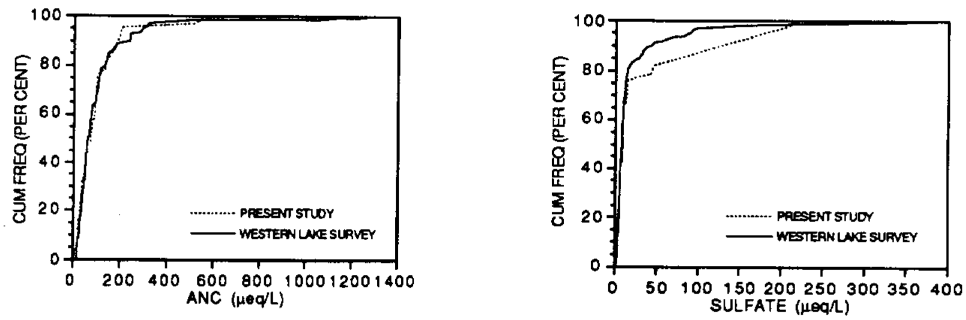

Figure 1.5. Cumulative frequency distributions for chemistry of the target population of lakes in this study and the WLS.

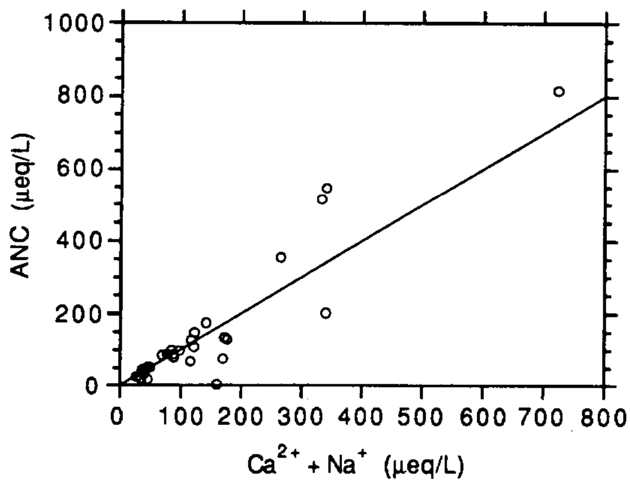

Figure 1.6. ANC relative to the combined concentrations of calcium and sodium ion in the 30 lakes sampled in this study.

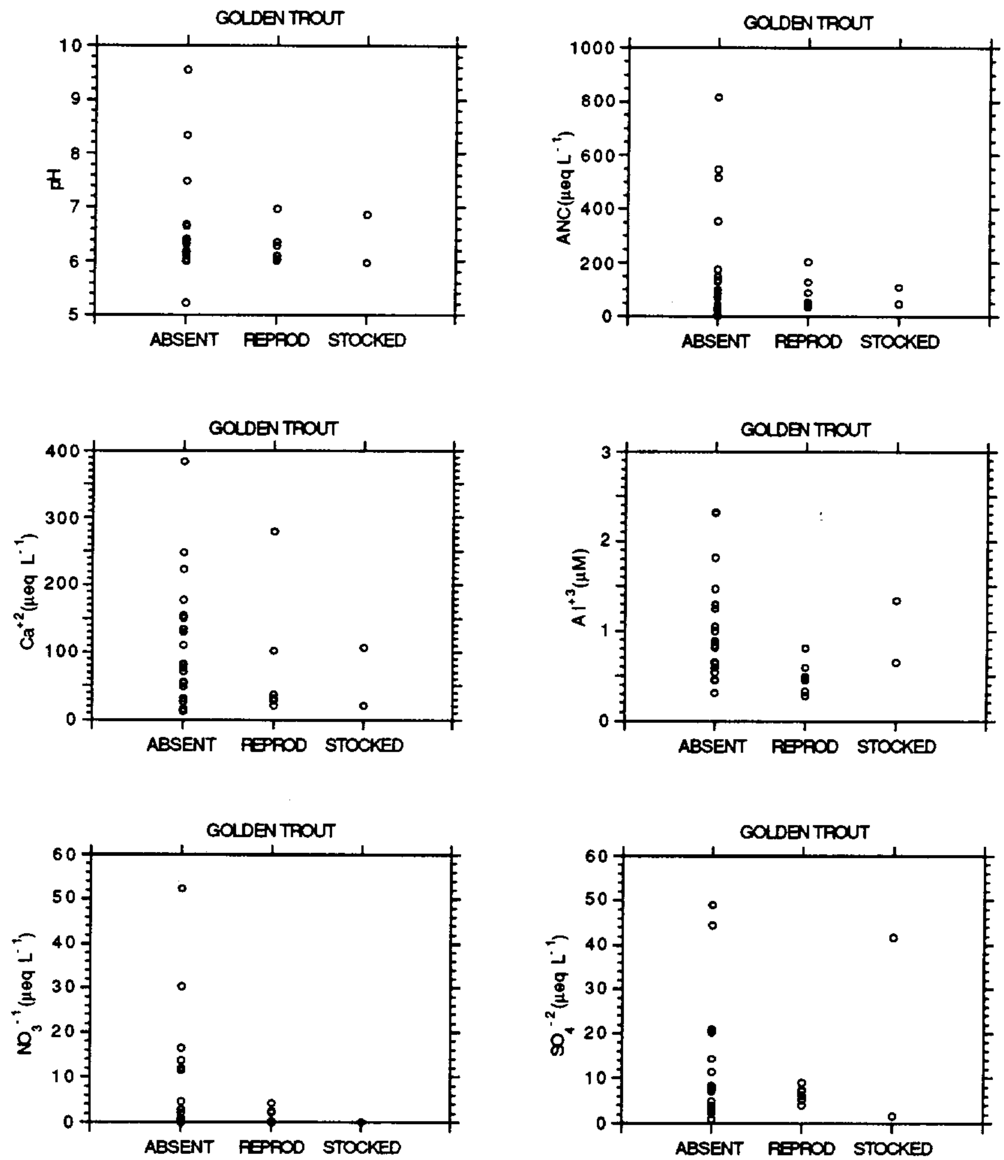

Fig. 1.7 Chemcal characteristics of lake habitats with and without golden trout populations.

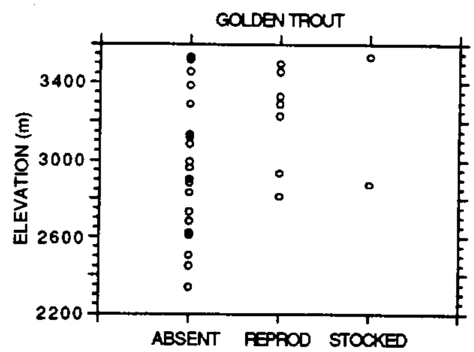

Fig. 1.7 (concluded). Chemcal characteristics of lake habitats with and without golden trout populations.

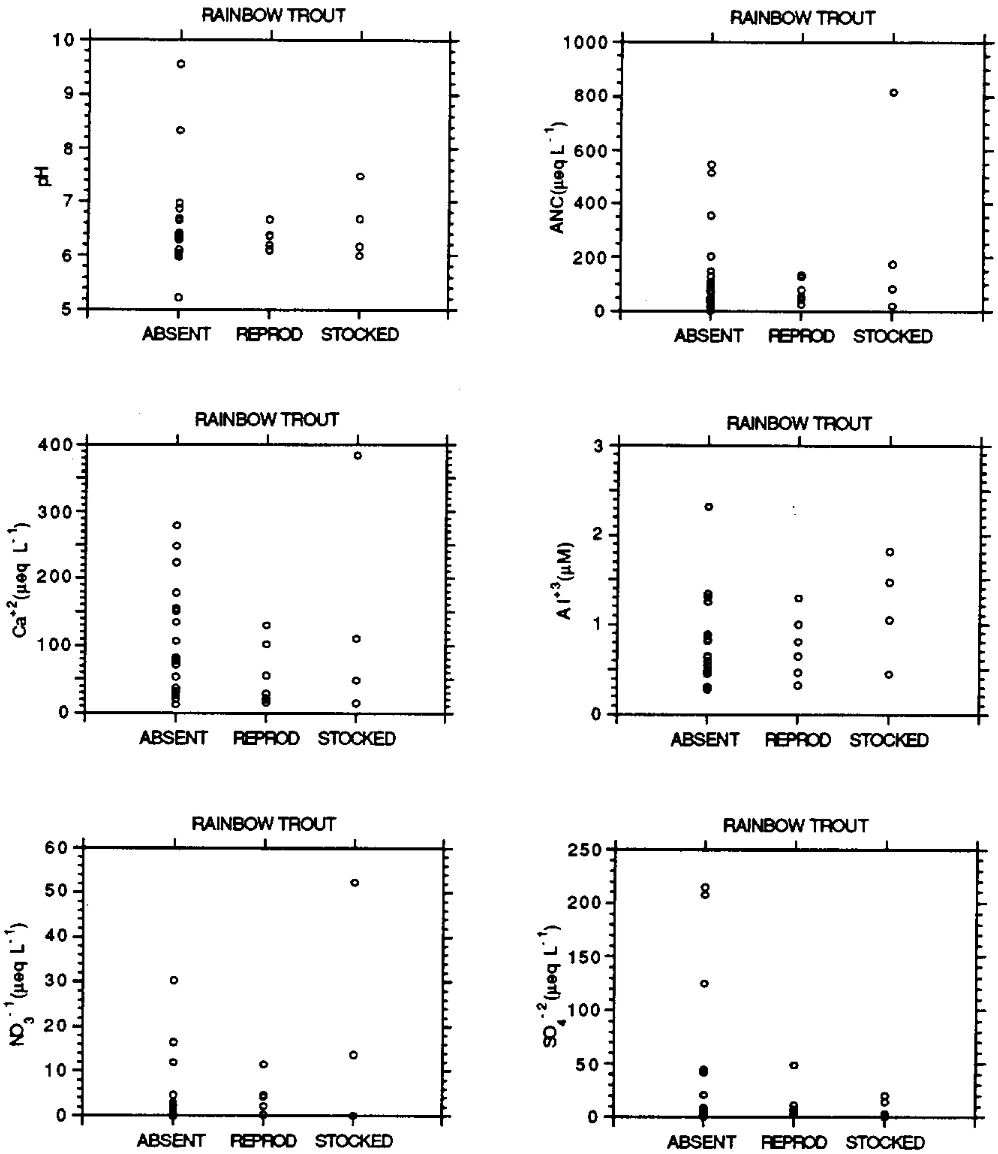

Fig. 1.8. Characteristics of lake habitats with and without rainbow trout populations.

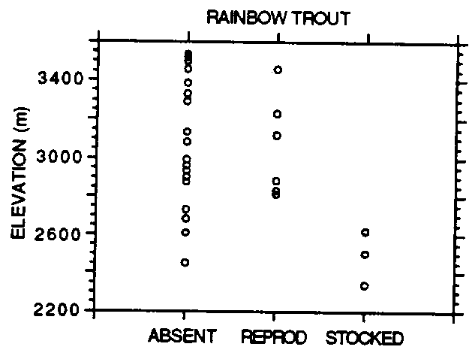

Fig. 1.8 (concluded). Characteristics of lake habitats with and without rainbow trout populations.

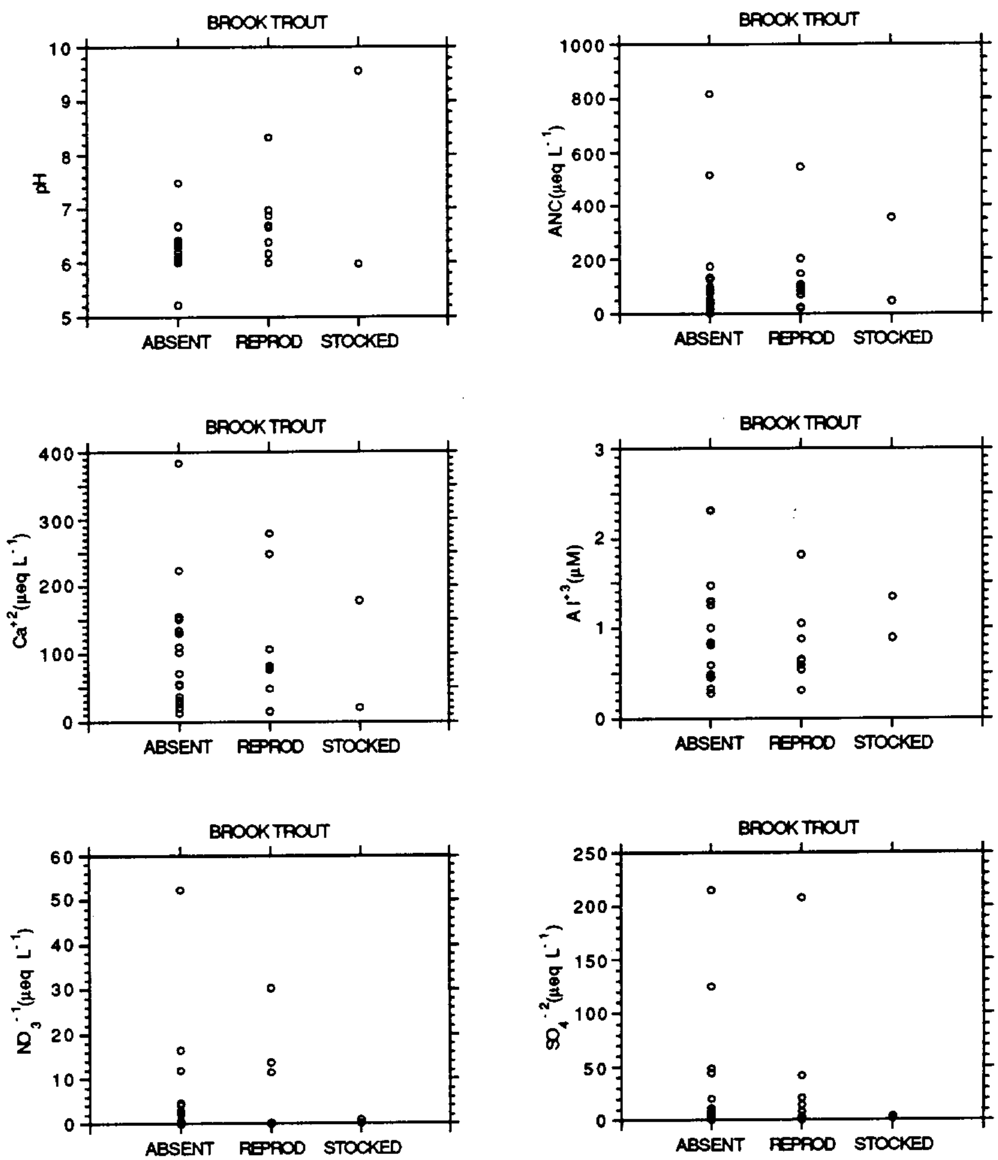

Fig. 1.9 Characteristics of lake habitats with and without brook trout populations.

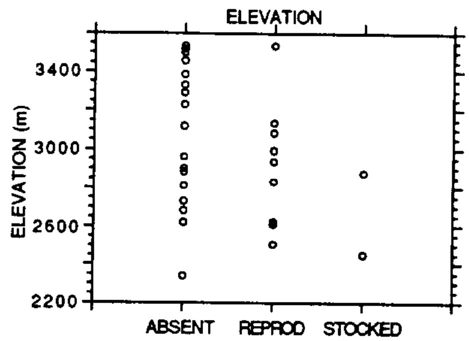

Fig. 1.9 (concluded). Characteristics of lake habitats with and without brook trout populations.

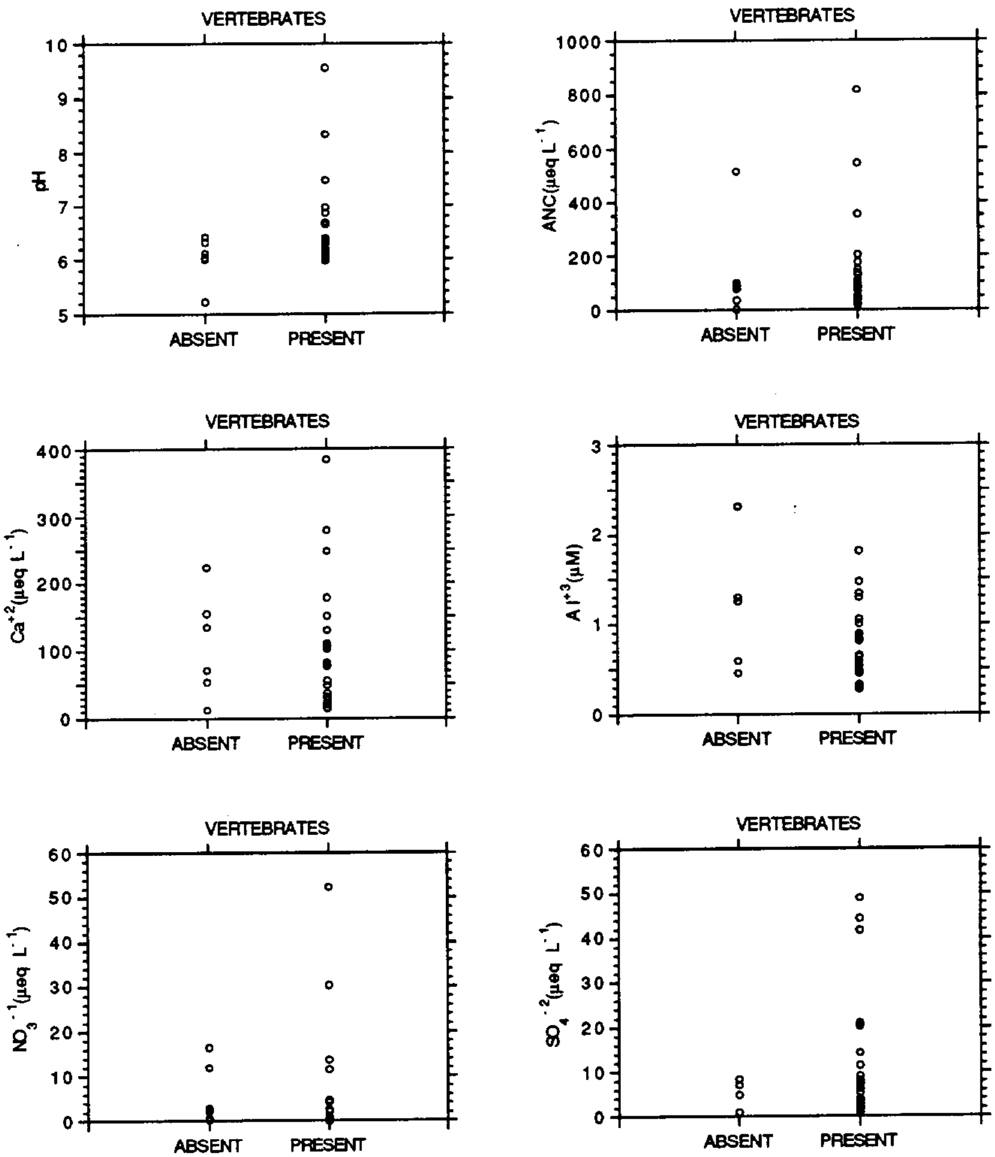

Fig. 1.10. Characteristics of habitats with and without vertebrate populations.

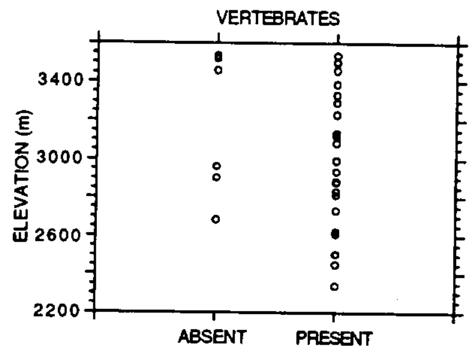

Fig. 1.10. Characteristics of habitats with and without vertebrate populations.

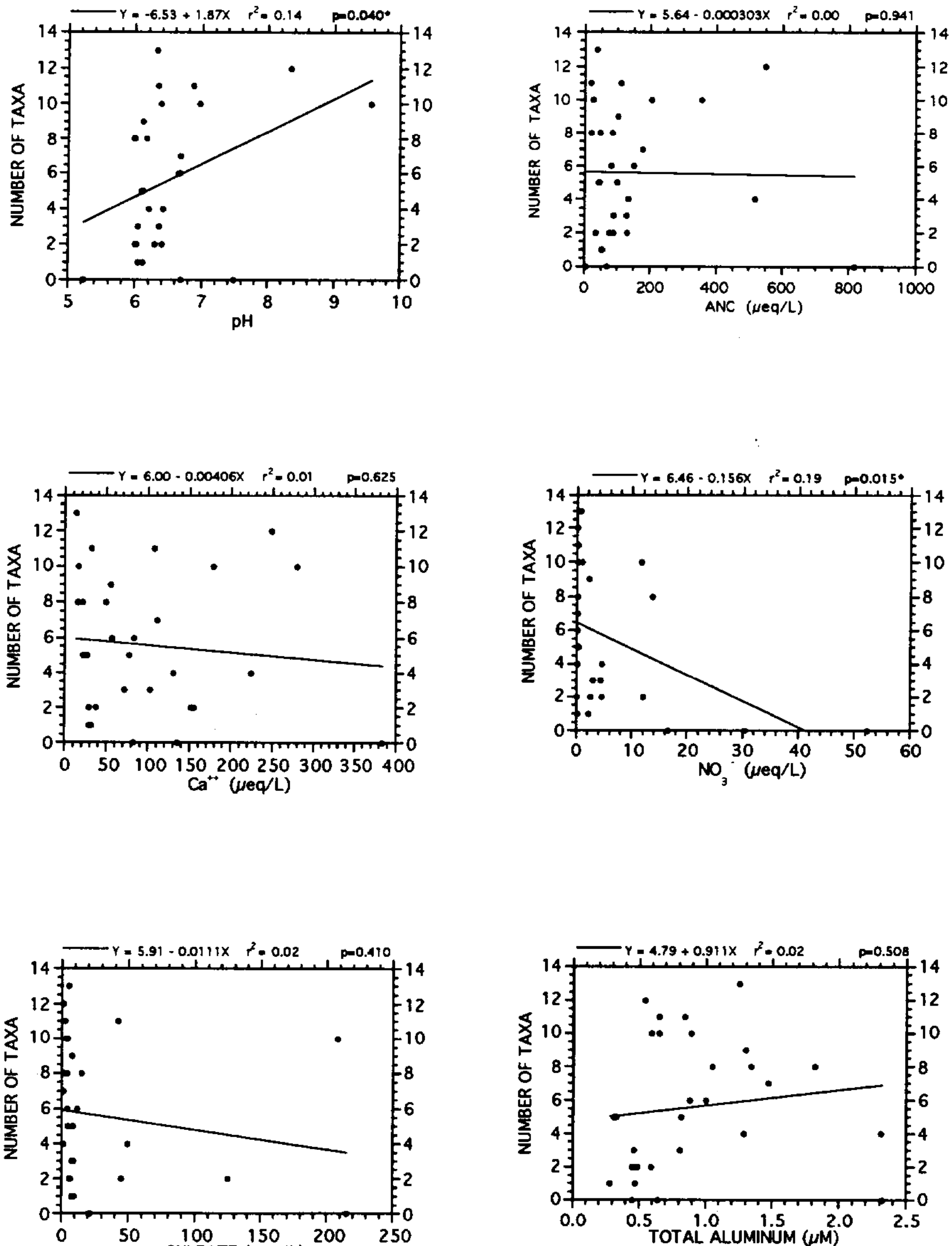

Fig. 1.11. Number of invertebrate taxa collected from lakes, relative to chemical characteristics and elevation.

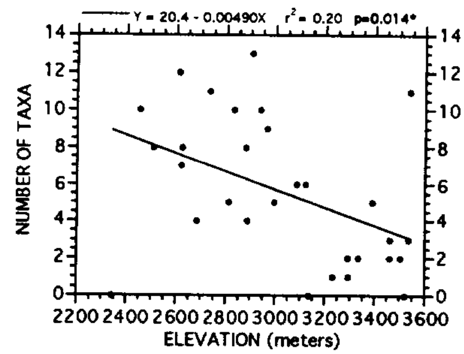

Fig. 1.11 (concluded). Number of invertebrate taxa collected from lakes, relative to chemical characteristics and elevation.

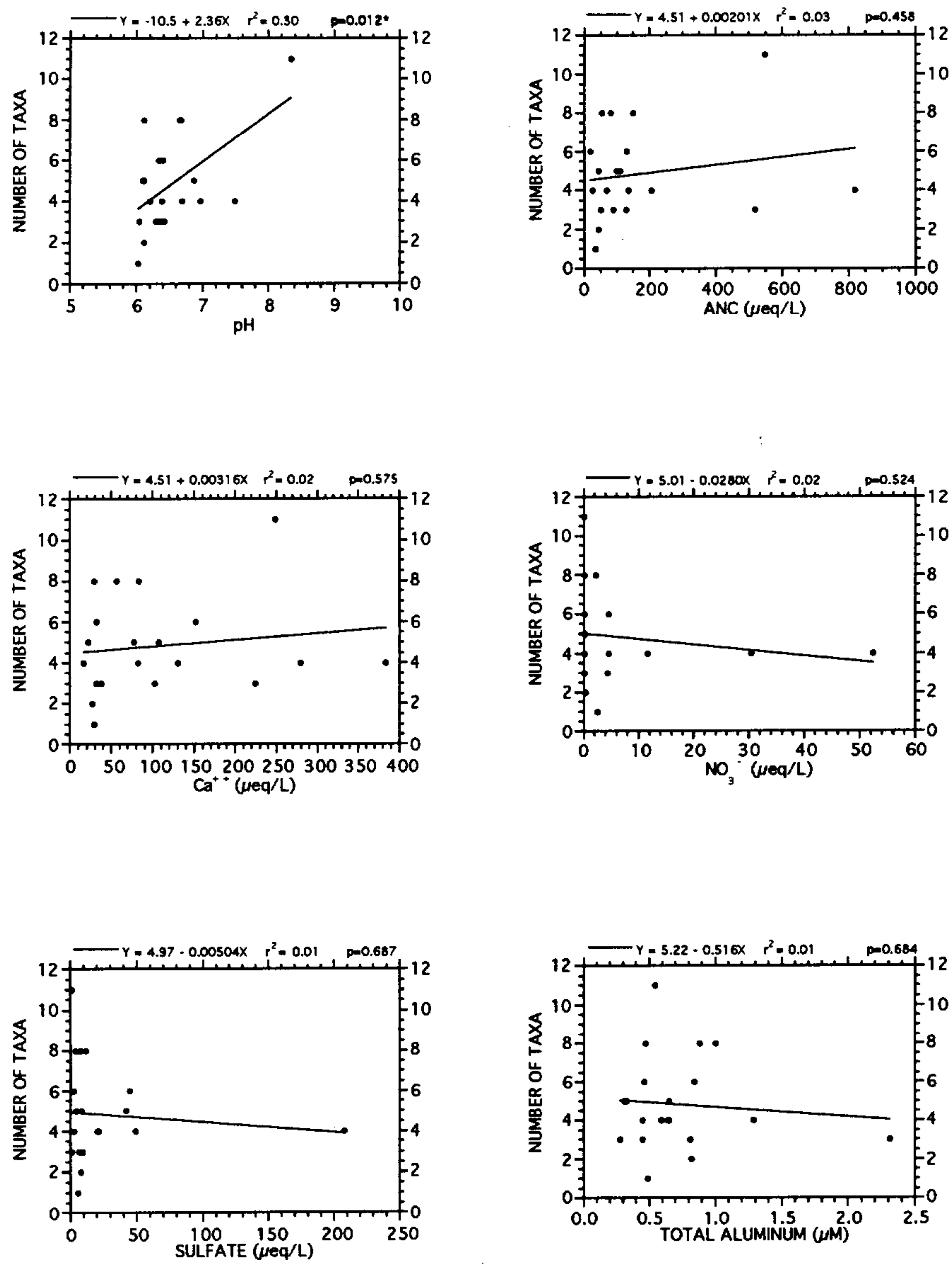

Fig. 1.12. Number of invertebrate taxa collected from streams, relative to chemical characteristics and elevation.

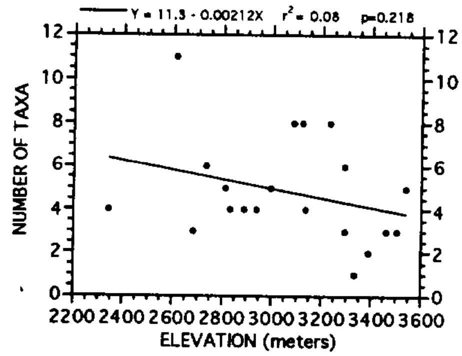

Fig. 1.12 (concluded). Number of invertebrate taxa collected from streams, relative to chemical characteristics and elevation.

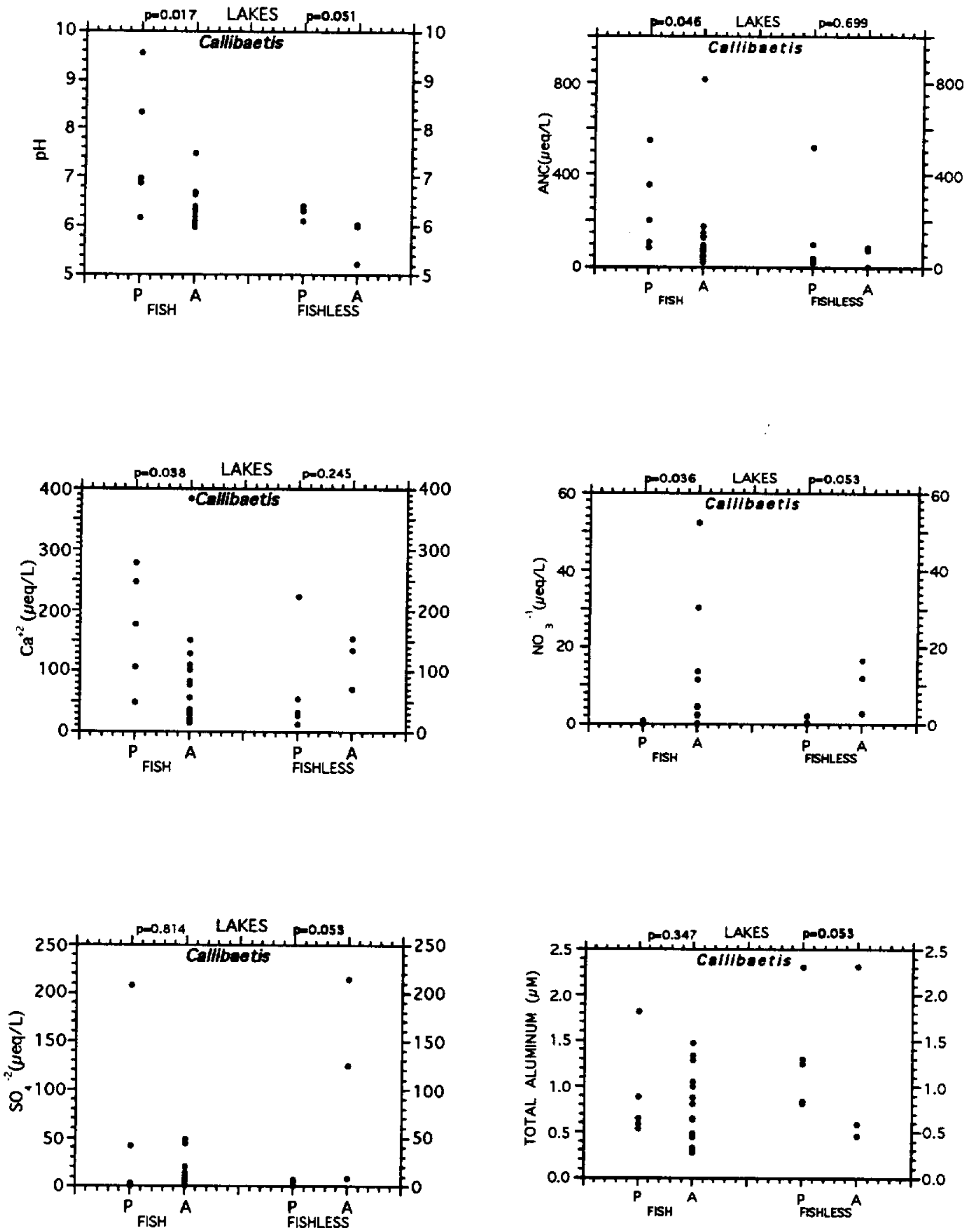

Fig. 1.13. Characteristics of habitats with and without *Callibaetis* mayfly populations where fish are present and absent.

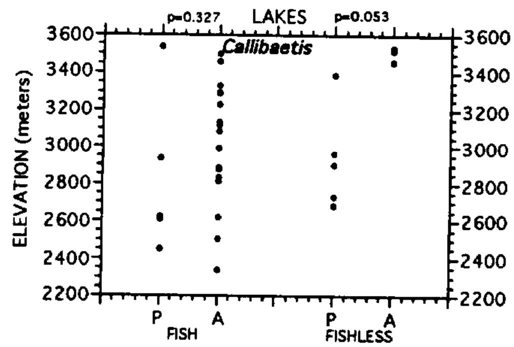

Fig. 1.13 (concluded). Characteristics of habitats with and without *Callibaetis* mayfly populations where fish are present and absent.

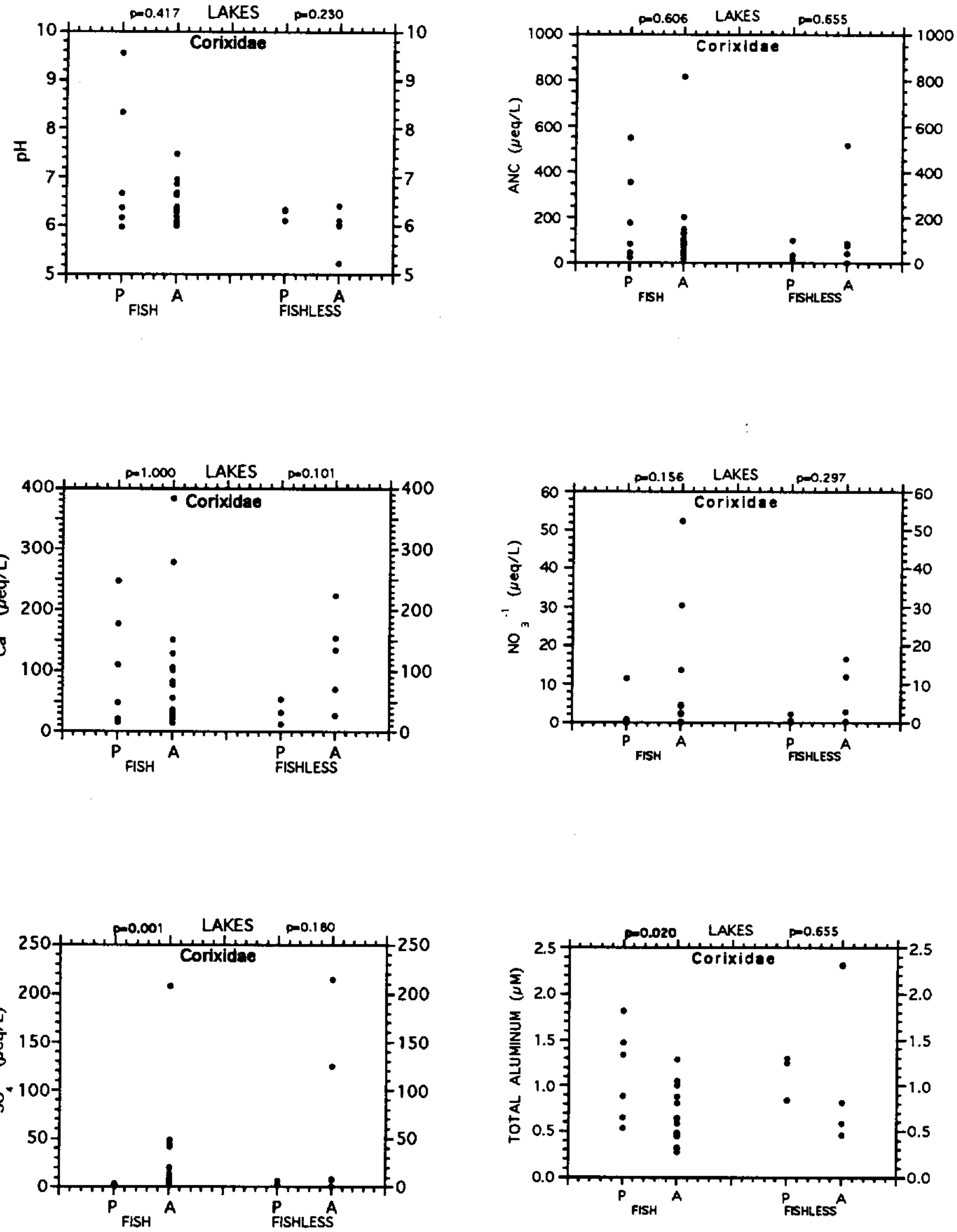

Fig. 1.14. Characteristics of habitats with and without corixid bugs, in lakes with fish present and absent.

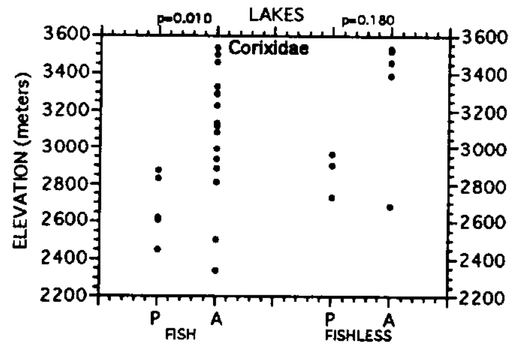

Fig. 1.14 (concluded) Characteristics of habitats with and without corixid bugs, in lakes with fish present and absent.

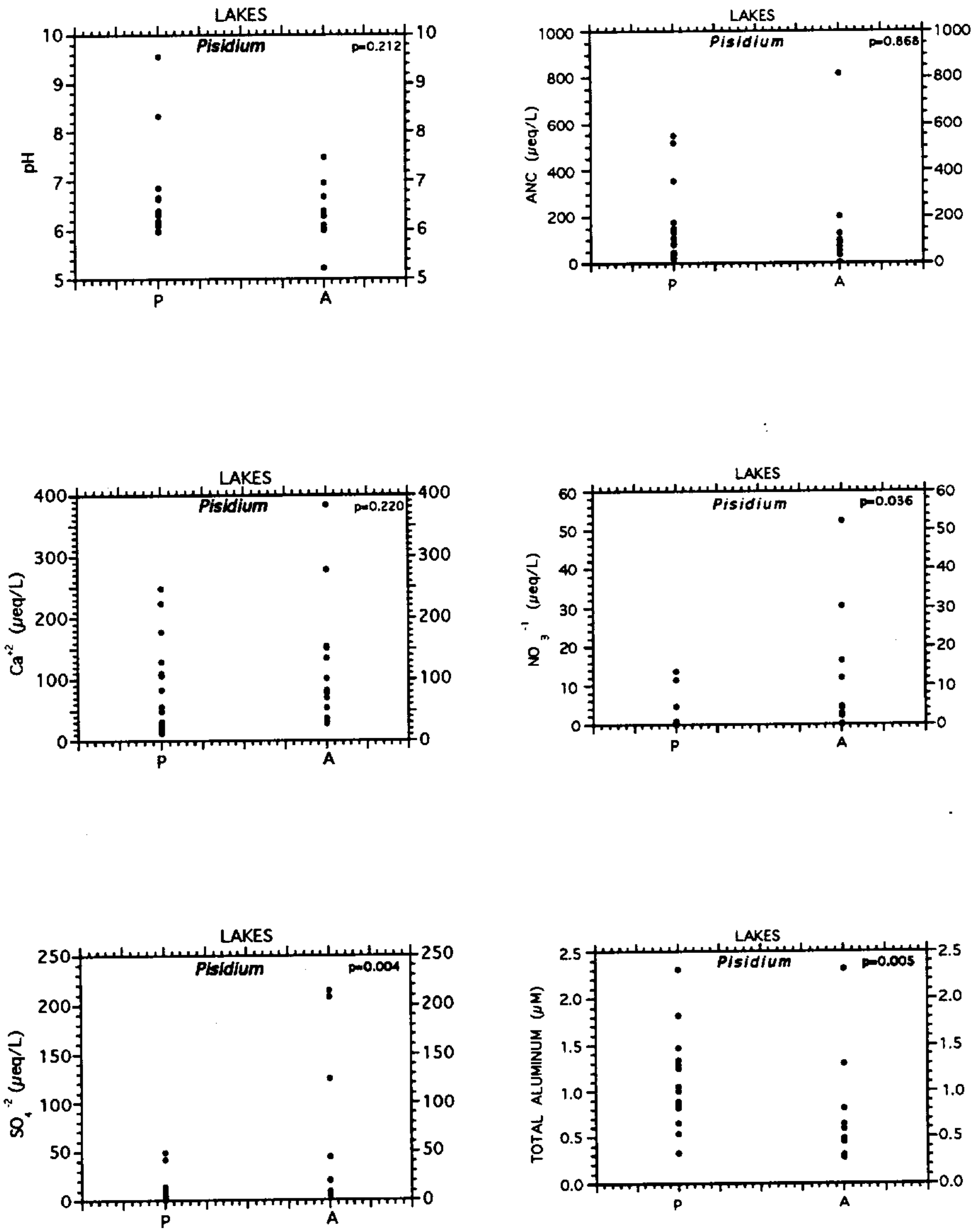

Fig. 1.15. Characteristics of lakes with and without *Pisidium* clams.

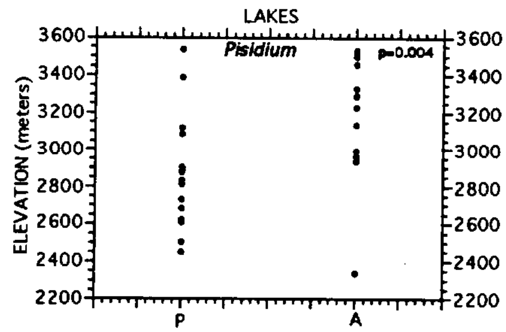

Fig. 1.15 (concluded). Characteristics of lakes with and without *Pisidium* clams.

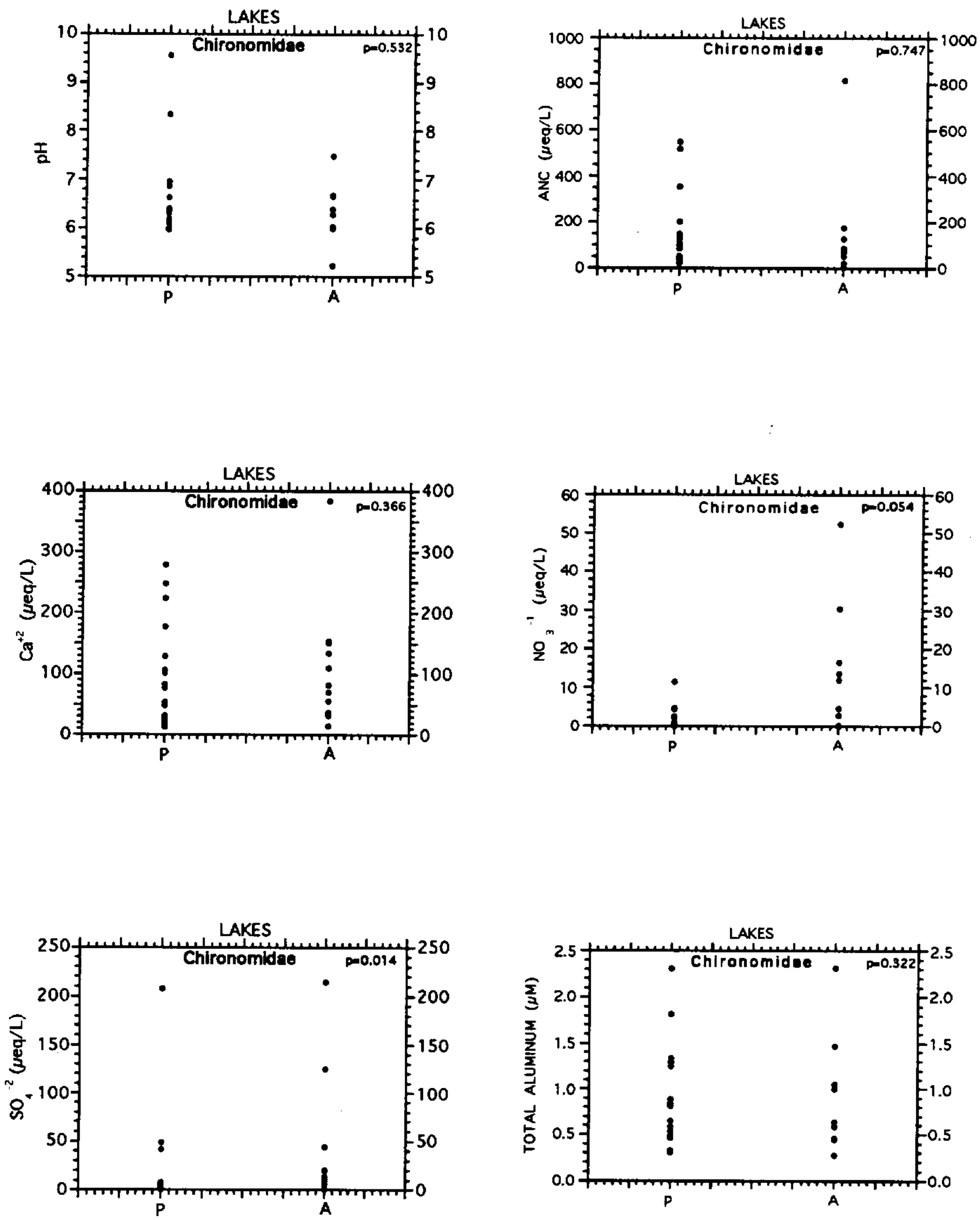

Fig. 1.16. Characteristics of lakes with and without chironomid midges.

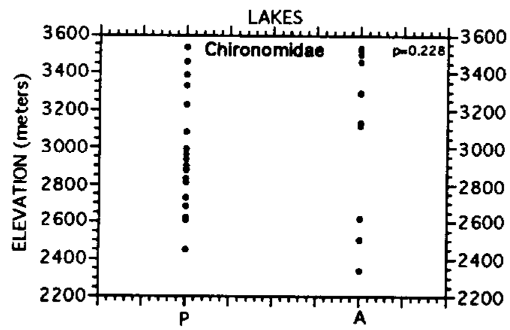

Fig. 1.16 (concluded). Characteristics of lakes with and without chironomid midges.

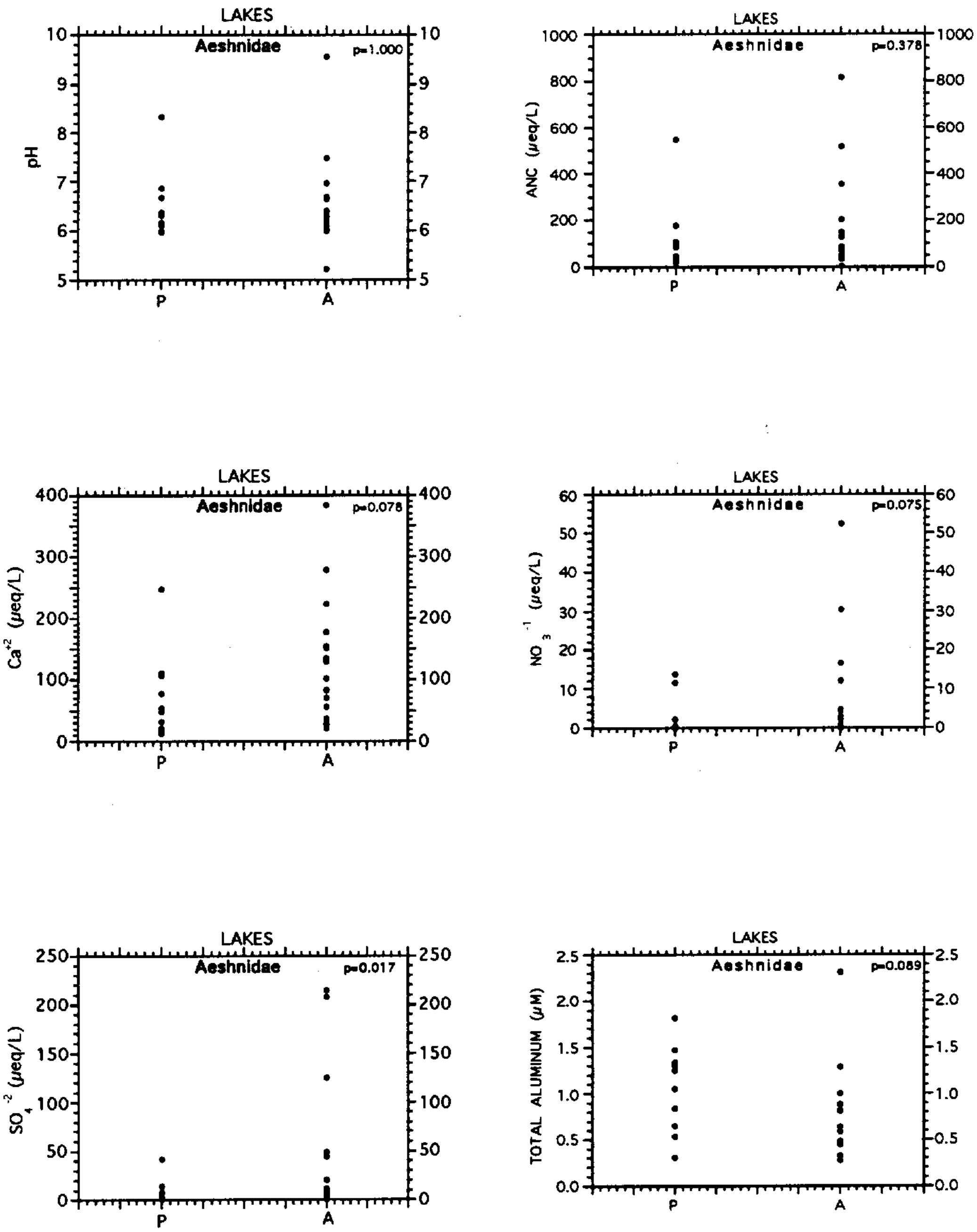

Fig. 1.17. Characteristics of lakes with and without aeshnid odonates..

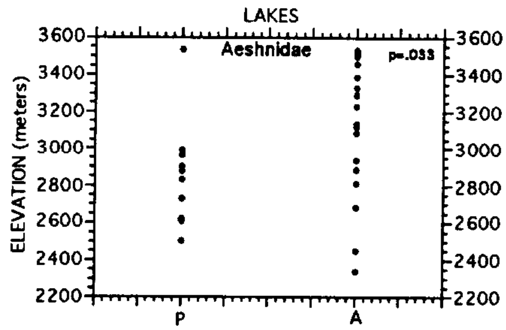

Fig. 1.17 (concluded). Characteristics of lakes with and without aeshnid odonates..

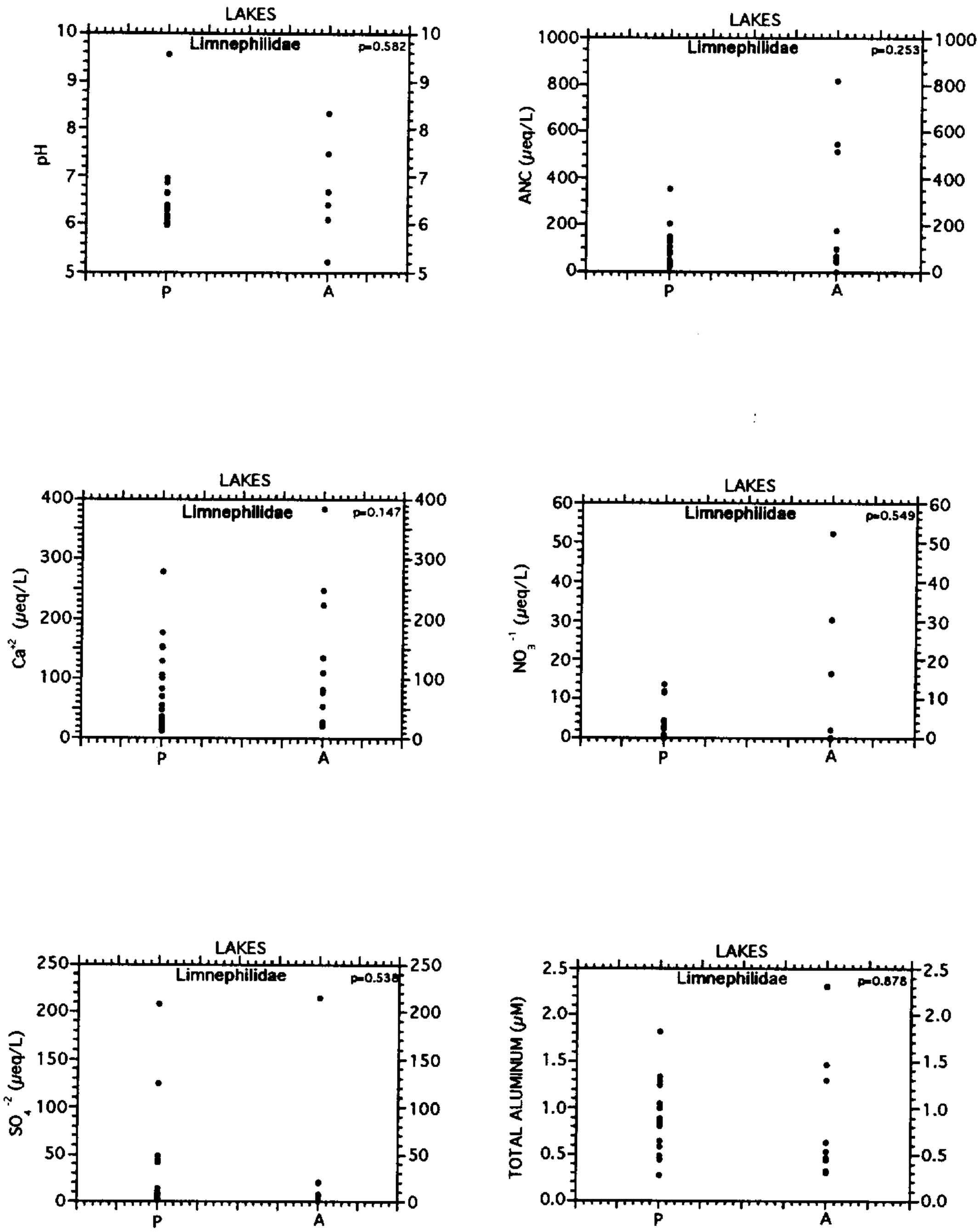

Fig. 1.18. Characteristics of lakes with and without limnephilid caddisflies.

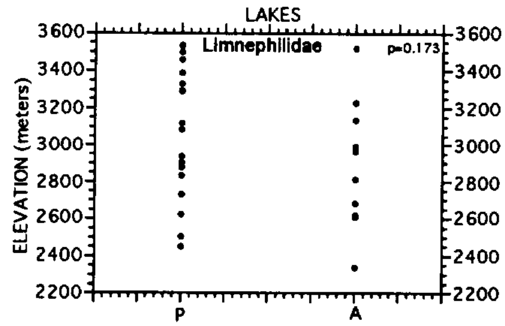

Fig. 1.18 (concluded). Characteristics of lakes with and without limnephilid caddisflies.

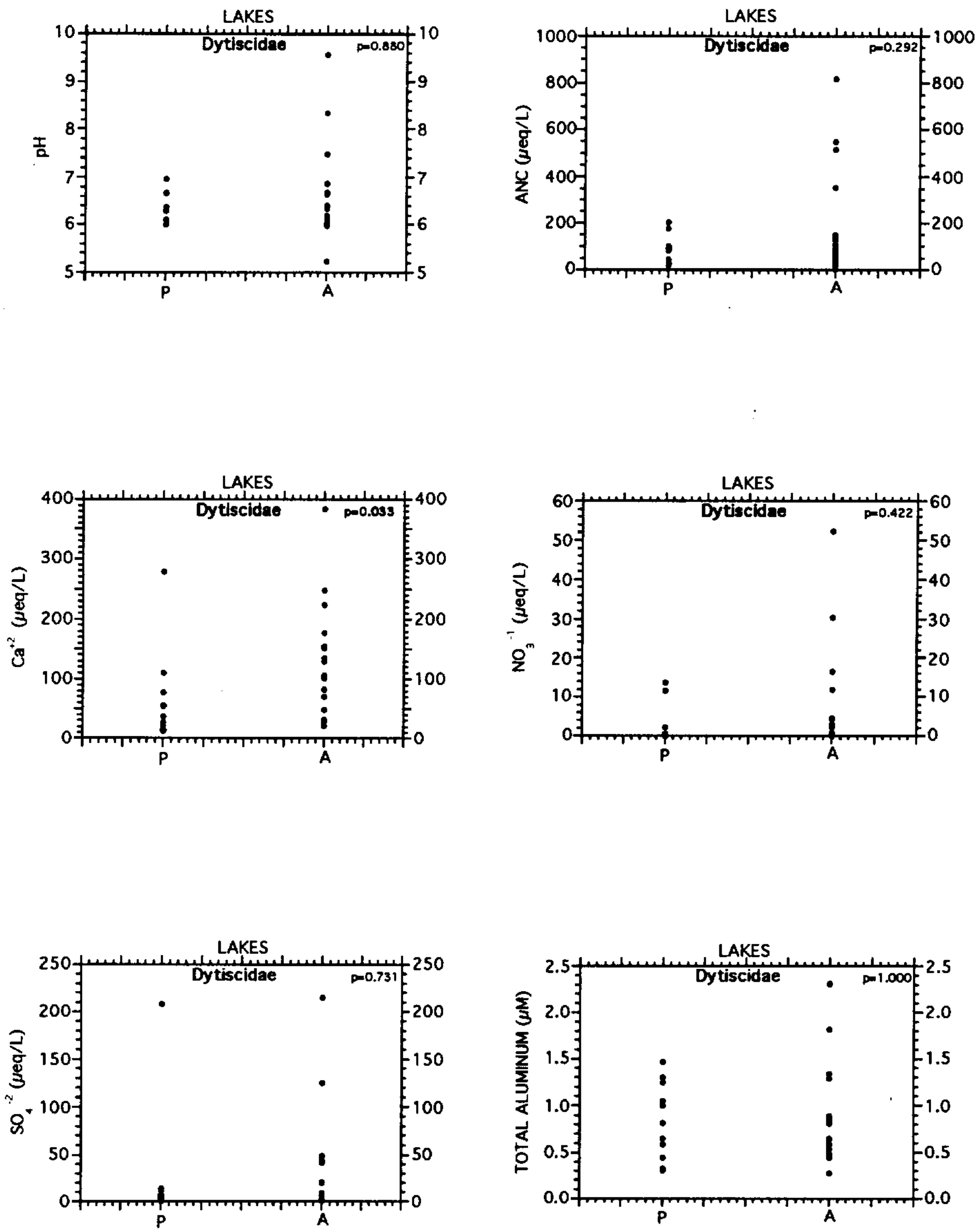

Fig. 1.19. Characteristics of lakes with and without dytiscid beetles.

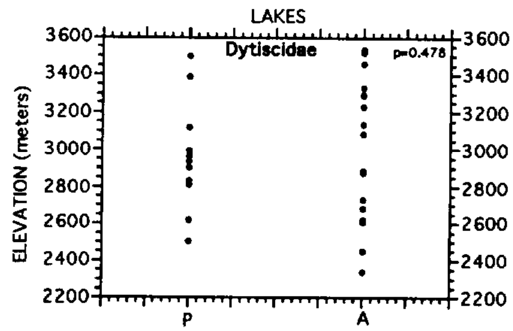

Fig. 1.19 (concluded). Characteristics of lakes with and without dytiscid beetles.

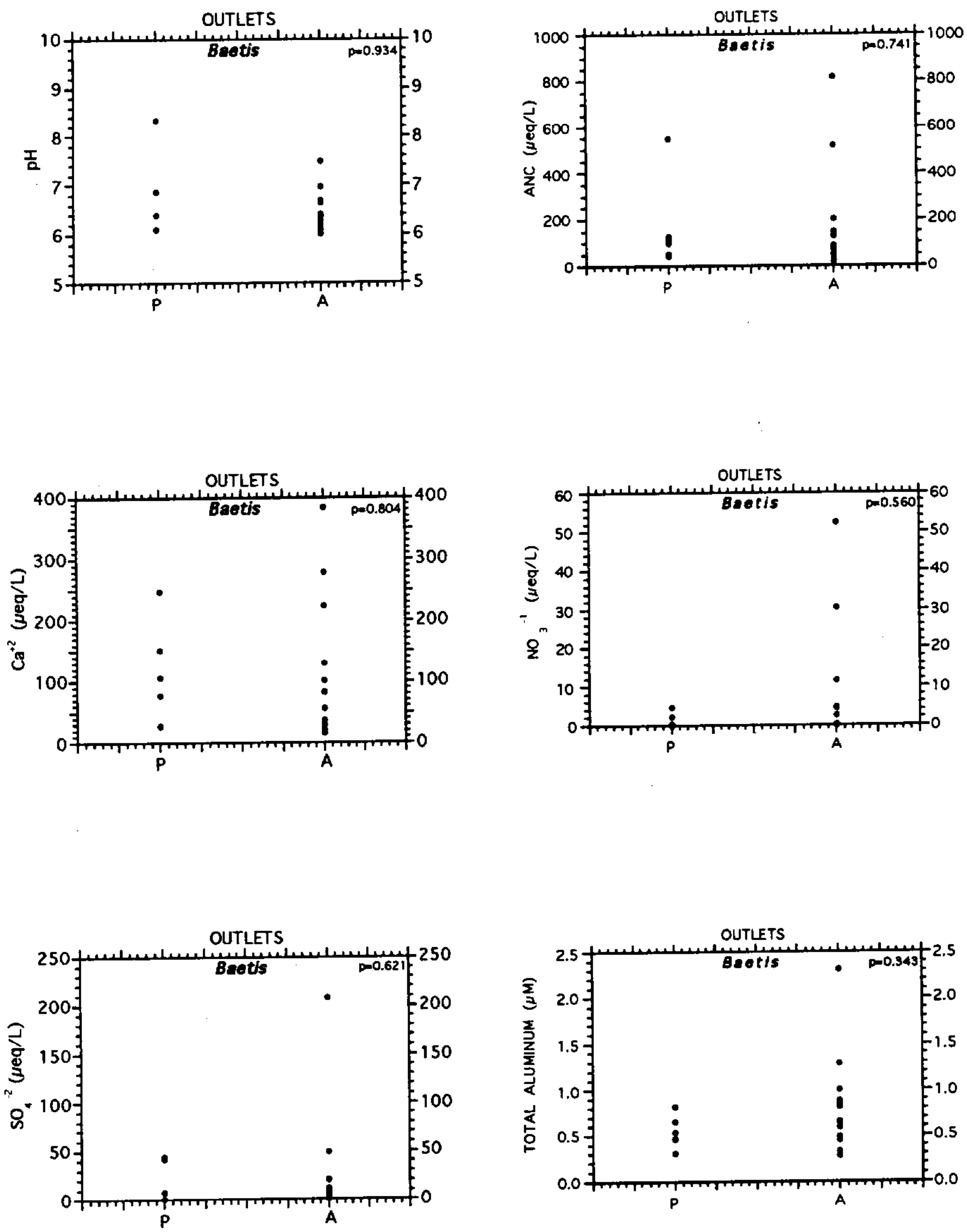

Fig. 1.20. Characteristics of outlet streams with and without *Baetis* mayflies.

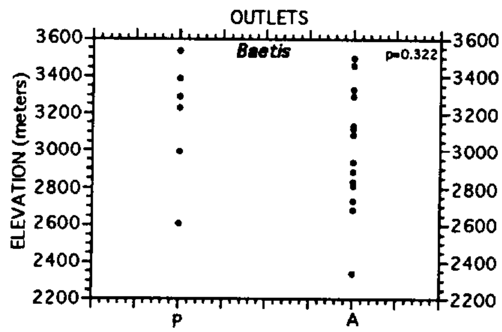

Fig. 1.20 (concluded). Characteristics of outlet streams with and without *Baetis* mayflies.

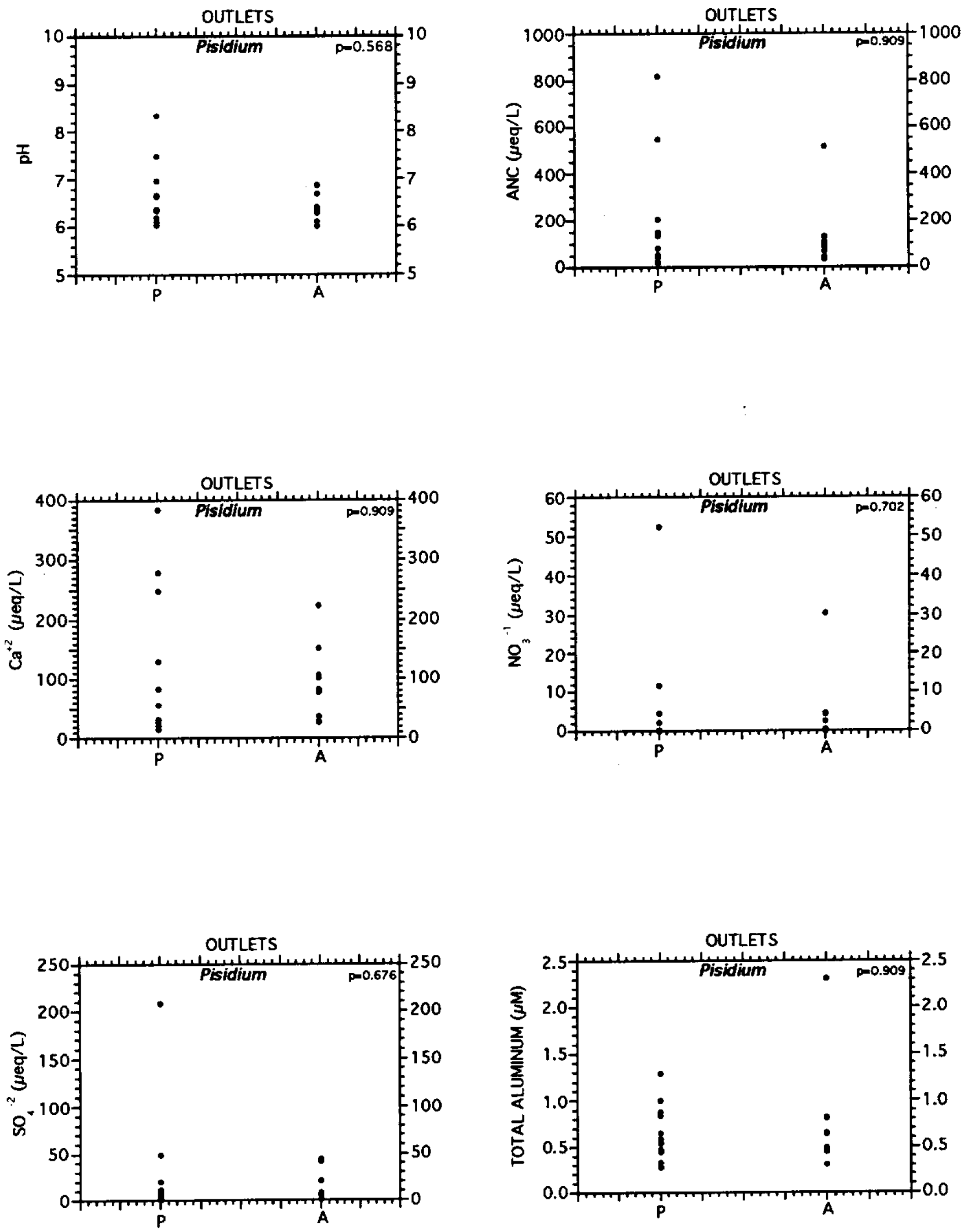

Fig. 1.21. Characteristics of outlet streams with and without *Pisidium* clams.

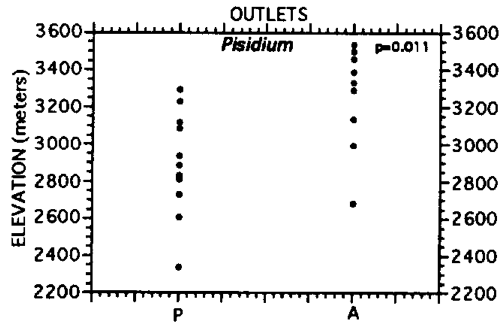

Fig. 1.21 (concluded). Characteristics of outlet streams with and without *Pisidium* clams.

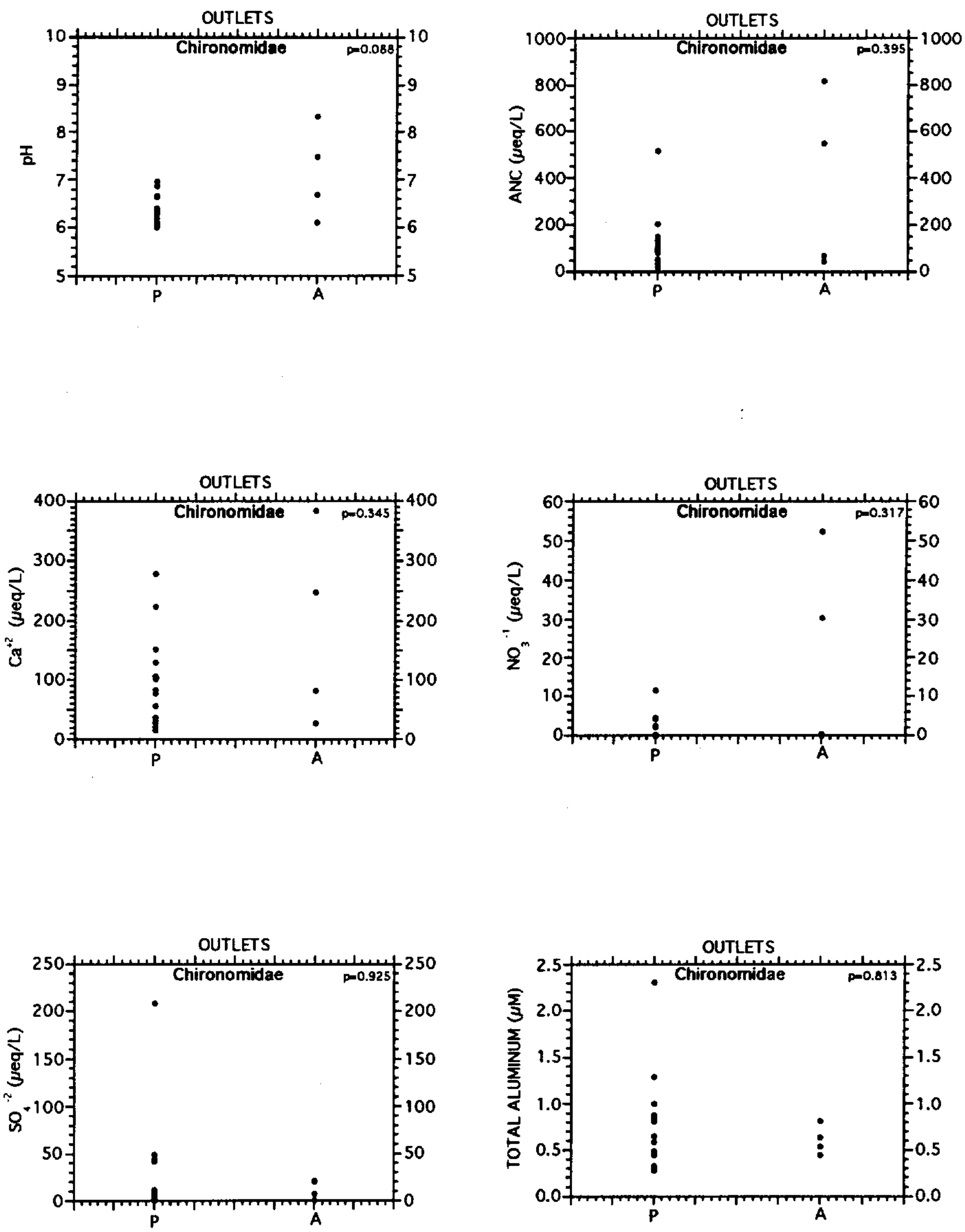

Fig. 1.22. Characteristics of outlet streams with and without chironomid midges.

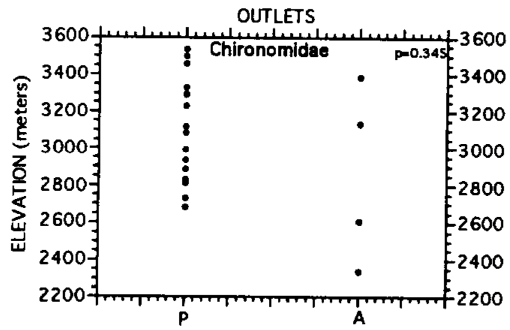

Fig. 1.22 (concluded). Characteristics of outlet streams with and without chironomid midges.

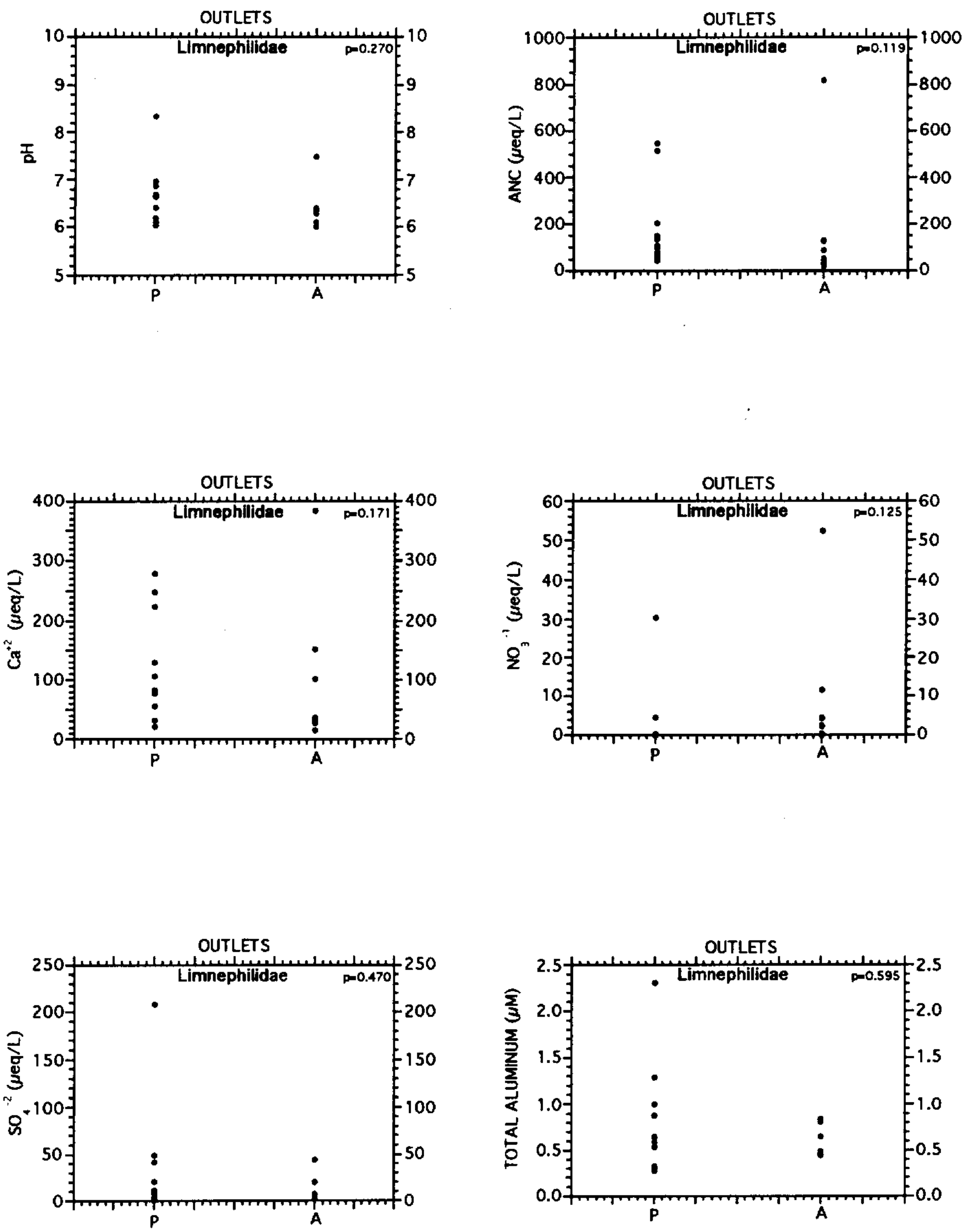

Fig. 1.23. Characteristics of outlet streams with and without limnephilid caddisflies.

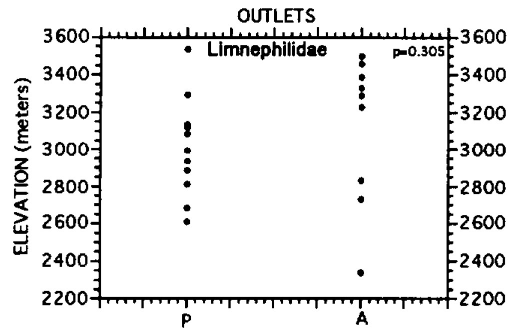

Fig. 1.23 (concluded). Characteristics of outlet streams with and without limnephilid caddisflies.

DISCUSSION AND CONCLUSIONS

Although this study focused on a different population of Sierra Nevada lakes (i.e., those above 8000 feet) than EPA's Western Lake Survey, chemical characteristics of sampled lakes were similar in both surveys (Figs. 1.3, 1.5, 1.6, and Table 1.2). The majority of high-elevation lakes in the study region have ANC < 100 μeq/L and are considered sensitive to acid deposition (Table 1.5). Only a small minority of lakes were chronically acidic from natural basin sources. Even though many of our lakes had pH values in the low 6 range at the time of measurements, there is no evidence that these pH levels, in addition to whatever acid pulses occur in the spring, have changed the numbers of fish in the lakes or their outflow streams.

Numerous populations of economically valuable fish are found at high elevations in the Sierra Nevada, and nearly all have been established by humans. The same Pleistocene glaciation that formed most of the lakes left insurmountable barriers to immigration from lowland populations. Our target population of lakes, each with surface area greater than one hectare, was estimated to be 1404 of which 881 contained one or more species of salmonid fish ("trout") and 523 lacked fish populations. We estimated that 126 of the fishless lakes contained yellow-legged frogs (*Rana muscosa)* and 284 contained only invertebrates. Although we projected that 112 lakes were devoid of fish and invertebrates due to naturally low pH and high sulfate and aluminum concentrations, a 1992 survey of all waters in the vicinity of the sampled acidic lakes (Bradford et al. 1993) showed that there were 10 acidic lakes in this area, and that most did contain some macroinvertebrates.

We have also estimated the number of lakes occupied by each of the 5 trout species (Table 1.13). Some lakes contained more than one trout species, but none contained more than two. Golden trout were projected to occur in the greatest number of lakes, followed closely by rainbow trout, another California native. Brook trout populations were estimated to be fewer in number, and brown and cutthroat trout were rare at high elevations.

Predictions of the effects of various levels of acid deposition on Sierra Nevada trout populations is problematic because projections require information on the tolerances of different species and life stages to pulsed acidification. At present, there is little information on trout vulnerability to acid inputs for those trout strains and physical-chemical conditions found in the Sierra Nevada. In addition, little is known regarding the combined effects of fluctuating water temperatures, high stream flows, and chemical changes on trout populations. Of particular importance is the timing of acid pulses from snowmelt or summer rainstorms relative to the occurrence of sensitive life history stages or transitions, such as spawning, egg development and hatching, and fry emergence from natal gravels. In Part II we describe the results of an experiment examining the effects of different levels of acid on golden trout eggs, and below we summarize the literature on trout responses to acidic inputs. These analyses indicate that the rank order of sensitivity of different trout taxa to increased acid inputs, going from the least to most vulnerable, is brook < brown < rainbow < golden < cutthroat trout, although responses of the three *Oncorhynchus* groups (golden, rainbow, cutthroat) are quite similar.

The distribution of trout populations relative to lake chemistry (Table 1.8) shows no evidence that any but a small cluster of naturally acidic lakes is unsuitable for fish. This is not unexpected, since toxicity thresholds in the literature (Part II and below) are well below pH measured in the field . Lakes with and without golden and brook trout, however, differed in aluminum concentration and pH, respectively, raising the possibility that populations with naturally low recruitment (e.g. due to poor spawning grounds) could disappear with minor chemical stress.

The following is our best estimate of concerns for the various trout species:

Oncorhynchus clarki (Cutthroat trout): We estimate only about 7 populations of this species within our area of coverage, which is almost exactly the number we have been able to confirm from agency records. Cutthroat trout are evidently the trout most sensitive to low pH and high aluminum (Woodward et al. 1991). Freshly fertilized eggs suffer mortality with 7 day exposure to pH 4.5 and monomeric aluminum 0-11.1 μM. Pre-hatching embryos start dying at 5.00/11.1 (pH/aluminum in mM), and alevin (sac fry) survival is severely reduced at 5.5/3.7 and 5.0/0. Swim-up larvae (just emerging from the gravel and starting feeding) suffer almost total mortality at 5.5/3.7, but are hardly affected at 5.0/0 or 5.0/1.9. The natural history of high elevation cutthroat trout in the Sierra has not been studied, but we asssume that they spawn during or after peak runoff like golden trout, so the egg stage would be most susceptible to pH depressions during snowmelt. Summer convective storms could affect them at any time during development, which probably lasts 1.5-2.0 months. The one lake we sampled containing cutthroat trout was relatively high in ANC (130 μeq/L), but a more important population near Mt. Williamson (one of the last pure populations of Colorado cutthroat, *O. clarki pleuriticus*, planted decades ago, E.P. Pister, pers. comm.) is in a granitic basin likely to have low buffering capacity. About 7 populations of cutthroat trout, then, would probably be eliminated if the pH of their limited spawning streams dropped to 4.5 for a few days early in development over 4-5 consecutive years. A similar effect during later stages would occur at pH 5.0 , aluminum 11.1 mM (embryos) and 5.5/3.7 (alevins and swim-up fry).

Oncorhynchus mykiss aguabonita (golden trout): We estimated approximately 469 naturally-reproducing populations of golden trout in our study area. Golden trout and cutthroat are closely related, so it is not surprising that they are similar in acid sensitivity (Deloney et al. 1993).

Survivorship of newly-fertilized eggs is first affected at 4.5/11.1 and even more severely reduced at 4.5/0 (i.e., aluminum ameliorates high H^+ effects) (see Part II). No data are available on later embryos. Golden trout alevins are more resistant than those of cutthroat trout, with mortality starting at 5.00/11.1, and swim-up fry of these two species show similar sensitivity, with mortality starting at 5.5/3.7.

About 469 populations of golden trout might be eliminated with several consecutive episodes of pH 4.5 early in development, i.e. during snowmelt, particularly if aluminum were present at low levels. It is possible that eggs or embryos destroyed by acid pulses could be replaced by eggs laid by later spawners. Acid pulses occurring later in development would have a similar effect at 5.00/11.1, for alevins, and 5.5/3.7, for swim-up fry. For golden trout, such acid pulses would have to occur no earlier than August and perhaps as late as mid-September. Since older trout are generally more tolerant of low pH, some populations might be preserved by planting fingerlings in late summer, as is customary. Sufficient eggs are available to maintain about half of these vulnerable populations, but management agencies (California Department of Fish and Game, U.S. Forest Service, National Park Service) are moving towards restoration of natural faunal assemblages, which do not include fish.

Oncorhynchus mykiss (rainbow trout): Data on the acid sensitivity of rainbow trout are similar to those for golden and cutthroat trout. The 349 natural populations of rainbow trout would die out after several consecutive years of acid pulses at pH 4.5 early in the summer, during snowmelt, or pH as high as 5.5 with increased aluminum later in the summer. Some of these populations could probably be preserved by planting, but again a large proportion probably would not be replaced due to changing agency policy regarding the introduction of non-native animals. As with golden trout, there exists the possibility that late spawning would sometimes replace embryos destroyed by early acid pulses.

Salmo trutta (brown trout): The estimated 112 populations of brown trout are found in better-buffered waters than the other species (Table 1.8). They are considered to be somewhat more tolerant of low pH and high aluminum than rainbow trout (Baker and Christensen 1991), with embryos dying at about pH 4.5-5.0, depending on stage and amount of aluminum. Brown trout spawn from September to late November at high elevations in the Sierra Nevada (T. Jenkins, unpublished), so only late alevins and swim-up fry would be subjected to snowmelt pulses of low pH. Assuming brown trout are similar to other species (e.g. brook trout, Ingersoll et al. 1990; golden trout, DeLonay et al. 1993), sac and swim-up fry are probably less sensitive to pH but more sensitive to inorganic monomeric aluminum compared to eggs and embryos. As a consequence, acid pulses of pH 5.0 with aluminum of 1.5 μM might eliminate brown trout recruitment (Reader and Dempsey 1989). Because brown trout waters are more highly-buffered than those occupied by other species, brown trout would probably be one of the last species (with brook trout, see below) to show effects of acid deposition. At present, exotic brown trout are rarely or never planted in high-elevation waters, so it is unlikely that lost populations would be artifically replaced.

Salvelinus fontinalis (brook trout): We have estimated about 185 reproducing populations of brook trout in our 1404 lakes. Like brown trout, brook trout spawn in the autumn and develop slowly through the winter and spring; they would therefore be exposed to snowmelt pulses when in the sac or swim-up fry stages. Brook trout also spawn in many lakes (Melack et al. 1989), so their susceptibility to total elimination by acid pulses is less than that of species that spawn only in streams. Brook trout are also considered to be the salmonids most resistant to low pH, with alevins and swim-up fry tolerating long-term exposure to a pH of 4.4 (with no aluminum) (Ingersoll et al. 1990). Even at pH 4.4, these stages of brook trout are not affected by inorganic aluminum at concentrations less than 43 μM. It is extremely unlikely that aluminum concentrations this high would be observed in the Sierra. Even Lake 45 at a pH of 4.7 had a total aluminum concentration of only 29 μM (Table 1.3). Lake 45 has been stocked several times with rainbow trout over several decades (Sequoia-Kings Canyon National Park database, courtesy of Dr. David Graber) but no fish were present at the time of our sampling in 1991 (Appendix A). It would be interesting to see if brook trout could survive these conditions.

It seems likely that the 185 brook trout populations would be the last to disappear from episodic deposition, even though a third are found at ANCs less than 20 μeq/L (Table 1.8). Although the study by Ingersoll et al. (1990) is probably the definitive laboratory bioassay, a large literature reviewed by Baker and Christensen (1991) suggests that brook trout populations could disappear at pH as high as 5.6 but as low as 4.3. Although Baker and Christensen give a critical pH value of 4.7-5.2 for effects on brook trout populations, it seems likely that responses to short-term, episodic pulses of acid might not be observed until pH is lowered to 4.5.

Aquatic Invertebrates: Aquatic invertebrates are largely native, are important indicators of environmental health, and provide food for fish populations. In our survey, the taxon richness of macroinvertebrate assemblages tended to be positively related to pH and negatively related to nitrate and sulfate concentrations, and elevation. Similarly, the average pH was higher, and nitrate, sulfate, and elevation lower, when common taxa (e.g. *Callibaetis*, *Pisidium*) were present versus absent. Interpretations of these relationships are difficult, however, because many of these chemical factors and elevation are correlated. With the exception of the amphipod crustacean *Hyallela azteca*, which cannot withstand chronic pH less than about 5.8 (Grapentine and Rosenberg 1992), the acid tolerance of littoral-zone invertebrates is largely unknown.

Limnetic forms such as water boatmen (Order Hemiptera, Family Corixidae) and dytiscid beetles can evidently withstand pH well below 5.0, and they thrive in acid lakes lacking fish (Evans 1989). Mayflies in general and the family Baetidae, in particular, are likely to be sensitive to pH below 5.5, based on experimental investigations conducted in streams.(Cooper et al. 1988; Hopkins et al. 1988; Smith et al. 1990, Kratz et al. 1994). At least one species of the caddis *Triaenodes* has been noted to be absent in streams below pH ca. 6.0 (Smith et al. 1990). There are also data suggesting that mollusks, such as snails (*Lymnaea, Physa, Gyraulus*) and clams (*Pisidium*), would be largely absent under acid conditions (Okland and Okland 1980, 1986). Chironomid larvae were found in all but the most acidic lakes, and at least some species can be expected to be exceptionally tolerant of low pH (Melack et al. 1989).

The situation for the invertebrate fauna of outlet streams is similar, with *Baetis, Paraleptophlebia* and other mayflies likely to be depleted at pH 5.2 or below (Cooper et al. 1988, Kratz et al. 1994). Some species of stoneflies would probably also disappear at pHs below 5.0, such as *Isoperla* and *Sweltsa* (Hall and Ide 1987). Corixids and dytiscids would presumably be able to resist any pH that could realistically occur in High Sierra lakes (Evans 1989).

Bradford et al.'s (1993) survey of acidic and non-acidic lakes in the eastern Sierra Nevada revealed few relationships between the occurrence of common macroinvertebrates and levels of lake acidity. Only limnephilid caddis larvae, particularly *Hesperophylax*, appeared to be affected by acidic conditions. Invertebrate taxa identified as sensitive in previous studies, such as baetid mayflies (Hopkins et al. 1989), amphipods (Mills and Schindler 1986), and sphaerid clams (Okland and Okland 1980, 1986) were not found in acidic lakes in Bradford et al.'s survey, but their infrequent collection in non-acidic lakes precluded statistical testing. Based on our survey and literature results we predict that some mayflies, particularly baetids, and amphipods will be reduced when pH declines to less than 5.5, whereas other taxa, such as mollusks and stoneflies will decrease when pH is lowered to < 5.0. Because they occur within well-buffered substrates, some taxa, such as clams, may be able to live in lakes with fairly low pHs (< 5.2). A number of taxa, such as corixids, dytiscid beetles, and some chironomids will be able to tolerate fairly acidic conditions.

Table 1.13. Estimated numbers and proportions of populations by species. Estimates for "all" populations include populations maintained by natural reproduction or by stocking.

SPECIES	CATEGORY	ESTIMATED POPULATION SIZE	PERCENT OF POPULATIONS
Golden	Natural Reproduction	469	34
Golden	All Populations	498	36
Rainbow	Natural Reproduction	349	25
Rainbow	All Populations	461	33
Brook	Natural Reproduction	185	13
Brook	All Populations	221	16
Brown	Natural Reproduction	112	8
Cutthroat	Natural Reproduction	7	0.5

Table 1.14. Estimates of the thresholds for damage from low pH and associated aluminum in trout populations, derived from the highest and lowest values for each effect in Baker and Christensen 1991 (brook, brown and rainbow trout) and other studies, as noted, for golden and cutthroat trout. Critical values are thresholds for damage to natural populations in the field.

SPECIES	EXPOSURE REGIME	pH	EFFECT
Brook	Chronic	4.7-5.2	Critical
Brook	Chronic	4.9-5.4	Recruitment Failure
Brook	Chronic	4.5-5.0	Stocking Failure
Brook	Chronic	4.3-5.6	Population Loss
Brown	Chronic	4.8-5.4	Critical
Brown	Chronic	4.9-5.3	Recruitment Failure
Brown	Chronic	4.7-5.0	Stocking Failure
Brown	Chronic	4.6-6.0	Population Loss
Rainbow	Chronic	4.9-5.5	Critical
Rainbow	Chronic	-	Recruitment Failure
Rainbow	Chronic	4.4-5.5	Stocking Failure
Rainbow	Chronic	-	Population Loss
Golden[1]	Episodic (2 or 7 day)	4.5-5.5	Critical
Cutthroat[2,3]	Episodic (7 day)	4.5-5.5	Critical

[1]DeLonay et al. 1993 and Part II
[2]Woodward et al. 1989
[3]Woodward et al. 1991

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Part II. A Field Experiment to Determine the Acid Sensitivity of California Golden Trout (*Oncorhynchus mykiss aguabonita*) eggs to a simulated acid pulse in the Sierra Nevada, California

INTRODUCTION

Acid deposition and its effects on aquatic ecosystems have been major foci of scientific research during the past two decades. This research effort is being driven largely by concerns that acid inputs may negatively affect fish populations. In North America, fishery declines as a result of chronic or episodic acidification are already documented for eastern Canada (Harvey and Lee 1982; Hulsman and Powles 1983; Watt et al. 1983; Gunn and Keller 1984; LaCroix 1985; Beggs and Gunn 1986) and the eastern United States (Schofield 1976; Baker and Harvey 1984; Haines and Baker 1986; Jordahl and Benson 1987; Schofield and Driscoll 1987; Fiss and Carline 1993). Although fisheries in western North America have not declined owing to surface water acidification, waters in western North America are currently receiving acidic inputs and are extremely susceptible to future pH changes because of low acid neutralizing capacities (see recent reviews in Charles 1991).

In order to predict the potential impact of acid deposition on fish populations, numerous laboratory experiments have been performed (e.g. Brown 1983; Kwain and Rose 1985; Cleveland et al. 1986; Hunn et al. 1987; Hutchinson et al. 1989; Woodward et al. 1989; Ingersoll et al. 1990; Parkhurst et al. 1990; Woodward et al. 1991; DeLonay et al. 1993). Often, these studies have evaluated the effects of both pH and aluminum, since the solubility of aluminum in water increases exponentially below pH 6 (Drever 1982), and monomeric aluminum is known to be toxic to fishes (e.g. Baker and Schofield 1982). The majority of such studies have focused on trout (*Oncorhynchus* sp., *Salmo* sp.) and char (*Salvelinus* sp.) since these species are widespread in North America, are often the dominant fish species in poorly-buffered waters, appear quite sensitive to pH reductions, and constitute important recreational and commercial fisheries. These experiments have used eggs and fry because these stages are more sensitive to pH depressions than adults (see review by Baker and Christensen 1991) and would therefore be affected first by acid stress. In addition, these early life stages represent a life history bottleneck and will therefore have important consequences for the structure of adult populations.

Although laboratory experiments have provided many data on fish responses to changes in pH and aluminum, a larger goal of researchers is to use these studies to make predictions of how fish populations will respond to regional changes in water chemistry as a result of surface water acidification (VanWinkle et al. 1986; Christensen et al. 1988). A major assumption of this approach is that responses by fish to acid and aluminum additions under highly artificial laboratory conditions are representative of field responses. Although studies that compare results of laboratory and field bioassays for the same fish species under similar water chemistry conditions are nearly nonexistent, available evidence suggests that laboratory and field responses may differ. In a study of Atlantic salmon (*Salmo salar*), Lacroix (1985) reported that estimates of critical pH levels for embryos differed between laboratory and field studies. Results such as these point to the need to conduct experiments under field conditions to allow comparisons with data from laboratory bioassays. If laboratory and field studies consistently produce different results, field experiments may provide the better index of actual responses since they are conducted under more realistic conditions.

Several types of field acidification studies have been conducted. For example, several researchers have exposed early life stages of fish to waters that have become chronically acidified due to acid deposition. Researchers adopting this approach generally have constructed artificial nests in several streams or lakes representing a continuum from unacidified to highly acidified, and monitored the survival of eggs or yolk-sac larvae (Hulsman and Powles 1983; Gunn and Keller 1984; Lacroix 1985; Jordahl and Benson 1987; Fiss and Carline 1993). Although such experiments have provided much-needed data on fish responses to different acid and aluminum levels under field conditions, they are limited by the available water chemistry. In areas containing acidified streams, there may not be a sufficient pH range available to determine critical pH thresholds. In areas sensitive to acid deposition but not yet experiencing surface water acidification, the lack of any acidic streams or lakes precludes such studies.

Another approach used to assess acid impacts in the field is the experimental acidification of entire bodies of water (Hall et al. 1980; Mills et al. 1987; Ormerod et al. 1987). Although such studies allow the quantification of community-wide responses to experimental acidification, it is difficult to find comparable bodies of water to serve as controls. Even when only a portion of a system is acidified and effects within the acidified portion are compared to conditions in the unacidified portion (e.g. in streams, where a downstream manipulation is compared with an upstream control), there is no replication of treatments. In addition, it is difficult to find a number of comparable water bodies to evaluate fish or community responses to a gradient of acid levels.

Artificial stream channels may represent an excellent compromise between laboratory dose-response experiments and whole system acidifications, because they allow replicated experiments with multiple treatment levels conducted under near-natural conditions. Stream channels have been used in past studies to determine the effects of pH depressions on aquatic invertebrates (Servos and Makie 1986; Hopkins et al. 1989; Kratz et al. 1994), but have been used only rarely to evaluate the effects of acid addition on fish (e.g. Zischke et al. 1983).

We conducted a field experiment with the eggs of California golden trout (*Oncorhynchus mykiss aguabonita*) in stream channels in an alpine watershed in the Sierra Nevada, California. Although nearly all water bodies above 2500 m in this mountain range were historically fishless (Hubbs and Wallis 1948; Christenson 1977), introduced trout now occupy approximately 63% of Sierran lakes and streams, and constitute an important recreational fishery (Part I). Of the introduced species, *O. mykiss aguabonita* is now the most widespread (Part I). Although surface waters of the Sierra Nevada currently show no sign of chronic acidification, depressions of pH and ANC associated with snowmelt and summer rain events are known to occur (Melack and Stoddard 1991). There is concern that possible increases in acid deposition in the Sierra Nevada may result in greater pH depressions during snowmelt, when eggs and yolk-sac fry of several trout species are present within stream substrates. Therefore, we examined the effect of a brief pH depression on the eggs of golden trout in stream channels during the snowmelt period. We used eggs in our experiment because the egg stage appears to be most sensitive to acid additions (Baker and Schofield 1982; Ingersoll et al. 1990; Woodward et al. 1991; DeLonay et al. 1993).

The goals of our study were three-fold. First, we constructed a geochemical model of aluminum dissolution that predicted aluminum concentrations in waters flowing through a typical high elevation basin in the Sierra Nevada as a function of pH. We used the results of this model to choose aluminum/acid addition treatments that would mimic aluminum concentrations expected under different pH levels in high elevation waters in the Sierra Nevada. Second, we sought to determine the effect of current and reasonably foreseeable pH depressions associated with snowmelt on the survival of newly-fertilized golden trout eggs. We manipulated only pH, because our geochemical model showed that toxic levels of aluminum would be expected only for pH < 5.0 (see Results), and such low pH levels are not expected in the Sierra Nevada in the near future. Information on the effect of acid additions on golden trout eggs under field conditions will be valuable in predicting current and future effects of acid inputs on fish populations in the Sierra Nevada. The third goal of our research was to allow a comparison between the results of our field experiment and the results of recent laboratory bioassays conducted with golden trout (DeLonay et al. 1993). Such a comparison will provide information on how reliably results from highly artificial laboratory experiments predict field responses to pH depressions.

METHODS

Geochemical Model

We estimated the total aluminum concentration in water flowing through a high-elevation granitic Sierran basin at different surface water pH levels using Geochem-PC Version 1.5 software, with microcrystalline gibbsite as the dominant basin mineral. Total aluminum included monomeric aluminum and Al-OH and $Al\text{-}SO_4$ complexes. Concentrations of monomeric aluminum were estimated from aluminum activity calculated for microcrystalline gibbsite.

Study Site

The study site for the stream channel experiment was located in the Harvey Monroe Hall Research Natural Area, Inyo National Forest, California, just outside the eastern border of Yosemite National Park (119° 17' 30" N; 37° 57' 30" W). The experimental stream channels were adjacent to Mine Creek, approximately 200 m below the Spuller Lake outlet at an elevation of 3145 m. Spuller Lake and Mine Creek are inhabited by introduced brook trout (*Salvelinus fontinalis*). We chose this site for three reasons. First, this catchment has been the object of a long-term monitoring program conducted by researchers from the University of California, Santa Barbara (Melack et al. 1993). A meteorological / hydrological station used in this project was located 100 m upstream from the experimental channels and provided measurements of air and water temperature and stream discharge. Second, the poorly buffered water of Mine Creek is typical of high-altitude streams in the Sierra Nevada (Part I). Therefore, the results of our experiment should be applicable to streams throughout the high elevations of this range. Third, this site was reasonably accessible (4 km from a road), so we could carry all equipment and supplies to the study site by skiing or hiking.

Stream Channel Setup

The 15 experimental channels were constructed from plastic raingutter, each 1 m long, 10 cm wide, and 7 cm deep, and fastened to a wood frame (Figure 2.1). The channel frame was adjusted to provide a 12 cm drop from the upstream to the downstream end of each channel. Each channel was divided into 5 sections of equal size by partitions made of 3 mm plastic mesh, and channels were filled with 1.5 cm diameter gravel obtained from a nearby gravel pit. This gravel diameter is typical of that found in natural golden trout nests (Stefferud, in press), and was very similar geochemically to the granitic substrates found in Mine Creek at the study site.

Water was supplied to the channels through 5 cm (i.d.) flexible plastic pipe from a pool on Mine Creek approximately 10 m upstream and 3 m above the study site. Water was diverted by siphoning to ensure a constant delivery of water regardless of stream discharge. Water flowed from the flexible pipe into a 15 cm (i.d.) PVC pipe situated at the upstream end and perpendicular to the stream channels (Figure 2.1). Water was delivered to each channel via 1.2 cm (i.d.) PVC pipes inserted at right angles and evenly spaced along the delivery PVC pipe. Flow into each channel was controlled by a plastic ball valve. Effluent water was collected in a plastic trough placed at the downstream end of the channels (Figure 2.1). From the exit trough, water flowed across granite cobble for approximately 2 m before re-entering Mine Creek. Discharge from each channel was 14-18 l/min throughout the experimental period.

The acid delivery system was designed to deliver acid to the channels by gravity, because the remoteness of the study site (approximately 4 km from the nearest road) and the management guidelines for Research Natural Areas (no generators) made the use of mechanical pumps impractical. The delivery system was made of a 10 l plastic tub into which a 20 l plastic jug was inverted (Figure 2.2). Acid was delivered to individual channels from the plastic tub via 3 mm (i.d.) plastic tubing connected to the 1.2 cm (i.d.) pipes feeding each channel. As the acid level in the tub dropped, acid was added from the 20 l jug by gravity flow. This system maintained a constant head (± 2 mm) in the tub and thereby ensured a constant flow of acid to channels. The acid delivery rate to each channel was regulated by a plastic needle valve placed in each line. Two identical acid delivery systems were used in the experiment, each supplying five channels. Preliminary trials showed that the acid delivery system maintained pH within 0.1 pH unit of target levels.

Of the 15 channels, 4 were used as controls (no acid addition) and 10 were dosed with acid. The acid solution was a 1:1 mixture by equivalents of 16 N HNO_3 and 36 N H_2SO_4, diluted with stream water to make a 0.1 N solution. Experimental pH levels were 6.6 (ambient), 5.7, 5.4, 5.2, 5.0, and 4.8, with two replicate channels at each level. One channel was used to test the acid delivery system and was not used in the experiment (Figure 2.1). Treatments were assigned to channels so that replicates of each pH level were spaced regularly across channels, eliminating any potential biases resulting from channel position (Hurlbert 1984).

Channels were set up at the study site from June 10 to 20, 1993. Because golden trout living above 2500 m in the Sierra Nevada typically spawn from mid-June to mid-July (Curtis 1934; California Department of Fish and Game, personal communication; R.A. Knapp, personal observation) when much of the Sierra Nevada is still snow-covered, it was necessary to excavate 2-3 m of snow to place channels so that the experiment could be conducted during the snowmelt period. Water was diverted into channels starting one week before eggs were placed in the channels. On July 2, newly-fertilized golden trout (*Oncorhynchus mykiss aguabonita*) eggs were obtained from the Cottonwood Lakes, Inyo National Forest, by California Department of Fish and Game personnel. Eggs were transported to the study site and buried in channel substrates within 18 hours of collection. Fifteen eggs were dispersed in each of the 5 sections of each channel (75 eggs per channel), and buried approximately 3 cm deep.

Exposures

Experimental acidifications began on July 15 and continued until July 17. Acid delivery was halted from 0200-0800 hours on July 16 and 0200-0700 hours on July 17 when acid solutions froze. The total duration of the experimental acidification was 40 hours, similar in duration to the spring ionic pulses that occur in the Sierra Nevada (1-10 days; Melack and Williams, unpublished data). In addition, the pulsed delivery of acid simulated the repeated brief acid pulses which occur during snowmelt (Gunn and Keller 1984). We measured pH with Orion portable pH meters that we re-calibrated with pH 4 and pH 7 buffers once per hour. pH was checked in each channel approximately once per hour. When the channel pH deviated by more than 0.1 from the target pH, the rate of acid delivery was adjusted and channel pH was rechecked approximately every 10 minutes until the target pH was re-established.

Water samples were collected on July 9, July 17, and July 18 (before, during, and after the experimental acidification, respectively) for determinations of pH, ANC, specific conductance, total aluminum, and major ion concentrations (Cl^-, NO_3^-, SO_4^{-2}, Ca^{++}, Mg^{++}, Na^+, and K^+). Water samples were collected in acid-washed polyethylene bottles from the outlet of each channel, and from approximately 5 m upstream and downstream of the point at which water from the channels re-entered Mine Creek. Samples were kept cool and in the dark during transport and storage. Laboratory analyses of pH, ANC, and specific conductance were made within 48 hours of collection, and the remaining analyses were performed within 4 months of collection. Water samples for pH, ANC, and specific conductance were unfiltered, samples for major ions were filtered through 1 μm Nucleopore polycarbonate filters, and samples for aluminum were filtered through 0.1 μm Nucleopore polycarbonate filters and acidified (1% HNO_3) within 24 hours of sample collection. Filters and sample bottles were rinsed with at least 20 ml of sample water before sample collection. In the laboratory, pH was measured with a combination electrode designed for samples of low ionic strength, and ANC was determined by incremental titration with 0.1 N HCl. Specific conductance was measured with a conductivity bridge, and readings were standardized to 25° C. Calcium, magnesium, sodium, and potassium were measured by flame atomic absorption, and ion chromatography was used to measure chloride, sulfate, and nitrate. Aluminum was analyzed by atomic absorption using the graphite furnace technique (U.S. Environmenal Protection Agency 1979).

Eggs were excavated from channels on July 26-27. Because of the cold water temperatures experienced by the eggs throughout the experiment (see Results), embryos showed no evidence of eye formation when excavated, indicating that they were still in an early developmental stage. Dead eggs were distinguished from live eggs by their distinctive white color compared to the yellow color of live eggs.

Statistical Analyses

Differences among treatments were analyzed using one-way analyses of variance if variances were similar among treatments, or could be transformed to make them similar. Otherwise, treatment effects were analyzed using non-parametric Kruskal-Wallis one-way analyses of variance.

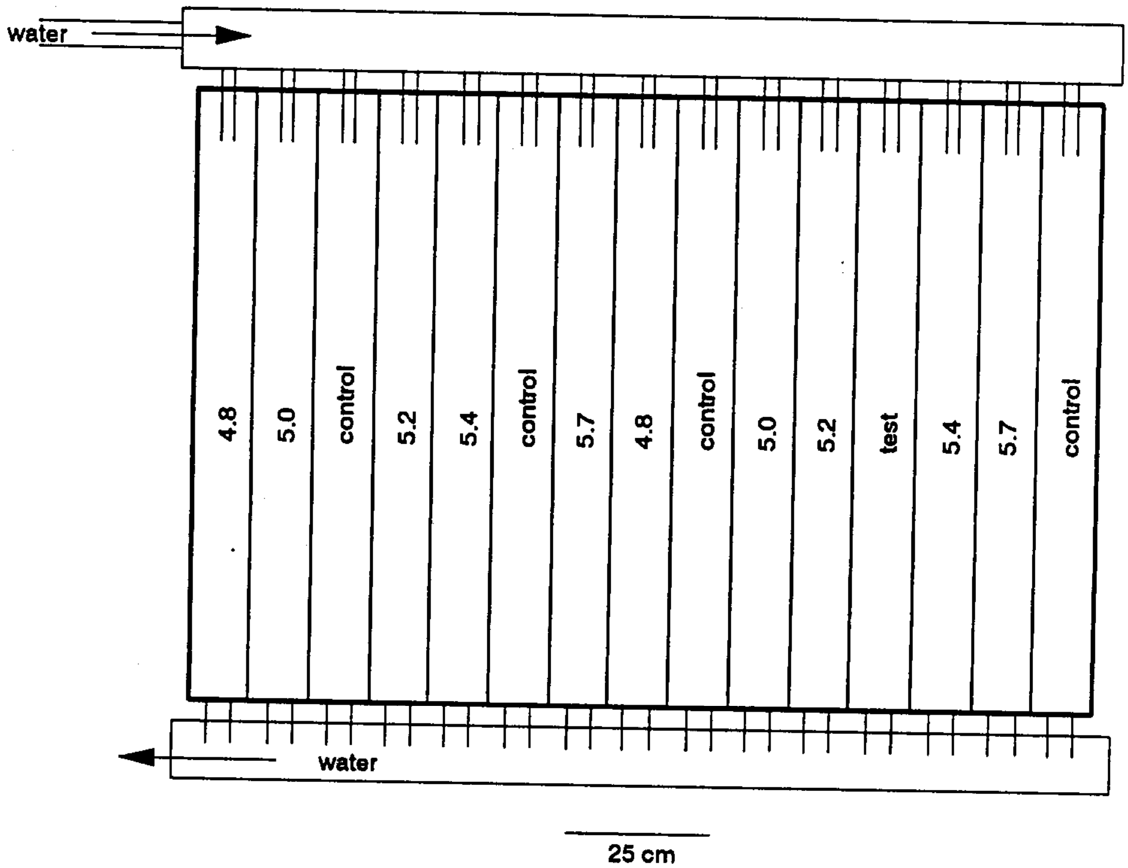

Figure 2.1. A schematic diagram of the stream channels. Each channel is labeled with the pH treatment assigned to it. "Control" channels were unacidified. The single "test" channel was used prior to the experiment to test the acid delivery apparatus and was not used in the experiment.

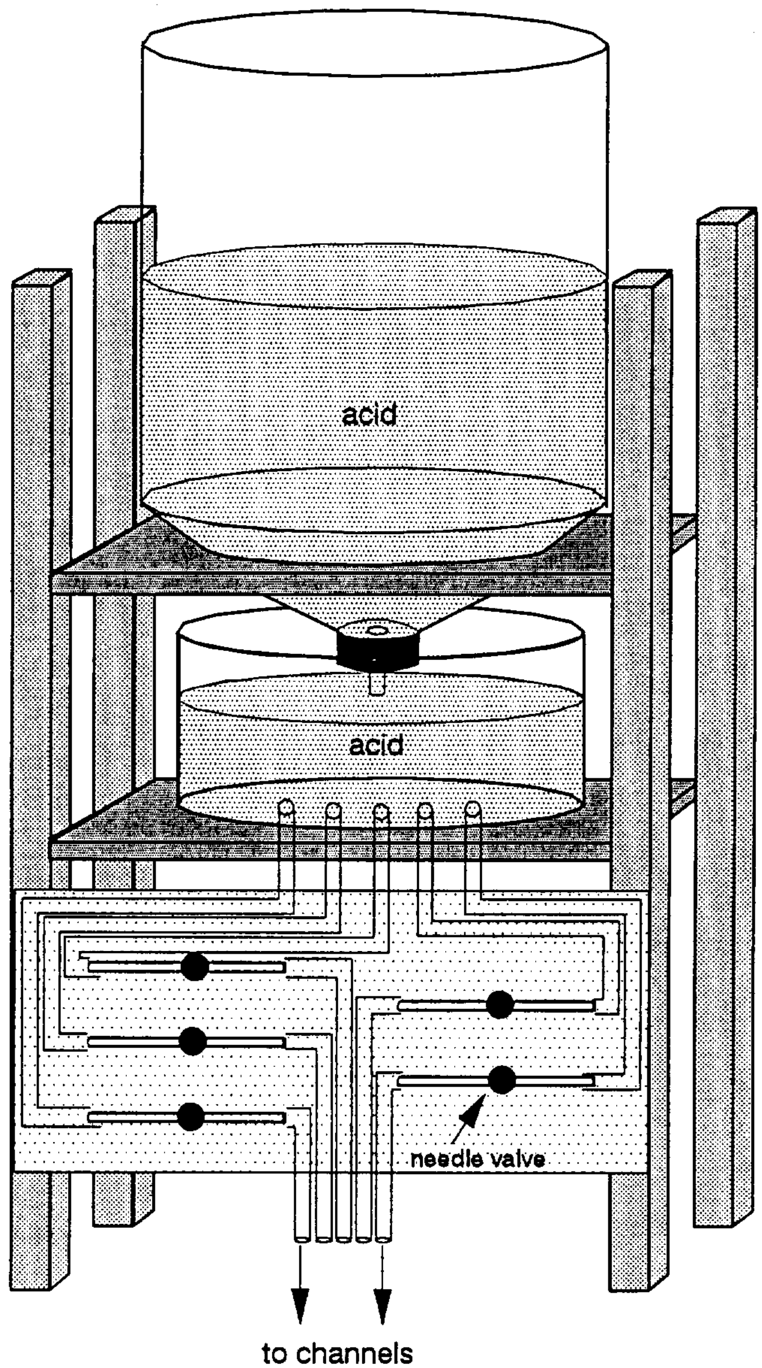

Figure 2.2. A three-dimensional diagram of the acid delivery apparatus.

RESULTS

The concentrations of total and monomeric aluminum predicted from our geochemical model for a range of pH levels are presented in Figure 2.3. Based on this model, potentially toxic concentrations of monomeric aluminum (> 100 μg/l) are expected only at pH < 5.0. Since microcystalline gibbsite is the dominant basin mineral throughout much of the Sierra Nevada (A. Brown, personal communication), these aluminum concentrations should be applicable to many high elevation waters in the Sierra Nevada.

Water and air temperatures and discharge in Mine Creek during summer, 1993, are shown in Figure 2.4. Eggs were buried in the experimental streams when the maximum daily water temperature was approximately 1° C, and removed when the maximum daily water temperature was approximately 6° C (Figure 2.4A). Although the data logger failed to record water temperature during the experimental acidification, temperatures taken with a hand-held thermometer showed that maximum daily water temperature was 4° C during this time. Air temperatures ranged from -7 to 15°C over the experimental period (Figure 2.4B). The experimental acidification was conducted in the middle of the broad snowmelt discharge peak (Figure 2.4C). The low discharges during the experimental acidification were attributable to low air temperatures (Figure 2.4B) which reduced the rate of snowmelt.

Although preliminary tests of the acid delivery system indicated that pH could be maintained within 0.1 pH unit of the target pH, pH levels fluctuated considerably during the experiment (Figure 2.5, Table 2.1). Large fluctuations in pH occurred when nearly-empty acid reservoirs were replaced with full ones. Smaller fluctuations could be attributable to small temporal changes in water chemistry. Correcting deviations from target pH's was problematic, because cold air temperatures made precise needle valve adjustments difficult. Most pH deviations, however, were detected and eliminated relatively quickly. As a result, average channel pH over the duration of the experiment (calculated as the weighted average of hydrogen ion concentration) was always within 0.11 pH units of the target pH, and in 7 of the 10 acidified channels, average channel pH was within 0.05 pH units of the target pH. Field and laboratory pH measurements were not significantly different (one-way ANOVA: $n = 28$, $F_{1,26} = 0.15$, $p > 0.6$).

pH did not differ significantly among treatments before acidification (one-way ANOVA: $n = 14$, $F_{5,8} = 1.75$, $p > 0.2$; Table 2.2) or after acidification (one-way ANOVA: $n = 14$, $F_{5,8} = 0.35$, $p > 0.8$; Table 2.3), but differed significantly among treatments during acidification (one-way ANOVA: $n = 14$, $F_{5,8} = 30.69$, $p = 0.0001$; Table 2.1). ANC was not different among treatments before or after acidification (one-way ANOVA: $n = 14$, $F_{5,8} < 0.8$, $p > 0.5$), but differed significantly among treatments during acidification (one-way ANOVA: $n = 14$, $F_{5,8} =$

229.08, $p < 0.00001$; Figure 2.6). ANC was completely depleted in the low pH treatments. Specific conductance was also similar among all treatments before and after acidification (one-way ANOVA: $n = 14$, $F_{5,8} < 1.91$, $p > 0.1$), but was significantly different among treatments during acidification (one-way ANOVA: $n = 14$, $F_{5,8} = 146.51$, $p < 0.00001$; Figure 2.7). Acid additions increased the conductivity of the water. There were no treatment effects on total dissolved aluminum concentrations before, during, or after acidification (one-way ANOVA: $n = 14$, $F_{5,8} < 2.0$, $p > 0.1$; Figure 2.8).

All major ion concentrations except Mg^{++} were similar among treatments before acidification (Kruskal-Wallis one-way ANOVA; d.f. = 5, KW < 10.8, $p > 0.05$; Table 2.2). Mg^{+2} was lower in control than acidified treatments (Kruskal-Wallis one-way ANOVA; d.f. = 5, KW = 11.25, $p < 0.05$). During acidification, treatment effects were significant only for NO_3^- and SO_4^{-2} (Kruskal-Wallis one-way ANOVA; d.f. = 5, KW > 12.1, $p < 0.04$; Table 2.1), owing to the addition of nitric and sulfuric acid. There were no differences in major ion concentrations among treatments after acidification (Kruskal-Wallis one-way ANOVA; d.f. = 5, KW < 6.1, $p > 0.2$; Table 2.3)

Egg survival among channels was high, averaging 74.8%. There were no differences in egg survival among the 6 pH treatments (one-way ANOVA of arcsine square-root transformed proportions; $n = 14$, $F_{5,8} = 0.81$, $p > 0.5$; Figure 2.9) despite treatment pH levels as low as 4.8. Therefore, golden trout eggs do not appear very sensitive to acid inputs.

Table 2.1. Mean pH and ion concentrations in stream channels and Mine Creek during experimental acidification (July 17, 1993). Ranges (for pH) and standard deviations are given in parentheses.

Sample Location	pH	Cl^- (μeq/l)	NO_3^- (μeq/l)	SO_4^{-2} (μeq/l)	Ca^{+2} (μeq/l)	Mg^{+2} (μeq/l)	Na^+ (μeq/l)	K^+ (μeq/l)
Mine Creek	6.58 (6.47-6.69)	0.5 (0.0)	0.0 (0.0)	8.9 (0.2)	30.0 (0.5)	3.6 (0.1)	8.6 (0.1)	2.4 (0.1)
Control	6.60 (6.25-6.80)	1.2 (1.0)	0.4 (0.8)	9.4 (0.3)	28.9 (0.5)	3.5 (0.0)	8.7 (0.5)	3.0 (0.5)
pH 5.7	5.74 (5.01-6.62)	0.6 (0.4)	4.6 (0.7)	23.6 (0.2)	29.6 (1.4)	3.6 (0.1)	8.4 (0.2)	2.6 (0.1)
pH 5.4	5.35 (4.67-6.18)	0.3 (0.1)	10.4 (0.8)	26.6 (0.4)	30.4 (0.6)	3.6 (0.1)	8.5 (0.1)	2.7 (0.2)
pH 5.2	5.19 (4.89-6.00)	0.2 (0.0)	16.0 (1.0)	29.0 (0.8)	30.6 (1.0)	3.6 (0.1)	8.5 (0.0)	2.6 (0.0)
pH 5.0	5.05 (4.55-5.81)	0.2 (0.0)	18.2 (1.4)	34.8 (1.2)	30.6 (0.8)	3.6 (0.0)	9.4 (0.4)	2.6 (0.1)
pH 4.8	4.84 (4.01-6.02)	0.2 (0.0)	18.8 (0.6)	37.5 (0.1)	30.6 (0.2)	3.6 (0.1)	9.4 (0.4)	3.0 (0.4)

Table 2.2. Mean pH and ion concentrations in stream channels and Mine Creek before experimental acidification (July 9, 1993). Ranges (for pH) and standard deviations are given in parentheses.

Sample Location	pH	Cl^- (μeq/l)	NO_3^- (μeq/l)	SO_4^{-2} (μeq/l)	Ca^{+2} (μeq/l)	Mg^{+2} (μeq/l)	Na^+ (μeq/l)	K^+ (μeq/l)
Mine Creek	6.22 (6.20-6.23)	0.6 (0.1)	1.6 (0.2)	8.8 (0.1)	27.8 (0.4)	3.8 (0.1)	7.3 (0.0)	2.3 (0.1)
Control	6.23 (6.21-6.25)	1.3 (0.1)	3.0 (0.4)	9.4 (0.4)	26.7 (1.1)	3.2 (0.1)	7.5 (0.1)	2.7 (0.4)
pH 5.7	6.26 (6.25-6.26)	1.5 (0.5)	2.0 (0.4)	8.9 (0.2)	26.7 (0.8)	4.0 (0.1)	7.4 (0.1)	2.4 (0.1)
pH 5.4	6.30 (6.26-6.33)	1.6 (0.6)	1.6 (0.2)	9.2 (0.4)	26.9 (0.4)	3.8 (0.1)	7.4 (0.0)	2.2 (0.0)
pH 5.2	6.26 (6.25-6.27)	1.6 (0.4)	1.9 (0.1)	9.0 (0.1)	27.4 (0.1)	3.8 (0.0)	7.3 (0.0)	2.2 (0.0)
pH 5.0	6.23 (6.21-6.25)	1.0 (0.1)	2.0 (0.1)	8.9 (0.0)	26.0 (0.4)	3.8 (0.1)	7.4 (0.1)	2.2 (0.0)
pH 4.8	6.26 (6.23-6.29)	1.2 (0.1)	1.7 (0.1)	9.1 (0.0)	26.0 (0.4)	3.8 (0.1)	7.4 (0.1)	2.4 (0.1)

Table 2.3. Mean pH and ion concentrations in stream channels and Mine Creek after experimental acidification (July 18, 1993). Ranges (for pH) and standard deviations are given in parentheses.

Sample Location	pH	Cl^- (µeq/l)	NO_3^- (µeq/l)	SO_4^{-2} (µeq/l)	Ca^{+2} (µeq/l)	Mg^{+2} (µeq/l)	Na^+ (µeq/l)	K^+ (µeq/l)
Mine Creek	6.44 (6.30-6.58)	0.4 (0.0)	0.0 (0.0)	8.8 (0.2)	28.1 (0.5)	3.5 (0.0)	9.2 (0.0)	2.4 (0.1)
Control	6.75 (6.64-6.79)	0.2 (0.0)	0.0 (0.0)	9.3 (0.4)	28.8 (0.8)	3.6 (0.0)	9.4 (0.0)	2.7 (0.2)
pH 5.7	6.75 (6.71-6.79)	0.2 (0.0)	1.0 (1.0)	9.0 (0.1)	28.8 (0.2)	3.5 (0.0)	9.2 (0.2)	2.5 (0.1)
pH 5.4	6.78 (6.74-6.81)	0.2 (0.0)	0.0 (0.0)	8.9 (0.1)	29.6 (0.4)	3.6 (0.1)	9.4 (0.1)	3.2 (0.2)
pH 5.2	6.76 (6.75-6.76)	0.3 (0.1)	0.8 (0.8)	9.4 (0.1)	29.6 (0.8)	3.6 (0.0)	9.4 (0.1)	2.6 (0.2)
pH 5.0	6.80 (6.79-6.80)	0.2 (0.0)	0.0 (0.0)	9.2 (0.2)	29.6 (0.9)	3.6 (0.0)	9.4 (0.1)	2.9 (0.3)
pH 4.8	6.78 (6.78-6.79)	0.2 (0.0)	0.0 (0.0)	8.8 (0.2)	29.6 (0.6)	3.6 (0.1)	9.2 (0.2)	2.5 (0.1)

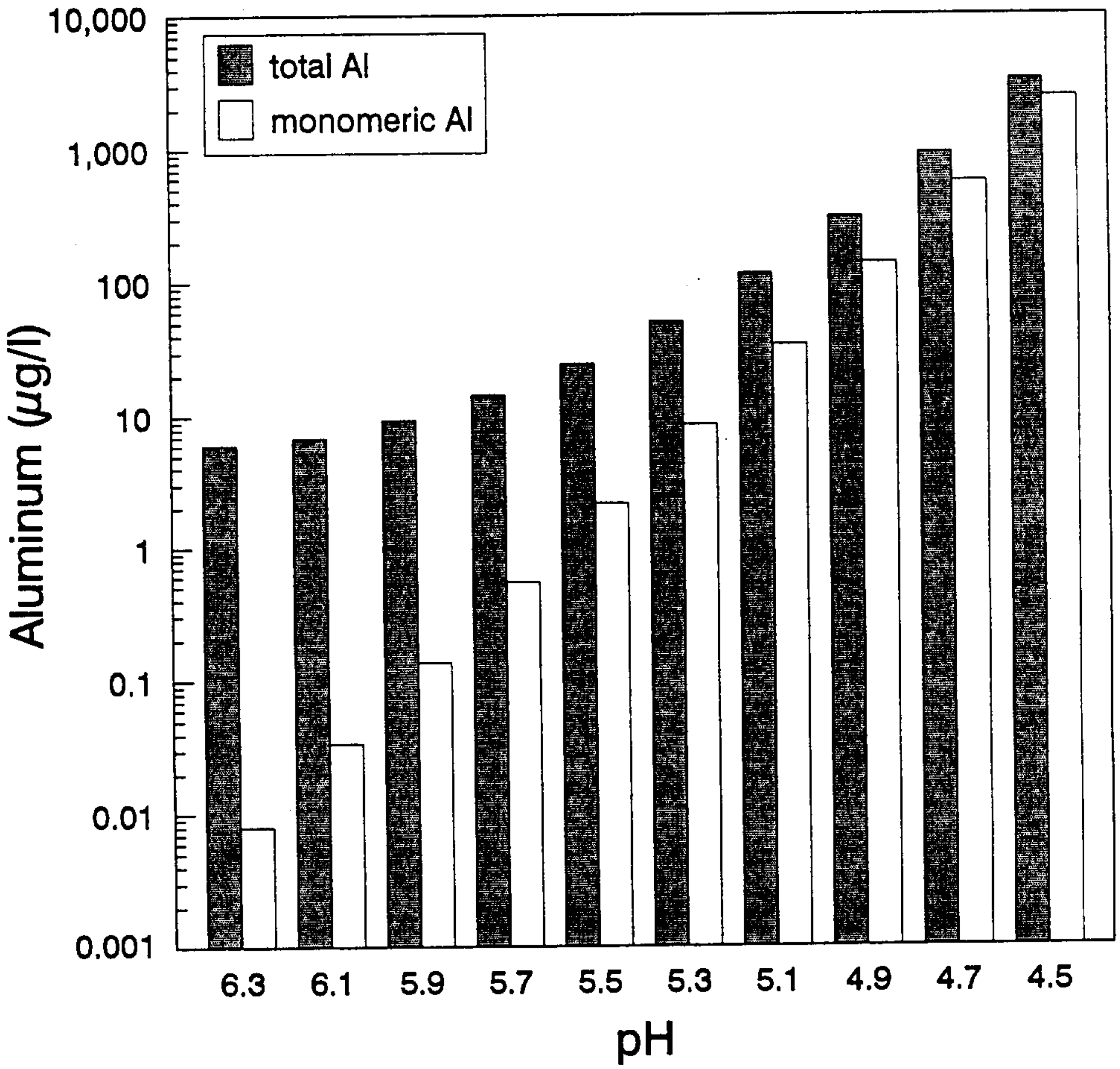

Figure 2.3. Concentrations of total and monomeric aluminum as a function of pH as predicted by a geochemical model of aluminum dissolution in waters in the high elevation Sierra Nevada. Aluminum concentrations are presented on a logarithmic scale.

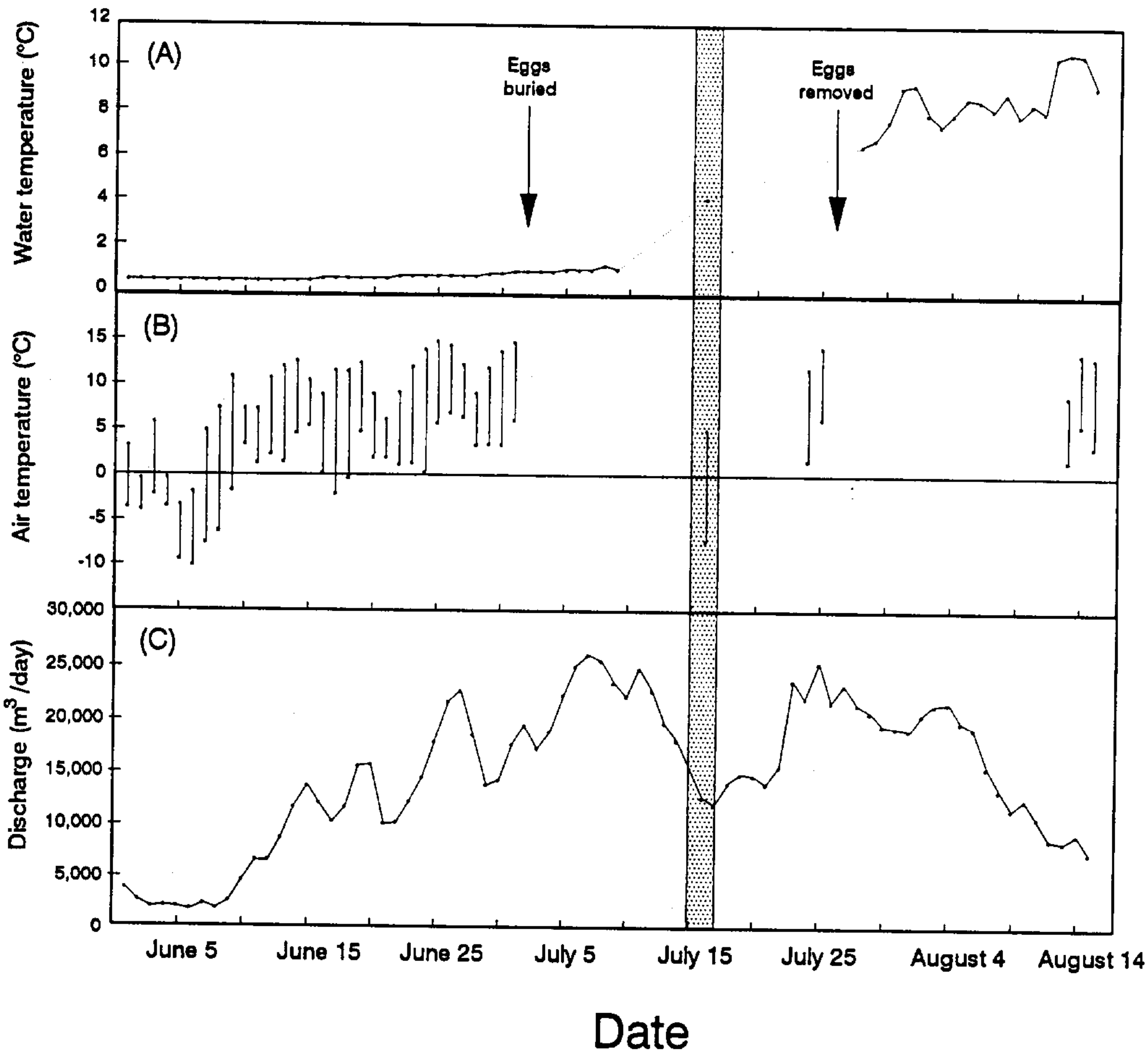

Figure 2.4. (A) Maximum daily water temperatures of Mine Creek; (B) minimum and maximum daily air temperatures; and (C) daily discharge of Mine Creek, measured at a meteorological / hydrological station approximately 100 m upstream of the study site. The stippled area indicates the period of acid addition. The water temperature logger failed to record data from July 10-27. Water temperature shown for July 16 was measured with a hand-held thermometer. The air temperature logger failed to record data from July 3-23 and July 26-August 12. Air temperature shown for July 16 was measured with a hand-held thermometer.

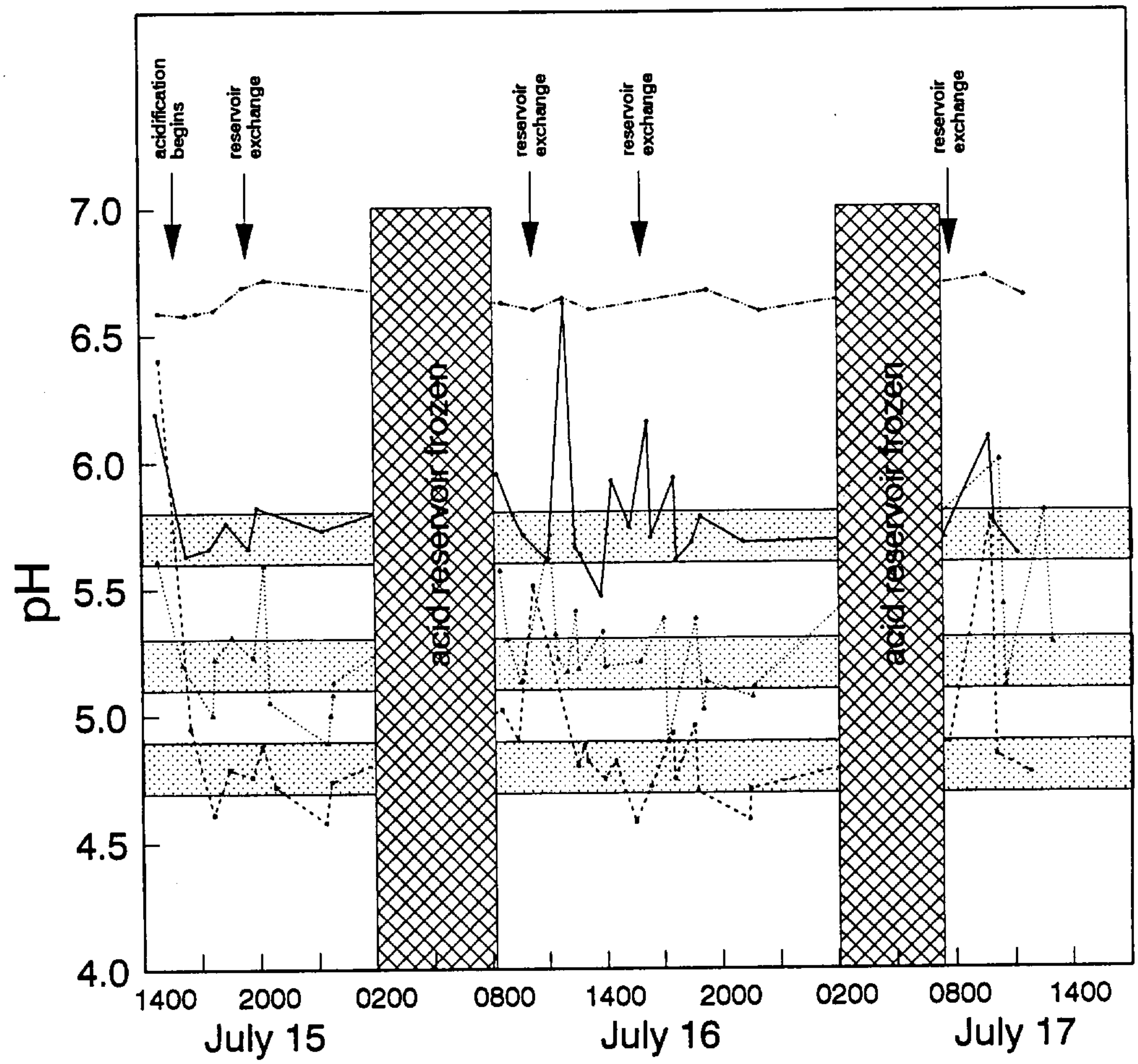

Figure 2.5. pH levels during the acidification experiment in one of the four control channels and three of the ten acidified channels. The channels shown were chosen at random from the pH 6.6 (control), 5.7, 5.2, and 4.8 treatments. The stippled areas delineate the target pH for each acidified channel. The x-axis is time of day. Arrows labeled "reservoir exchange" indicate the times at which acid reservoirs were exchanged. The cross-hatched areas indicate times when acid deliveries stopped because of frozen acid reservoirs.

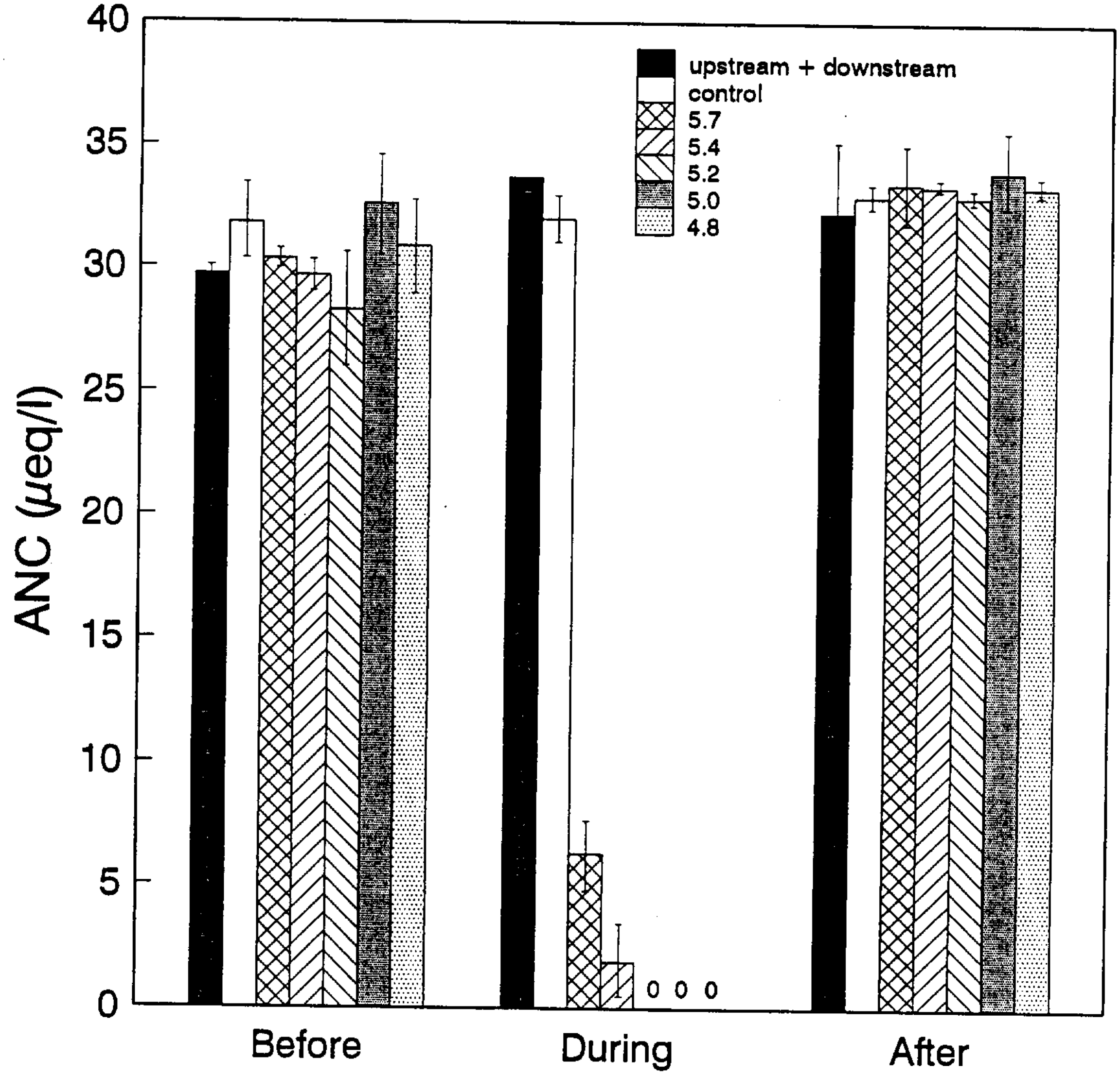

Figure 2.6. Acid neutralizing capacities (ANC; μeq/l) in the experimental channels and Mine Creek upstream and downstream of the channel outfall before, during, and after acidification. Error bars indicate ±1 standard error for the 2-4 replicate channels. The lack of an error bar indicates that the standard error was less than 0.1 μeq/l.

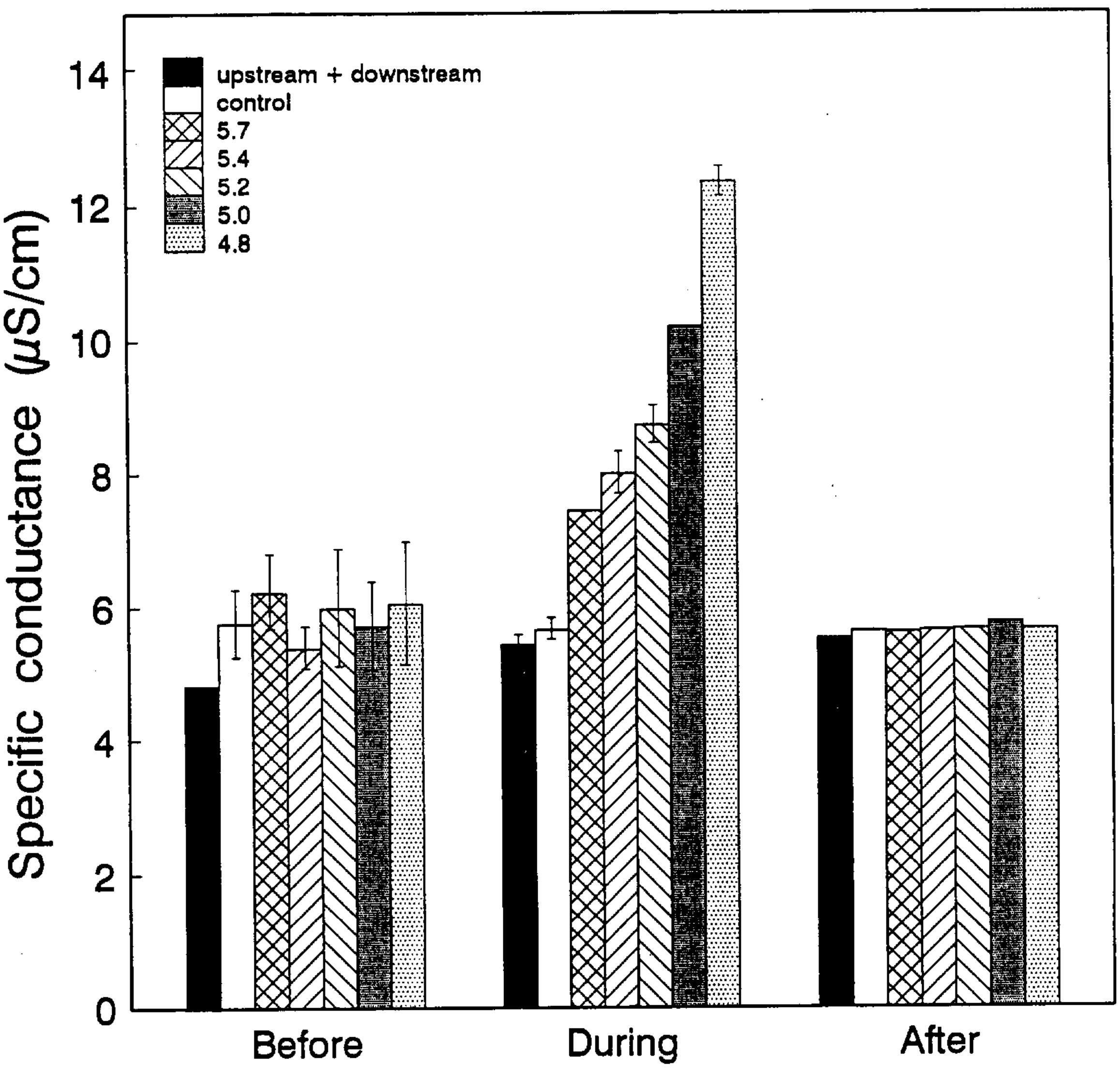

Figure 2.7. Specific conductance (µS/cm) in the experimental channels and Mine Creek upstream and downstream of the channel outfall before, during, and after acidification. Error bars indicate ±1 standard error for the 2-4 replicate channels. The lack of an error bar indicates that the standard error was less than 0.1 µS/cm.

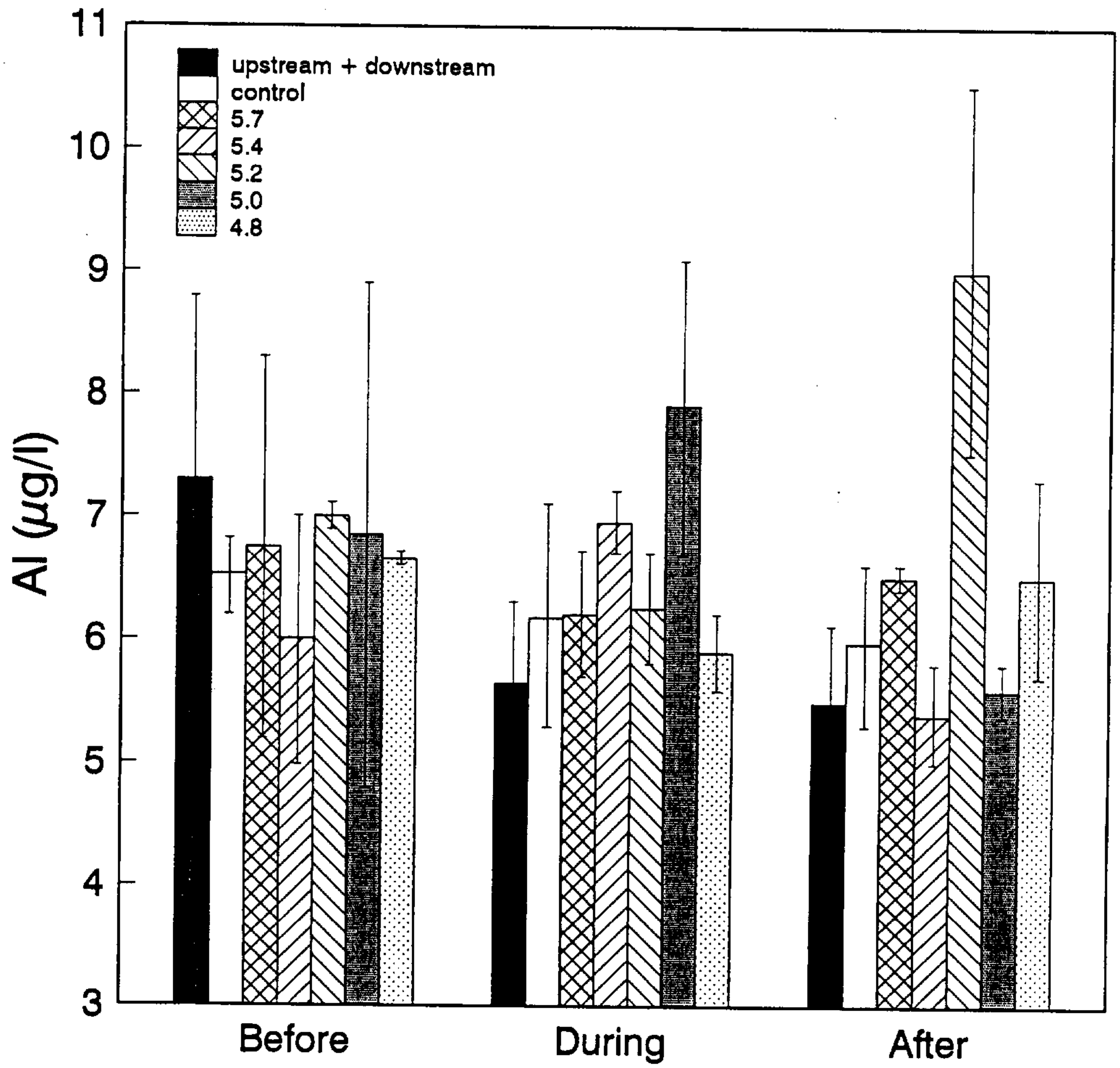

Figure 2.8. Aluminum concentrations (μg/l) in the experimental channels and Mine Creek upstream and downstream of the channel outfall before, during, and after acidification. Error bars indicate ±1 standard error for the 2-4 replicate channels.

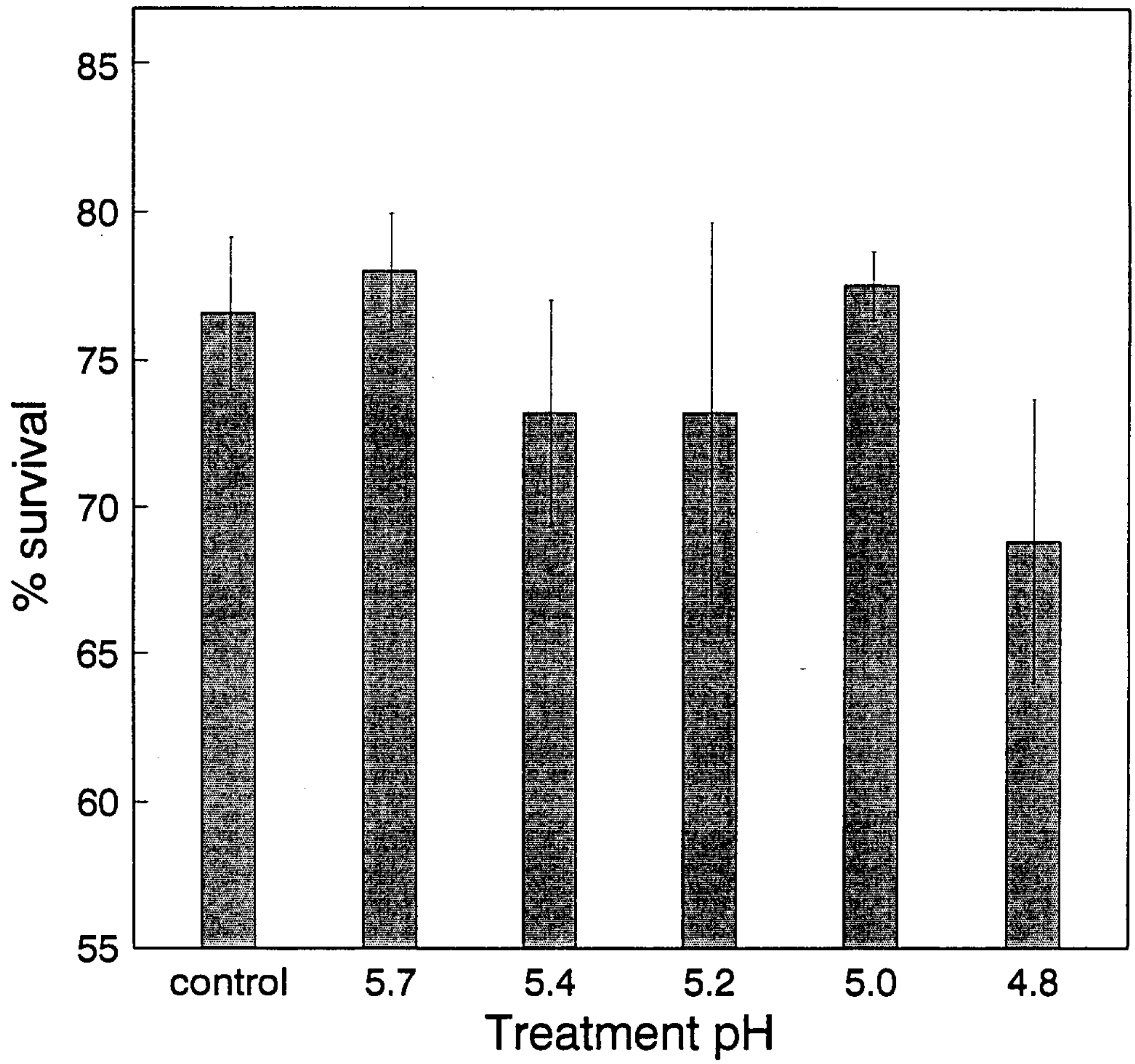

Figure 2.9. Percent survival of newly-fertilized golden trout eggs as a function of pH in the experimental channels. Error bars indicate ±1 standard error for the 2-4 replicate channels. Eggs were excavated and viability determined 9-10 days after the experimental acid pulse ended.

DISCUSSION AND CONCLUSIONS

Our results support the findings of a laboratory bioassay on golden trout eggs that showed that no significant mortality occurred until pH was reduced to 4.5 (DeLonay et al. 1993). Newly-fertilized eggs of other trout species subjected to laboratory acid additions, including brook, cutthroat, lake, and brown trout, show a similar tolerance of acid inputs, with significant mortality occurring only at pH 4.5 in the absence of aluminum (brook trout: Cleveland et al. 1986; Hutchinson et al. 1989; cutthroat trout: Woodward et al. 1989, Woodward et al. 1991; lake trout: Hutchinson et al. 1989; brown trout: Brown 1983).

The similarity of our field results with the laboratory results of DeLonay et al. (1993) despite the different rearing conditions between the two experiments, suggests that highly artificial laboratory conditions do not result in underestimates of the influence of acid inputs on the survival of early trout stages. Water temperatures to which eggs were exposed were particularly different between the field and laboratory bioassays. DeLonay et al. (1993) held newly-fertilized eggs at 10°C during their experiment, whereas eggs in our experiment were held at 1-6°C. Golden trout living above 2500 m in the Sierra Nevada begin spawning as soon as ice on lakes and streams begins breaking up (Curtis 1934; California Department of Fish and Game, personal communication; R.A. Knapp, personal observation), so exposure temperatures were probably more realistic in our experiment. The existing literature, however, appears equivocal on the influence of temperature on the survival of early life stages of fish. Robinson et al. (1976), Falk and Dunson (1977), Korwin-Kossakowski and Jezierska (1985), and Gunn (1986) all suggested that low water temperatures decreased acid toxicity, but Parkhurst et al. (1990), in a carefully controlled laboratory experiment, found no relationship between water temperature and acid toxicity to early life stages of trout.

The relative insensitivity of golden trout eggs to pH levels between 6.6 and 4.8 suggests that egg survival would not be affected by foreseeable increases in acid deposition in the Sierra Nevada. Since the egg stage of golden trout is the most vulnerable to acid inputs (DeLonay et al. 1993), golden trout would probably not serve as a good indicator of acid stress. It might be argued that the absence of aluminum inputs in our experiment could underestimate the impact of increased acid deposition on golden trout. Based on our geochemical model of the rates of aluminum dissolution in granitic Sierran watersheds and the results of DeLonay et al. (1993), we do not believe that aluminum concentrations under severe surface water acidification (pH = 5.0) would have a significant impact on golden trout eggs or yolk-sac larvae. DeLonay et al. (1993) reported that golden trout eggs do not show any significant mortality at pH 5.0 even with a monomeric aluminum concentration of 300 µg/l. (DeLonay et al. [1993] present only total aluminum values, but studies done by Woodward et al. [1991] using the identical dosing methods showed that concentrations of total aluminum and inorganic monomeric aluminum in the test water were very similar at pH 5). Yolk-sac larvae showed no significant mortality at pH 5.0 with 100 μg/l of aluminum, and significant mortality at pH 5.0 occurred only at an aluminum concentration of 300 μg/l. Our geochemical model, however, predicts that the concentration of monomeric aluminum in high elevation Sierra Nevada waters would be only 68.5 μg/l at pH 5.0, substantially below the toxicity threshold for golden trout eggs or yolk-sac larvae. Therefore, even in the event of episodic pH depressions to 5.0 in the Sierra Nevada, neither acid nor aluminum would likely have an impact on the survival of golden trout eggs or yolk-sac larvae.

The increased sensitivity of swim-up larvae to aluminum relative to eggs or yolk-sac larvae (DeLonay et al. 1993) may make this life stage vulnerable at pH 5.0. It does not appear, however, that this life stage would ever experience the reduced pH levels associated with snowmelt. The spawning period of golden trout living in the high elevation Sierra Nevada usually coincides with, or immediately follows, peak snowmelt (Curtis 1934; California Department of Fish and Game, personal communication; R.A. Knapp, personal observation). Eggs and, perhaps, yolk-sac fry would be subject to episodic pH depressions associated with snowmelt, but swim-up larvae would not, since they would not be present in streams until at least August (emergence time for rainbow trout is 52 days at 12°C; Bjornn and Reiser 1991). This may apply to all species of spring-spawning salmonids living at high elevations, because observations of spawning at high elevation sites in the Rocky Mountains show similar patterns (Van Velson 1985). Swim-up larvae would be subject to episodic pH depressions associated with summer rain storms, but it is not known how brief pH depressions associated with such events affect later developmental stages of trout. Nor is it certain that dissolved aluminum would rise significantly in stream gravels during a low-pH rainstorm of a few minutes or hours.

Although our study confirms the findings of previous studies on the tolerance of early stages of golden trout to low pH conditions, additional field experiments maintaining constant pH and aluminum levels could quantify the effects of acid pulse duration on the survival of early life stages of golden trout. Correlational bioassays could be conducted in the Sierra Nevada where eggs are placed in several streams that vary naturally in acidity (Bradford et al. 1993). Streams in the Bench Lake area of the Sierra Nevada lie in a watershed that is primarily granitic, but which contains several small outcrops of metamorphic rock rich in iron pyrite. These rocks release sulfate ions, and depending on the relative mix of metamorphic and granitic rocks in basins, receiving streams can have pH levels ranging from 6.5 to approximately 4.2. Given this situation, it would be relatively simple to bury eggs in streams differing in pH and aluminum concentrations. Such bioassays could eliminate the difficulties we experienced in maintaining constant pH levels, would expose eggs to realistic aluminum concentrations, and assays could be run for much longer periods than were possible with our experimental set up. Results from such an experiment, combined with the results of field experiments and published laboratory bioassays would allow us to construct models estimating the effect of increased acid deposition on populations of golden trout.

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Watt, W.D., C. Scott, and W.H. White. 1983. Evidence of acidification of some Nova Scotian rivers and its impact on Atlantic salmon, *Salmo salar*. Can. J. Fish. Aquat. Sci. 40: 462-473.

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Zischke, J.M., J. Arthur, K. Norlie, R. Hermanuts, D. Stunden, and T. Henry. 1983. Acidification effects on macroinvertebrates and fathead minnows (*Pimephales promelas*) in outdoor experimental channels. Water Res. 17: 47-64.

Appendix A. Additional details concerning lakes and their fish populations: Note: Golden trout are termed *O. aguabonita* in this appendix, the name that prevailed until they were included with rainbow trout in *O. mykiss* (Behnke 1992, see references Pt. II)

Lake: 1--Birch Lake.

Vegetation in Lake Basin: Stunted willow and meadow around lake.

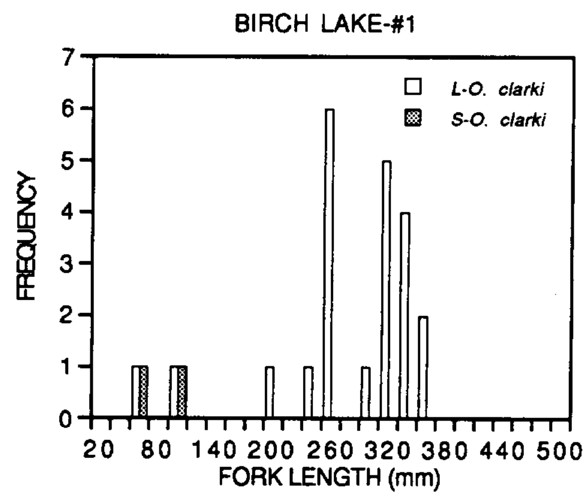
Physical Character of Littoral Zone: broken rock to sand.

Oxygen and Temperature Profiles on 10 July 90: No information

Observations on Basin Geology: Appeared to be primarily roof pendant metamorphic.

Characteristics of Fish Samples:

Size of fish of indicated species in lake (L) and outlet stream (S).



History of Fish Populations: No record of first plant, but cutthroat trout were common in a 1948 survey. Rainbow trout were stocked in 1946, 1953, and 1980. Lahontan cutthroat trout are stocked periodically at present. All fish in lake appear to be cutthroat, and some reproduction is occurring in the short outlet.

Appendix A. Additional details concerning lakes and their fish populations

Lake: 2--"Diamond" Lake.

Vegetation in Lake Basin: Some annual plants, but no grass or perennial vegetation.

Physical Character of Littoral Zone: Broken rock.

Oxygen and Temperature Profiles on 16 July 91 : None available. Lake mostly ice-covered at time of visit.

Observations on Basin Geology: Igneous intrusive and roof pendant metamorphics.

Characteristics of Fish Samples:

History of Fish Populations: No fish in lake, and no record of plants. This lake is inaccessible to stock, and dangerous on foot. It presumably cannot be planted by airplane due to the high canyon walls. The outlet flows under a long, treacherous talus that might have kept frogs from reaching the lake.

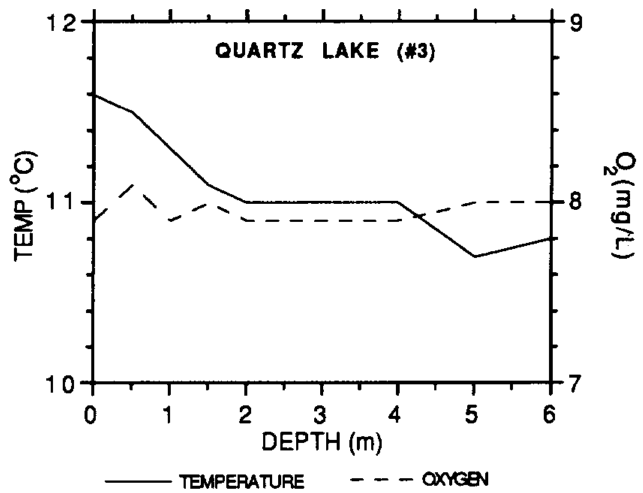
Appendix A. Additional details concerning lakes and their fish populations

Lake: 3--"Quartz" Lake.

Vegetation in Lake Basin: Some grass and whitebark pine, but mostly barren.

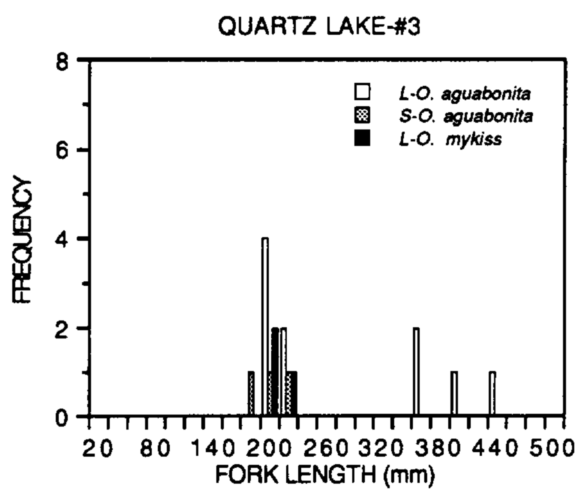
Physical Character of Littoral Zone: Broken rock and bedrock slabs.

Oxygen and Temperature Profiles on 24 July 91:



Observations on Basin Geology: Light-colored intrustive igneous, but unusually friable. Many deposits of quartz boulders in the area.

Characteristics of Fish Samples:



History of Fish Populations: No records of plants available. Probably planted in the 1920's.

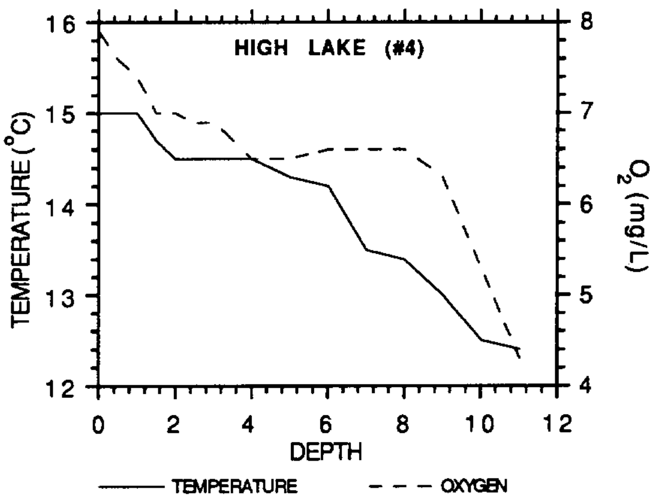
Appendix A. Additional details concerning lakes and their fish populations

Lake: 4--High Lake.

Vegetation in Lake Basin: Meadow around shore; stunted willow

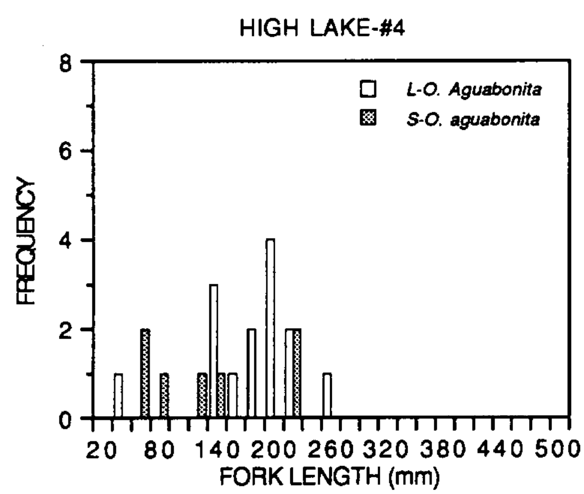
Physical Character of Littoral Zone: Sandy, broken rock.

Oxygen and Temperature Profiles on 12 July 90:



Observations on Basin Geology: Intrusive igneous.

Characteristics of Fish Samples:



History of Fish Populations: Date of original plant unknown, but possibly in late 1800s when nearby Cottonwood Lakes were stocked. Self-sustaining population in 1949, but planted with 2000 fingerlings biennially since 1955.

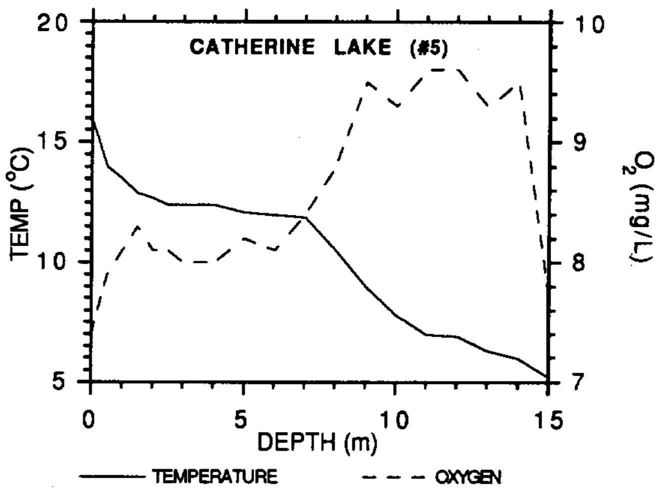
Appendix A. Additional details concerning lakes and their fish populations

Lake: 5--Catherine (also known as Tamarack) Lake.

Vegetation in Lake Basin: Meadow fringe on lake.

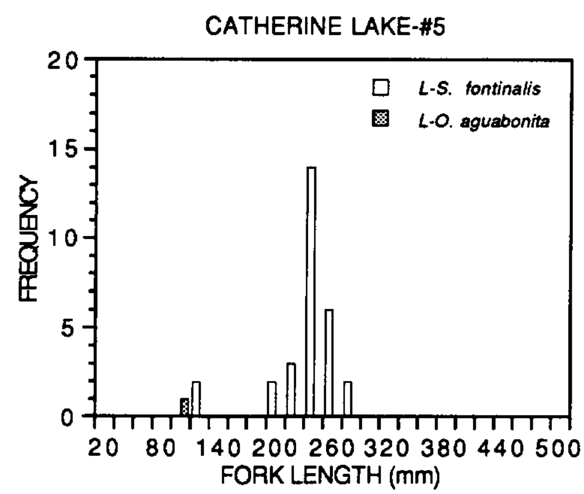
Physical Character of Littoral Zone: broken rock and bedrock slab. Some sand.

Oxygen and Temperature Profiles on 30 July 90:



Observations on Basin Geology: Dark metamorphic rock with granitic outcroppings.

Characteristics of Fish Samples:



History of Fish Populations: Planted with brook trout in 1944 and perhaps much earlier. Planted biennially with golden trout since 1956; brook trout are self-sustaining, and far larger and more numerous..

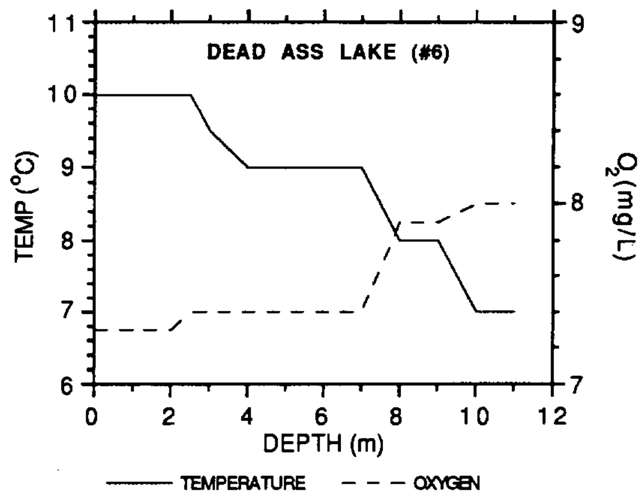
Appendix A. Additional details concerning lakes and their fish populations

Lake: 6--"Dead Ass" Lake.

Vegetation in Lake Basin: meadow fringing part of lake.

Physical Character of Littoral Zone: sand and broken rock.

Oxygen and Temperature Profiles on 6 Aug 91:



Observations on Basin Geology: Igneous intrusive.

Characteristics of Fish Samples: No fish.

History of Fish Populations: No record of stocking. More accessible lakes nearby were barren in 1934, but most have since been planted. Many bones of dead pack animals suggest that fisherman visited lake in the last century.

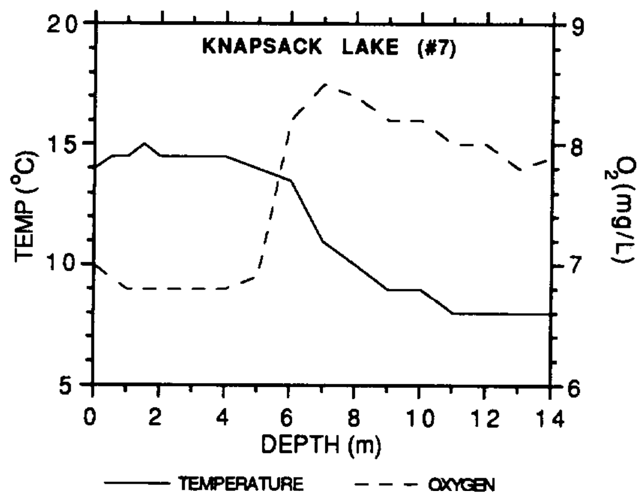
Appendix A. Additional details concerning lakes and their fish populations

Lake: 7--"Knapsack" Lake.

Vegetation in Lake Basin: Meadow around lake.

Physical Character of Littoral Zone: Broken rock and sand.

Oxygen and Temperature Profiles on 30 July 91:



Observations on Basin Geology: Igneous intrusive.

Characteristics of Fish Samples: No fish. Extremely large numbers of *Rana muscosa*.

History of Fish Populations: Due to its location, it is highly unlikely that it was ever planted, and it is probably never visited.

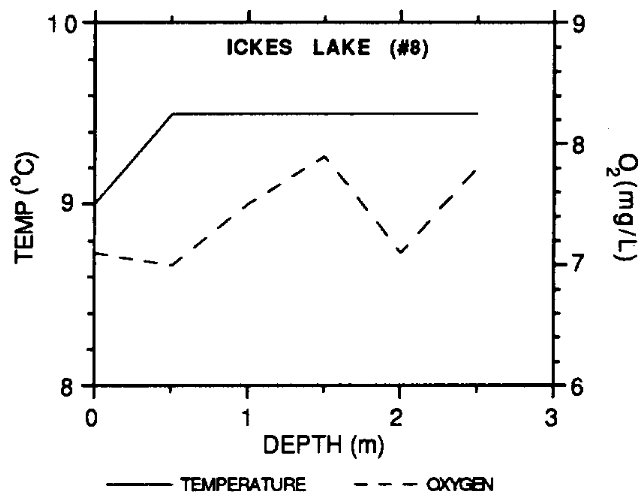
Appendix A. Additional details concerning lakes and their fish populations

Lake: 8--"Ickes" Lake.

Vegetation in Lake Basin: None evident.

Physical Character of Littoral Zone: Broken rock.

Oxygen and Temperature Profiles on 9 Sept 91:



Observations on Basin Geology: Looks like metavolcanic or metasedimentary, with outcroppings of granitic rocks.

Characteristics of Fish Samples: No fish.

History of Fish Populations: No information. Probably never planted.

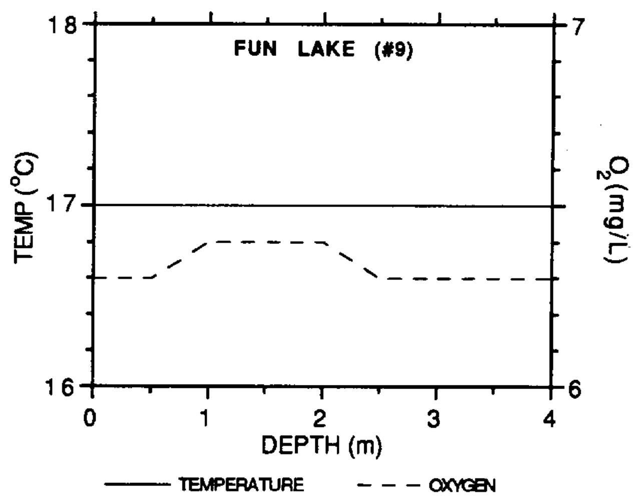
Appendix A. Additional details concerning lakes and their fish populations

Lake: 9--"Fun" Lake.

Vegetation in Lake Basin: Lodgepole forest and large meadow at inlet.

Physical Character of Littoral Zone: Emergent grasses, mud, large boulders.

Oxygen and Temperature Profiles on 4 Sept 91:



Observations on Basin Geology: Igneous intrustive.

Characteristics of Fish Samples: No fish.

History of Fish Populations: Probably never planted. No information available.

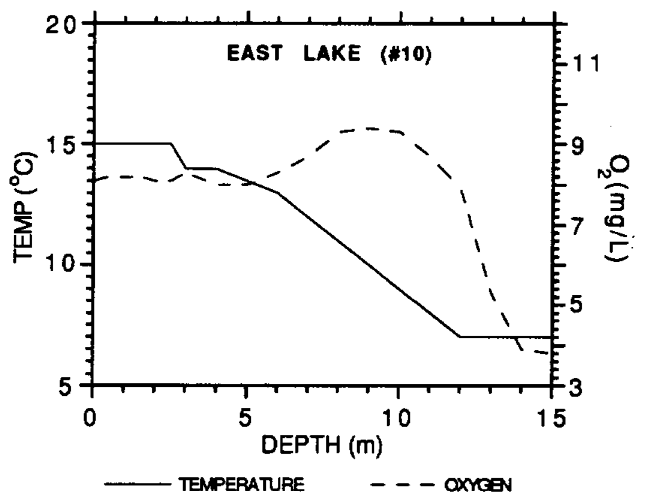
Appendix A. Additional details concerning lakes and their fish populations

Lake: 10--East Lake.

Vegetation in Lake Basin: Lodgepole forest with willows along stream.

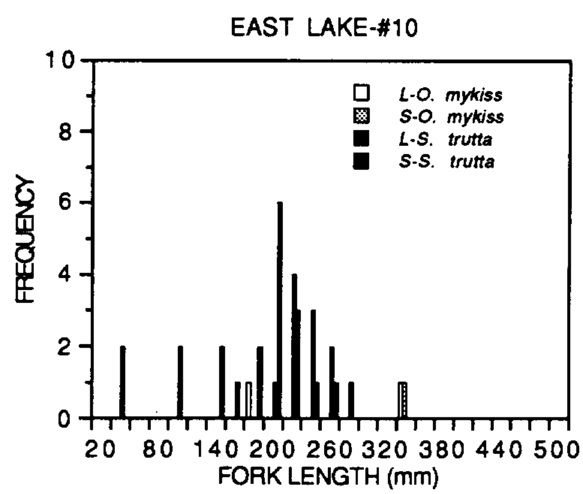
Physical Character of Littoral Zone: Sand, mud, log jams.

Oxygen and Temperature Profiles on 20 Aug 91:



Observations on Basin Geology: Igneous intrusive with possibly some metamorphic.

Characteristics of Fish Samples:



History of Fish Populations: Rainbow trout were planted in 1931, 1932, 1933, 1934. Brown trout were planted in 1930 and 1931. Brook trout were planted in 1930 and never observed subsequently. Evidently not planted at present.

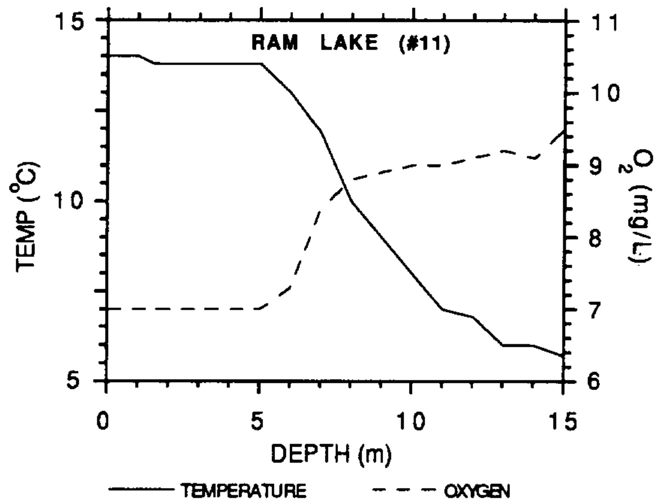
Appendix A. Additional details concerning lakes and their fish populations

Lake: 11--Ram Lake.

Vegetation in Lake Basin: Whitebark pine, fringing meadow.

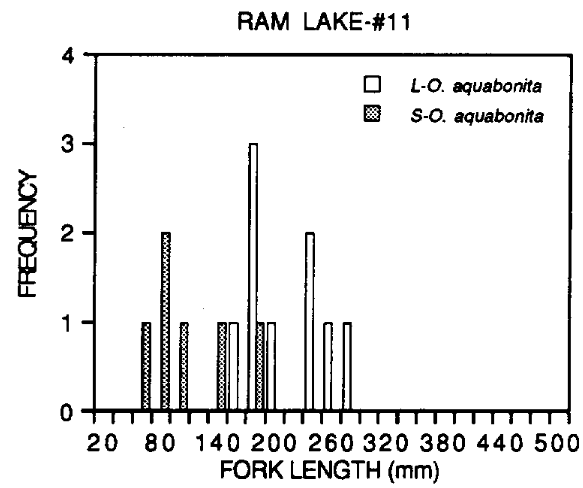
Physical Character of Littoral Zone: Broken rock and sand.

Oxygen and Temperature Profiles on 16 July 90:



Observations on Basin Geology: Igneous intrusive.

Characteristics of Fish Samples:



History of Fish Populations: Golden trout were present when it was surveyed in 1953, but they were obviously introduced much earlier. Evidently natural reproduction in the inlet sustains the population.

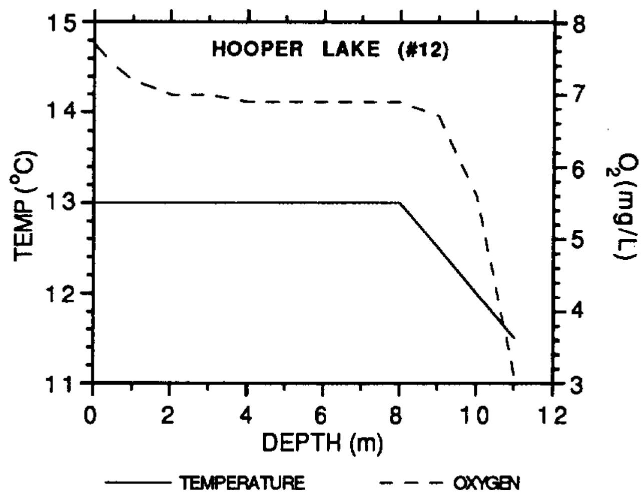
Appendix A. Additional details concerning lakes and their fish populations

Lake: 12--Hooper Lake.

Vegetation in Lake Basin: Whitebark pine, willows, meadow grasses.

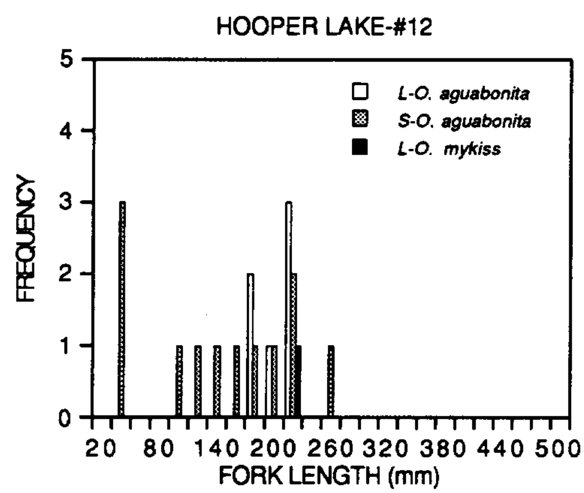
Physical Character of Littoral Zone: Broken rock and sand.

Oxygen and Temperature Profiles on 27 July 91:



Observations on Basin Geology: Igneous intrusive.

Characteristics of Fish Samples:



History of Fish Populations: No information on history, but it is stocked with 2000 golden trout every 3 years.

Appendix A. Additional details concerning lakes and their fish populations

Lake: 13--Merriam Lake.

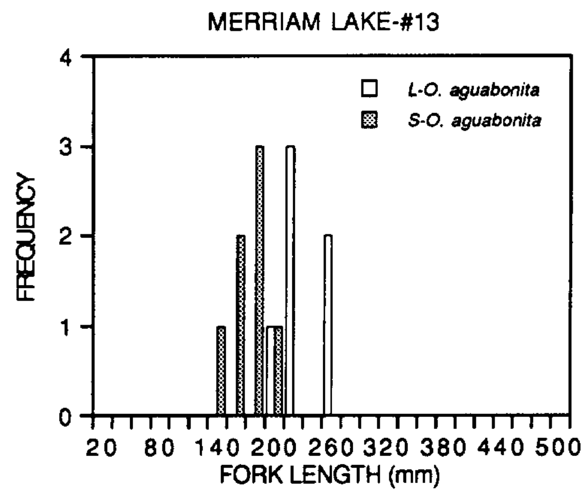
Vegetation in Lake Basin: Whitebark pine.

Physical Character of Littoral Zone: Broken rock.

Oxygen and Temperature Profiles: Not available.

Observations on Basin Geology: Igneous intrusive.

Characteristics of Fish Samples on 10 July 91:



History of Fish Populations: No record of planting, but contained a reproducing population of golden trout in 1951. Probably planted in 1920s by packers.

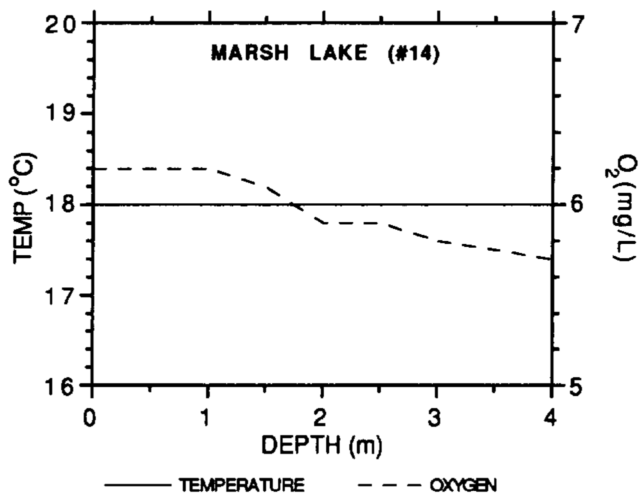
Appendix A. Additional details concerning lakes and their fish populations

Lake: 14--Marsh Lake.

Vegetation in Lake Basin: Lodgepole, willows, emergent grasses.

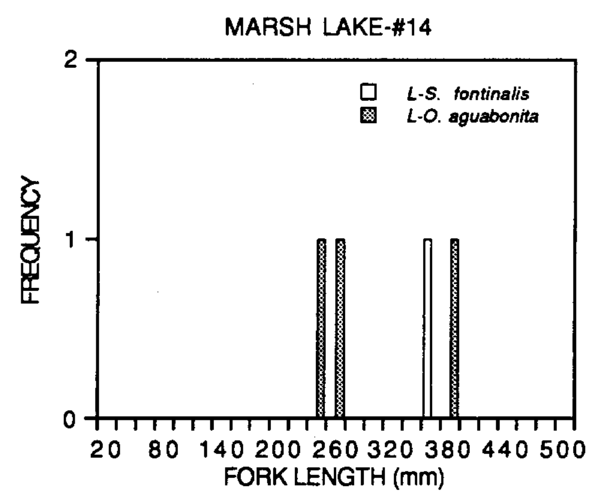
Physical Character of Littoral Zone: bedrock, mud and emergent grass.

Oxygen and Temperature Profiles on 13 Aug 91:



Observations on Basin Geology: Igneous intrusive.

Characteristics of Fish Samples:



History of Fish Populations: No information, but absence of young fish suggests that both brook trout and golden trout might be planted every few years.

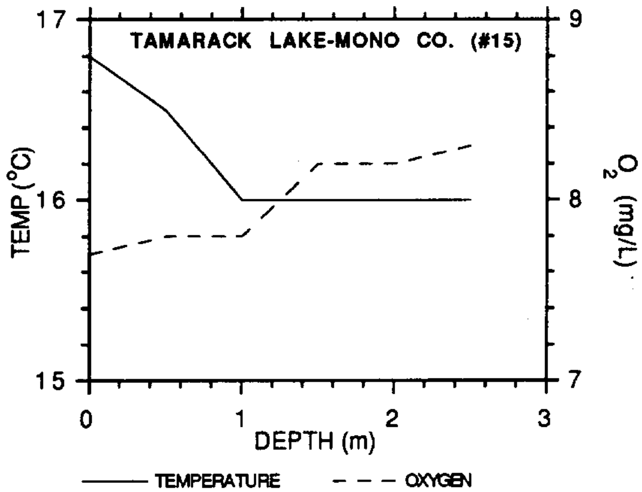
Appendix A. Additional details concerning lakes and their fish populations

Lake: 15--Tamarack Lake (Bridgeport).

Vegetation in Lake Basin: Lodgepole pine, willows.

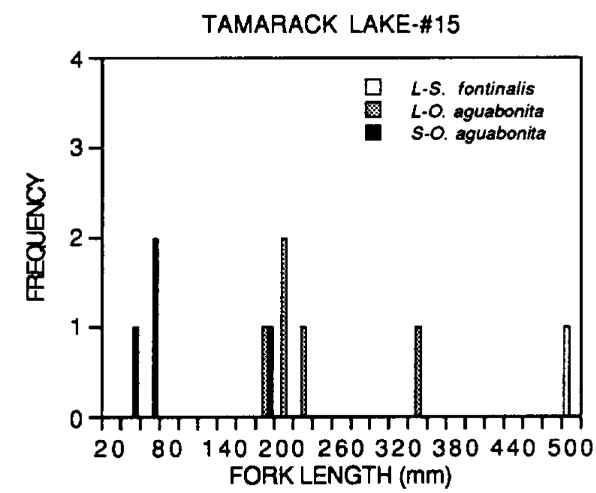
Physical Character of Littoral Zone: Broken rock.

Oxygen and Temperature Profiles on 13 Aug 90:



Observations on Basin Geology: Mixed, with mostly volcanic and metamorphic.

Characteristics of Fish Samples:



History of Fish Populations: Native cutthroat trout planted by rancher in 1874. Native sucker planted as forage fish in 1879. 1932-1948 brook trout stocked. Poisoned in 1949 to remove suckers. Re-stocked with rainbow trout in 1950. Accidently re-poisoned in 1952, killing most brook trout and all rainbow trout. No fish in 1955. Golden trout stocked from 1955 to present, but brook trout and golden trout are reproducing to some degree.

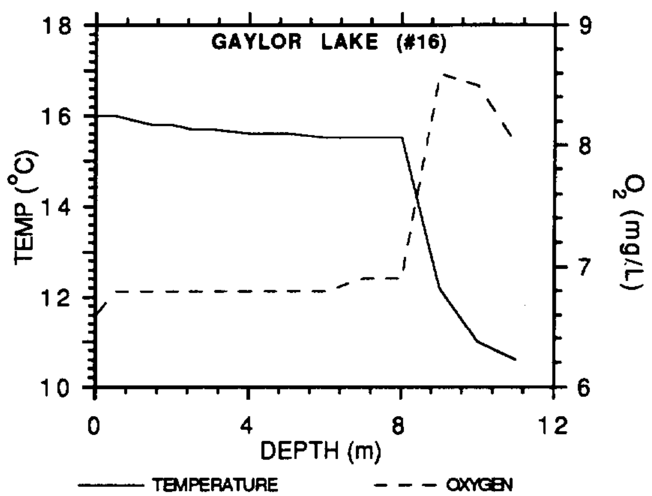
Appendix A. Additional details concerning lakes and their fish populations

Lake: 16--Lower Gaylor Lake.

Vegetation in Lake Basin: Whitebark pine and grass.

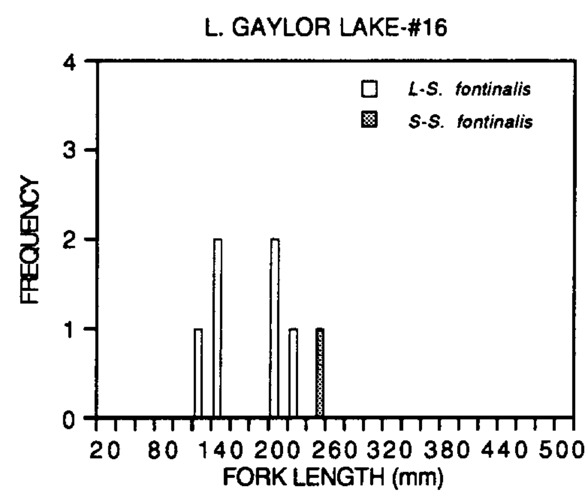
Physical Character of Littoral Zone: Sand and broken rock.

Oxygen and Temperature Profiles on 27 July 90:



Observations on Basin Geology: Mixed volcanic and igneous intrusive.

Characteristics of Fish Samples:



History of Fish Populations: Brook trout planted from 1947-1953, and in 1971. Rainbow trout planted from 1956-1972. Cutthroat trout planted in 1930 and perhaps later. Little or no spawning gravel in outlet or inlet, so only brook trout are reproducing in the lake.

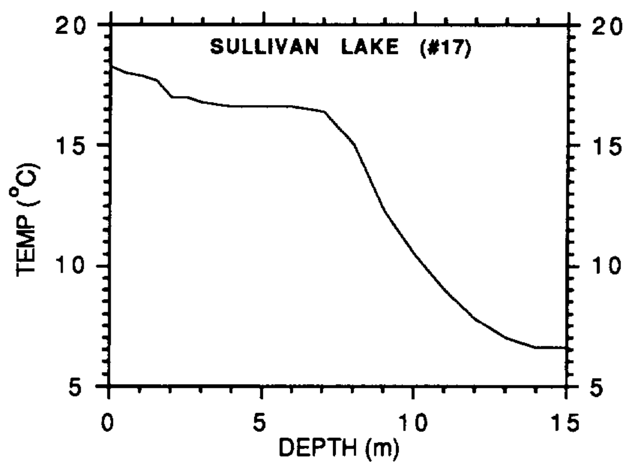
Appendix A. Additional details concerning lakes and their fish populations

Lake: 17--Sullivan Lake.

Vegetation in Lake Basin: Lodgepole, willows.

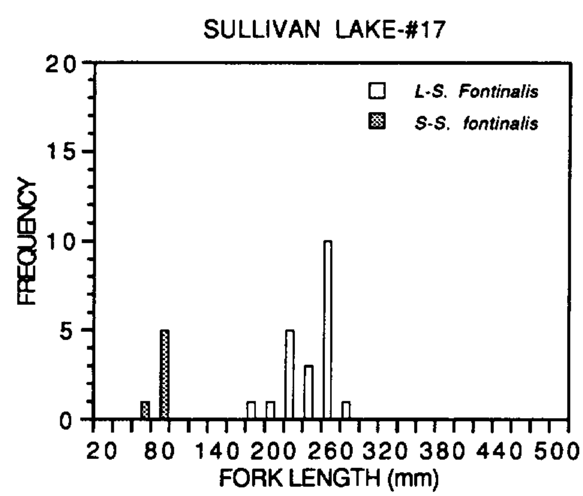
Physical Character of Littoral Zone: Mud, sand, log jams, bedrock slabs

Oxygen and Temperature Profiles on 2 Aug 90:



Observations on Basin Geology: Igneous intrusive and volcanic.

Characteristics of Fish Samples:



History of Fish Populations: Rainbow trout planted in 1941, 1943-1946, 1952-1959. Brook trout planted in 1942 and 1947-1948. Planting stopped in 1959. Probably only brook trout can reproduce, in the lake.

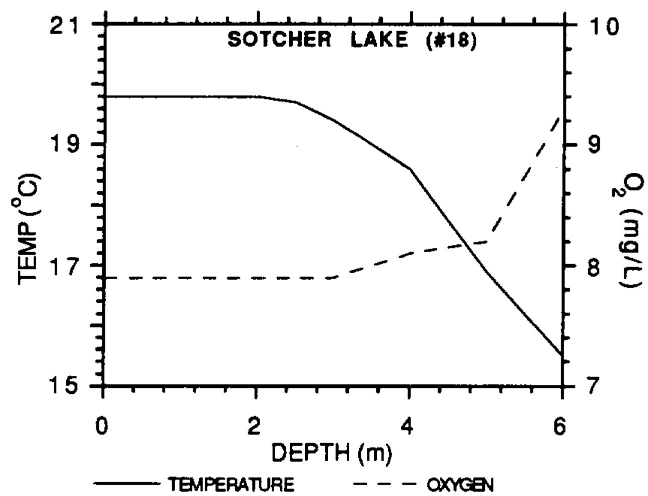
Appendix A. Additional details concerning lakes and their fish populations

Lake: 18--Sotcher Lake.

Vegetation in Lake Basin: Lodgepole, red fir, aspen and willow.

Physical Character of Littoral Zone: Bedrock slab, mud, sand, log jams and emergent grass.

Oxygen and Temperature Profiles on 23 July 90:



Observations on Basin Geology: Volcanic.

Characteristics of Fish Samples: No samples taken due to presence of endangered species. We collected brown trout, rainbow trout and tui chub (the endangered species) with a boat electrofishing apparatus.

History of Fish Populations: Stocked with fingerling or catchable-size rainbows starting in 1942, continuing to present. Brown trout were planted in 1962, 1963, 1965, 1966 and 1967. Limited spawning in inlets, but outlet stream apparently produces large numbers of young.

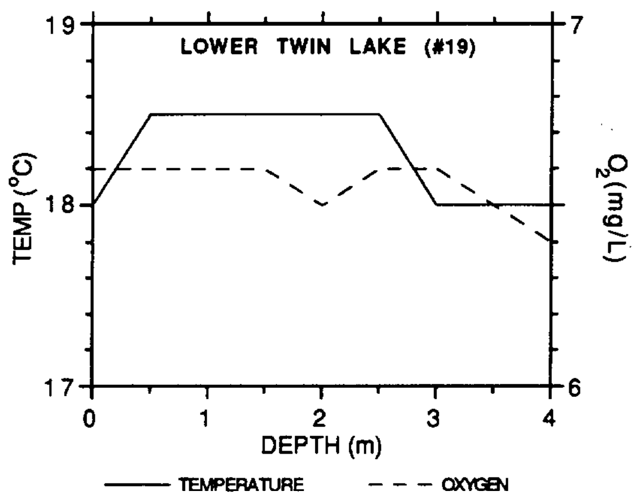
Appendix A. Additional details concerning lakes and their fish populations

Lake: 19--Lower Twin Lake.

Vegetation in Lake Basin: Lodgepole pine, willow.

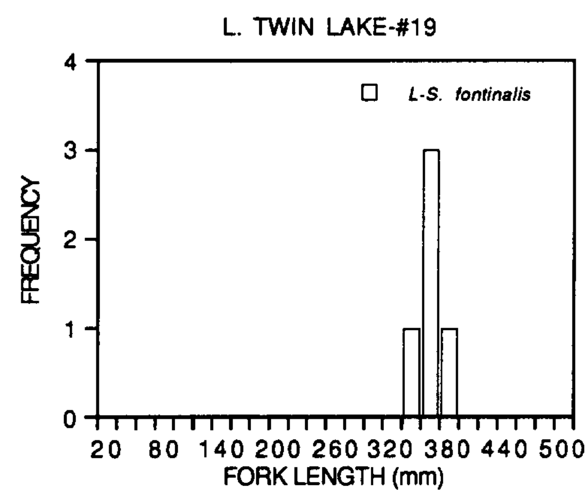
Physical Character of Littoral Zone: mud and log jams.

Oxygen and Temperature Profiles on 12 Aug 91:



Observations on Basin Geology: Intrusive igneous.

Characteristics of Fish Samples:



History of Fish Populations: No information on history, but 2000 rainbow trout are supposedly planted biennially. Only large brook trout seem to be present. Presumably they are spawning successfully in the lake.

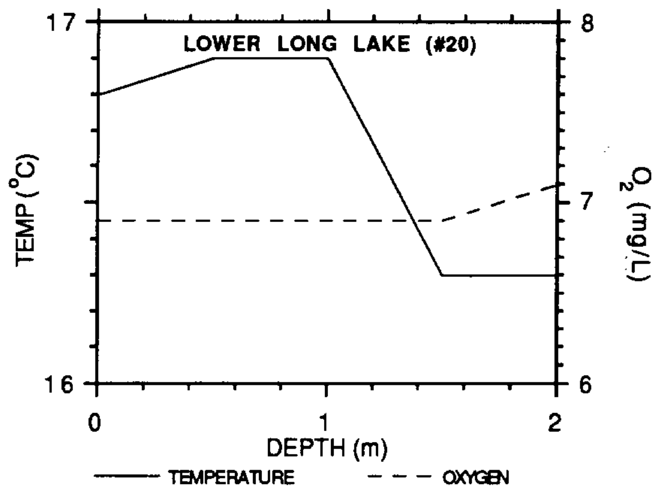
Appendix A. Additional details concerning lakes and their fish populations

Lake: 20--Lower Long Lake.

Vegetation in Lake Basin: Lodgepole forest.

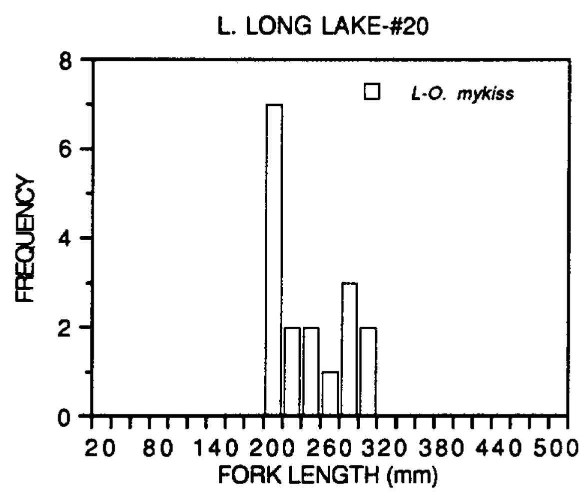
Physical Character of Littoral Zone: Bullrushes cover entire littoral zone.

Oxygen and Temperature Profiles on 4 Sept 90:



Observations on Basin Geology: Volcanic with scattered granitic outcrops.

Characteristics of Fish Samples:



History of Fish Populations: Rainbow trout planted biennially from 1940 to present. Brook trout planted in 1950, but there are no suitable spawning habitats for salmonids.

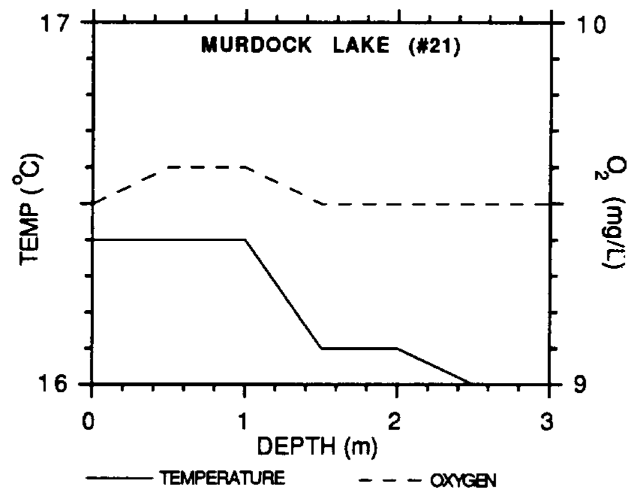
Appendix A. Additional details concerning lakes and their fish populations

Lake: 21--Murdock Lake.

Vegetation in Lake Basin: Lodgepole and willow.

Physical Character of Littoral Zone: Sand/mud mixture.

Oxygen and Temperature Profiles on 8 Sept 90:



Observations on Basin Geology: Igneous intrusive.

Characteristics of Fish Samples: No fish.

History of Fish Populations: No records of fish despite its proximity to trail. A fisherman said it once contained fish.

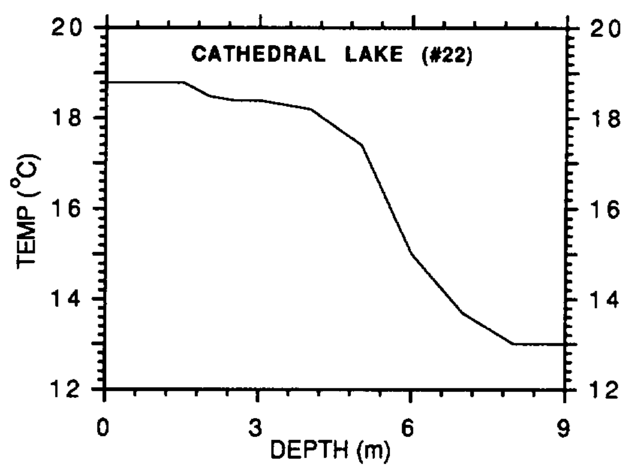
Appendix A. Additional details concerning lakes and their fish populations

Lake: 22--Lower Cathedral Lake.

Vegetation in Lake Basin: Lodgepole forest.

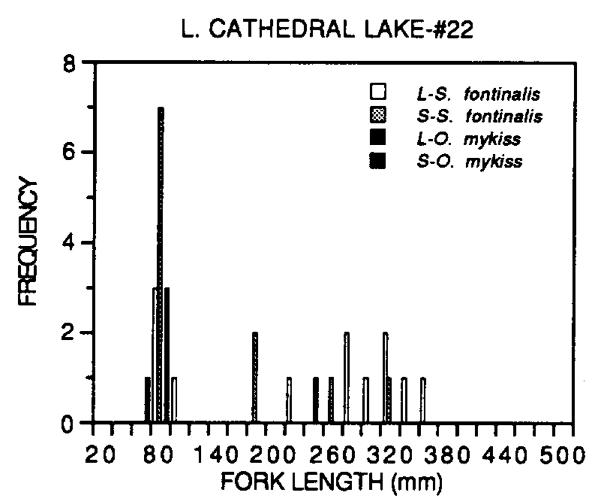
Physical Character of Littoral Zone: Sand/mud with bedrock slab and submerged logs.

Oxygen and Temperature Profiles on 6 Aug 90:



Observations on Basin Geology: Intrusive igneous.

Characteristics of Fish Samples:



History of Fish Populations: First planted in 1897 with brook and rainbow trout. Brook trout stocked periodically until 1971. Rainbow trout planted periodically from 1897 to 1990.

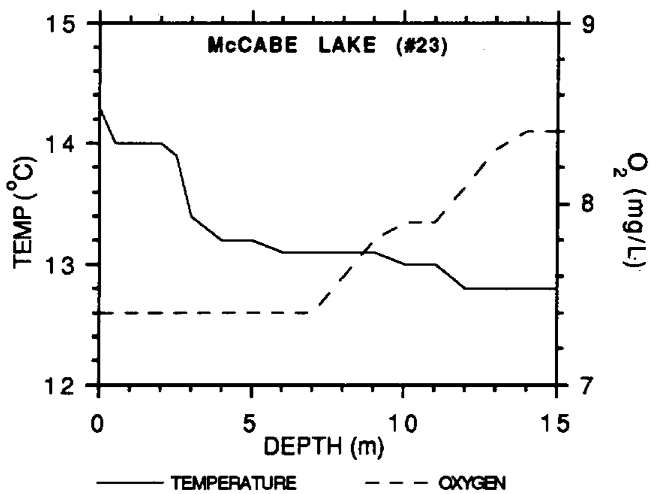
Appendix A. Additional details concerning lakes and their fish populations

Lake: 23--Middle McCabe Lake.

Vegetation in Lake Basin: Whitebark pine and willow.

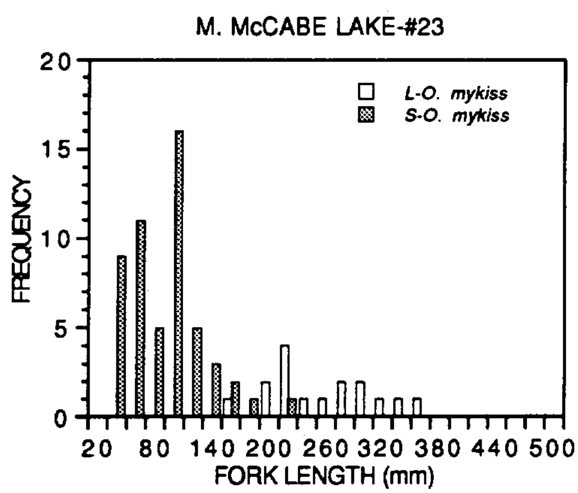
Physical Character of Littoral Zone: broken rock and submerged logs.

Oxygen and Temperature Profiles on 10 Sept 90:



Observations on Basin Geology: Intrusive igneous.

Characteristics of Fish Samples:



History of Fish Populations: Rainbow trout planted in 1933, 1941, 1948, 1955, 1961, 1968, 1973, 1976.

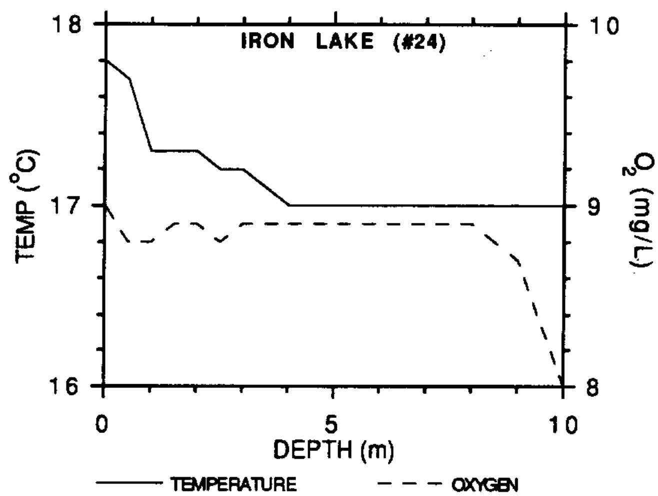
Appendix A. Additional details concerning lakes and their fish populations

Lake: 24--Iron Lake.

Vegetation in Lake Basin: Lodgepole pine, sugar pine.

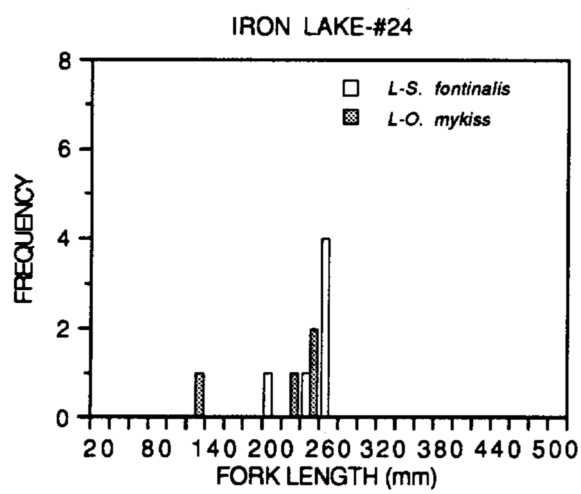
Physical Character of Littoral Zone: Sandy with large log jams.

Oxygen and Temperature Profiles on 31 Aug 90:



Observations on Basin Geology: Intrusive igneous with red inclusions.

Characteristics of Fish Samples:



History of Fish Populations: First planted with rainbow and brook trout near the turn of the century. Presently planted annually with 3000 rainbow trout fingerlings. Brook trout spawn in the lake.

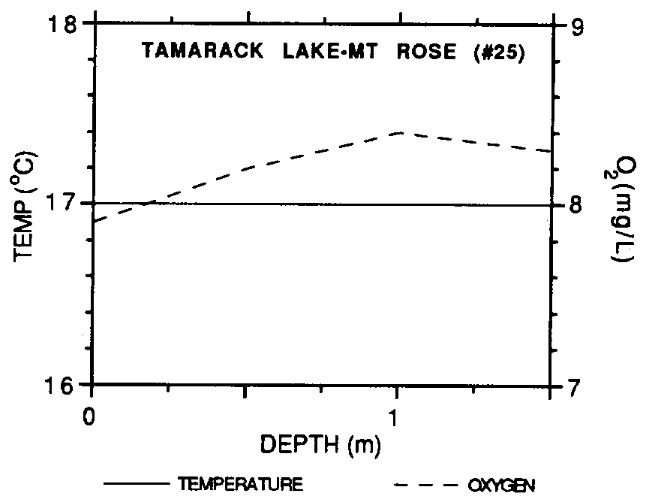
Appendix A. Additional details concerning lakes and their fish populations

Lake: 25--Tamarack Lake-Tahoe.

Vegetation in Lake Basin: Fir, meadow grasses, and willow.

Physical Character of Littoral Zone: Lake rimmed by wide beds of rushes.

Oxygen and Temperature Profiles on 23 Aug 91:



Observations on Basin Geology: Volcanic.

Characteristics of Fish Samples: No fish present.

History of Fish Populations: Brook trout planted many years ago, but managers discontinued stocking due to filling of the lake and frequent winter kills.

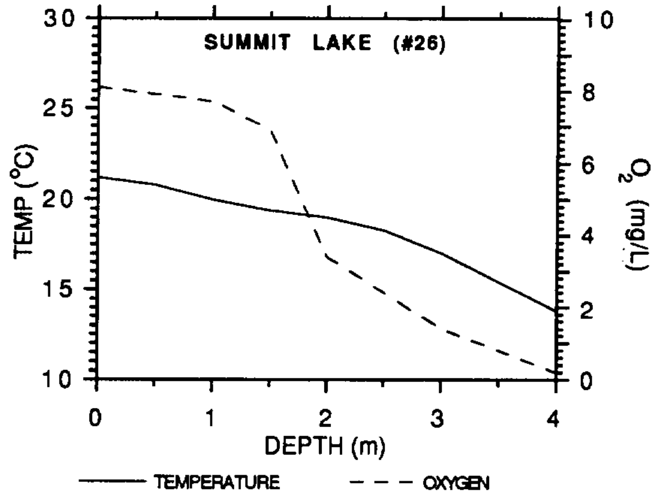
Appendix A. Additional details concerning lakes and their fish populations

Lake: 26--Summit Lake.

Vegetation in Lake Basin: Lodgepole pine.

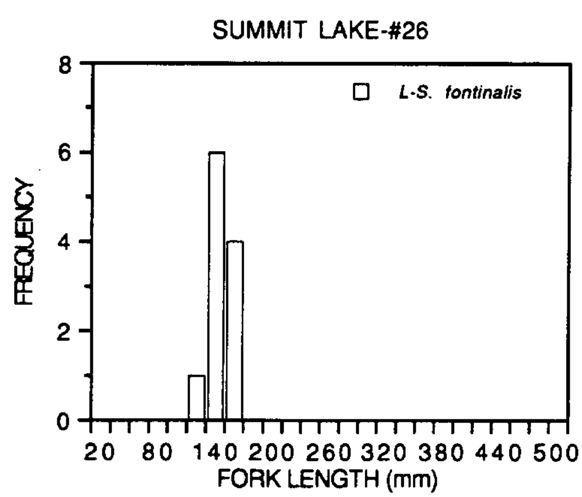
Physical Character of Littoral Zone: Heavy emergent vegetation fills the entire lake.

Oxygen and Temperature Profiles on 15 Aug 90:



Observations on Basin Geology: Lake bed looks like intrusive igneous, but volcanic deposits common in area. The drainage is extremely small.

Characteristics of Fish Samples:



History of Fish Populations: Originally contained Lahontan cutthroat trout native to waters lower in the drainage. Now planted with 500 brook trout fingerlings annually.

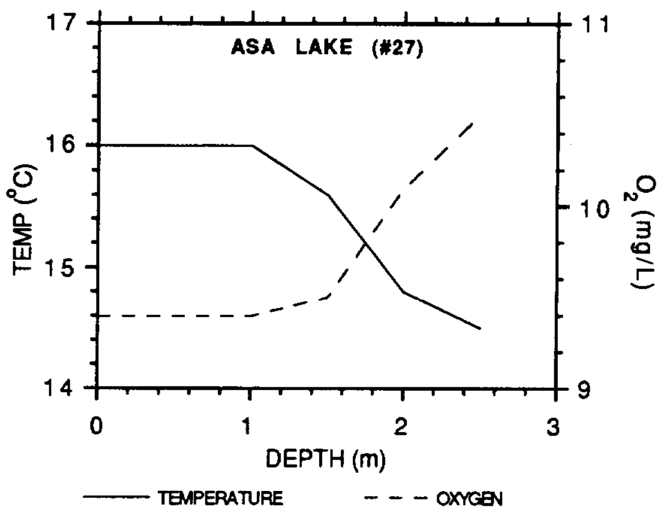
Appendix A. Additional details concerning lakes and their fish populations

Lake: 27--Asa Lake.

Vegetation in Lake Basin: Lodgepole pine.

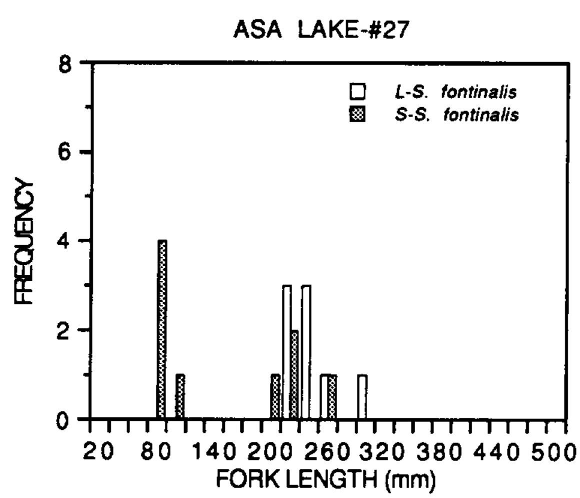
Physical Character of Littoral Zone: Many submerged logs and some emergent grasses. Mud/sand bottom.

Oxygen and Temperature Profiles on 16 Aug 90:



Observations on Basin Geology: Volcanic with many springs.

Characteristics of Fish Samples:



History of Fish Populations: Originally contained cutthroat trout native to waters lower in the drainage. Now planted with 500 brook trout fingerlings annually.

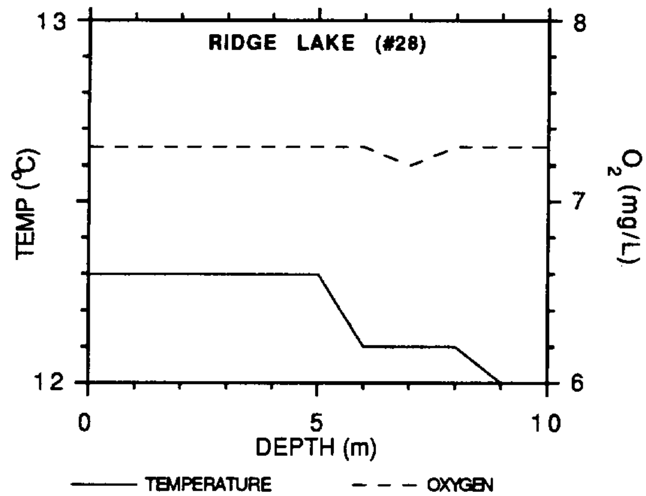
Appendix A. Additional details concerning lakes and their fish populations

Lake: 28--Ridge Lake.

Vegetation in Lake Basin: Whitebark pine.

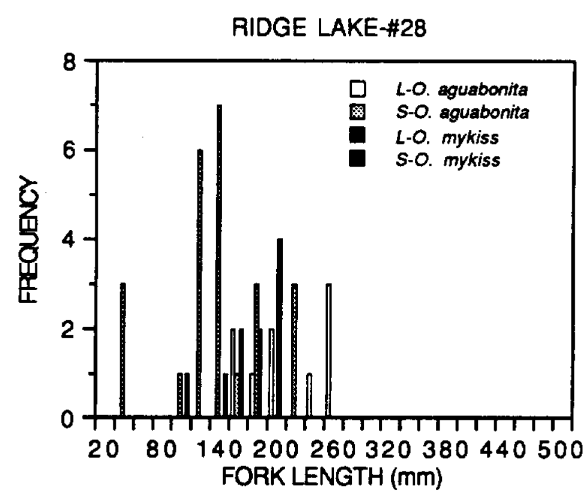
Physical Character of Littoral Zone: Sand and bedrock slab, with talus on one side.

Oxygen and Temperature Profiles on 29 Aug 90:



Observations on Basin Geology: Intrusive igneous.

Characteristics of Fish Samples:



History of Fish Populations: No historical information, but 2000 golden trout are planted biennially. Obviously some rainbow trout have also been planted by mistake. Good reproduction.

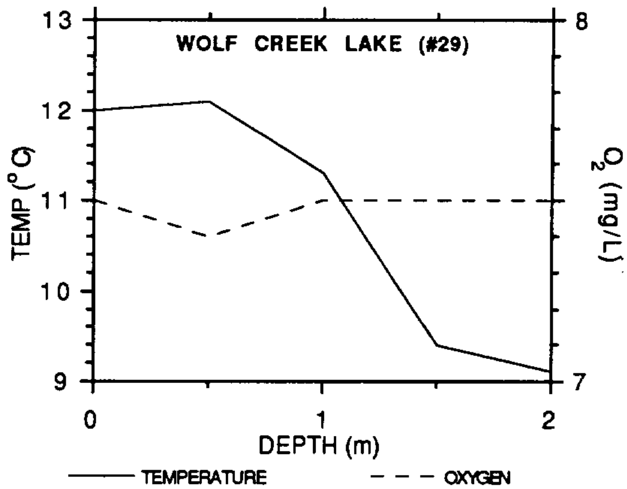
Appendix A. Additional details concerning lakes and their fish populations

Lake: 29--Wolf Creek Lake.

Vegetation in Lake Basin: Whitebark pine.

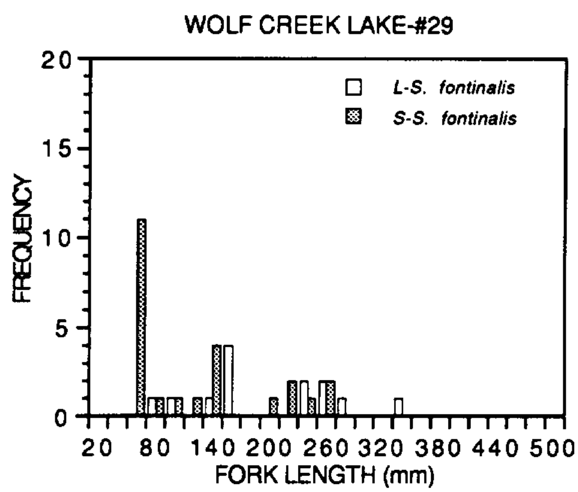
Physical Character of Littoral Zone: boulders, emergent grass, sand and mud.

Oxygen and Temperature Profiles 20 Aug 90:



Observations on Basin Geology: Volcanic and perhaps metavolcanic.

Characteristics of Fish Samples:



History of Fish Populations: Almost certainly this lake was planted with cutthroat trout native to the stream below, but until 1991 it contained a self-sustaining brook trout population. In 1991 the lake was poisoned to remove all brook trout for re-introduction of native cutthroat trout.

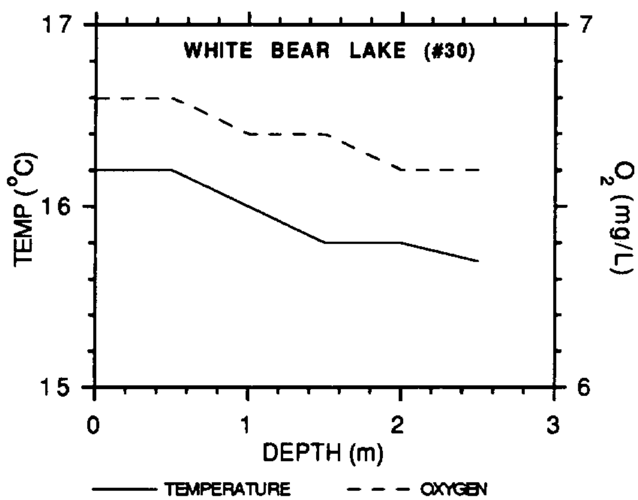
Appendix A. Additional details concerning lakes and their fish populations

Lake: 30--"White Bear" Lake.

Vegetation in Lake Basin: Lodgepole pine.

Physical Character of Littoral Zone: Mud bottom with submerged logs and some emergent grasses. Much bedrock.

Oxygen and Temperature Profiles on 6 Sept 90:



Observations on Basin Geology: Intrusive igneous.

Characteristics of Fish Samples: No fish present.

History of Fish Populations: No information.

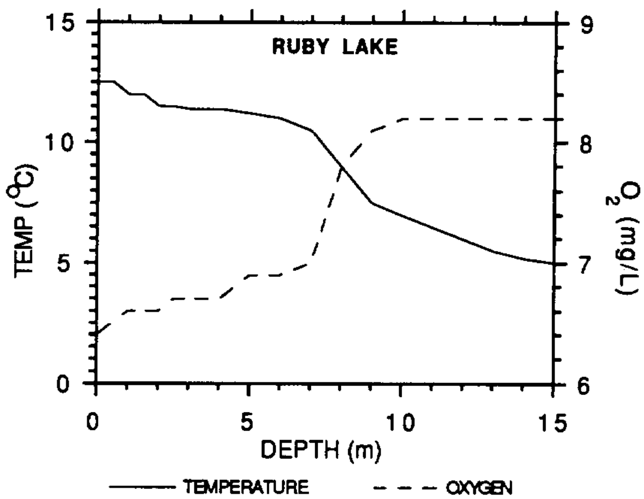
Appendix A. Additional details concerning lakes and their fish populations

Lake: Ruby Lake.

Vegetation in Lake Basin: Whitebark pine and willow. Meadow fring on lake.

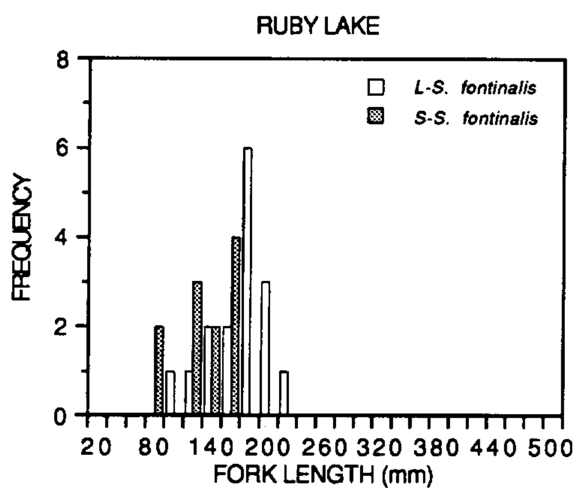
Physical Character of Littoral Zone: Broken rock and sand.

Oxygen and Temperature Profiles on 20 July 90:



Observations on Basin Geology: Intrusive igneous.

Characteristics of Fish Samples:



History of Fish Populations: Already contained fish by 1934. Rainbow and brook trout were abundant by 1947. Rainbow trout were planted from 1940 to 1957. Brown trout were planted in 1964 and 1965 to reduce densities of brook trout. Evidently only naturally produced brook trout now inhabit the lake.

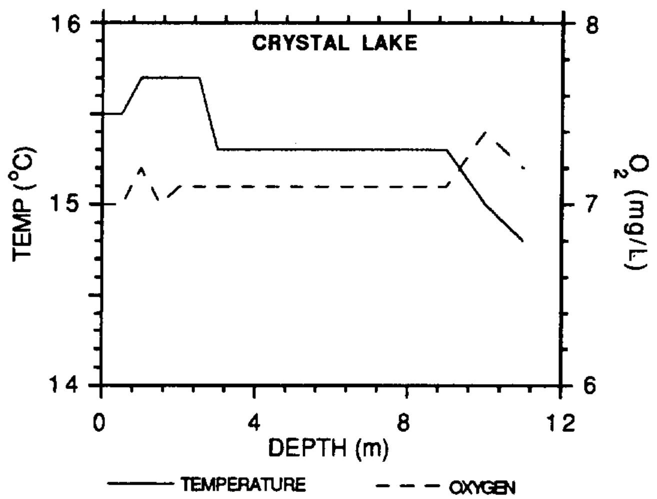
Appendix A. Additional details concerning lakes and their fish populations

Lake: Crystal Lake.

Vegetation in Lake Basin: Lodgepole, fir, willows.

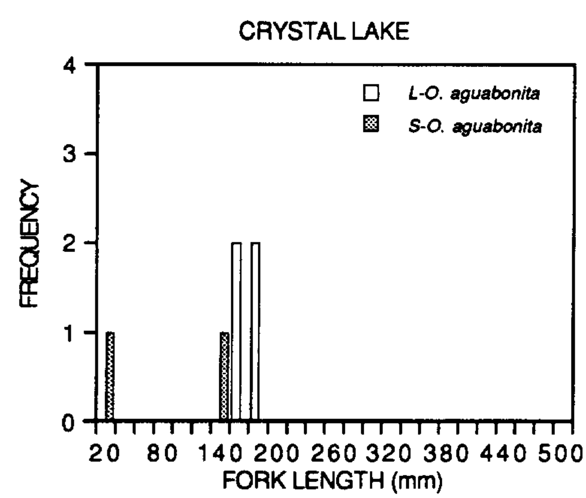
Physical Character of Littoral Zone: broken rock and submerged logs.

Oxygen and Temperature Profiles on 23 July 90:



Observations on Basin Geology: Intrusive igneous.

Characteristics of Fish Samples:



History of Fish Populations: Golden trout were introduced in 1938, then brook trout, then rainbow trout. Now 2000 golden trout are planted biennially.

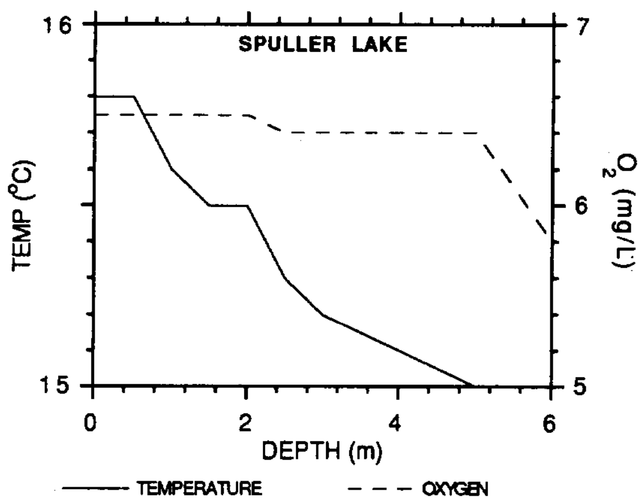
Appendix A. Additional details concerning lakes and their fish populations

Lake: Spuller Lake.

Vegetation in Lake Basin: Stunted willow and whitebark pine.

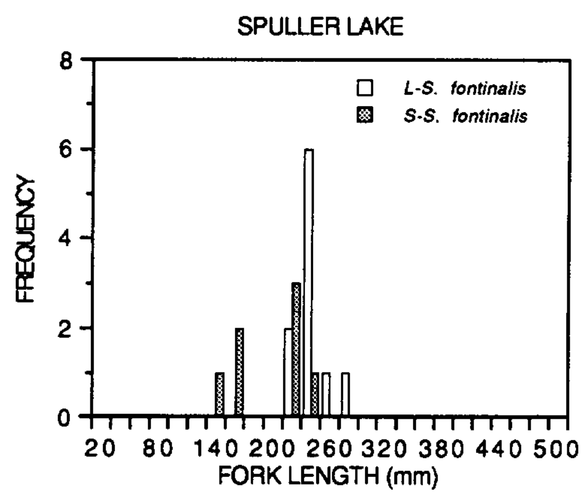
Physical Character of Littoral Zone: Sand and bedrock.

Oxygen and Temperature Profiles on 9 Aug 90:



Observations on Basin Geology: Some intrusive igneous and possibly metamorphic.

Characteristics of Fish Samples:



History of Fish Populations: Brook trout have been planted periodically since 1940. Probably not planted at present.

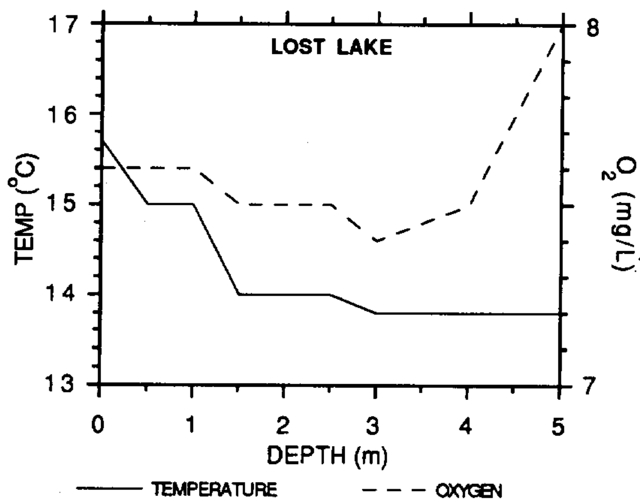
Appendix A. Additional details concerning lakes and their fish populations

Lake: Lost Lake

Vegetation in Lake Basin: Lodgepole pine.

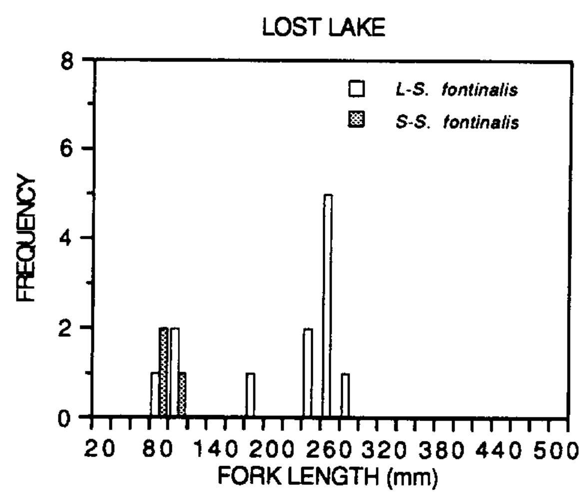
Physical Character of Littoral Zone: Sand/mud with bedrock, broken rock and submerged logs.

Oxygen and Temperature Profiles on 27 Aug 90:



Observations on Basin Geology: Intrusive igneous.

Characteristics of Fish Samples:



History of Fish Populations: No historical information, but it is supposedly planted yearly with 1000 golden trout fingerlings. Only brook trout were found in the lake and outlet stream.

Appendix A. Additional details concerning lakes and their fish populations

Lake: Lake "45".

Vegetation in Lake Basin: Meadow along lake..

Physical Character of Littoral Zone: Sand and broken rock.

Oxygen and Temperature Profiles on 10 Sept 91: Not available.

Observations on Basin Geology: Intrusive igneous outcrops surrounded by dark red metamorphics.

Characteristics of Fish Samples: No fish present.

History of Fish Populations: Planted with rainbow trout in 1946, 1964, 1971, 1976 and 1979.

APPENDIX B. Aquatic invertebrates collected from 35 sample lakes during the summers of 1990 and 1991. Qualitative densities are shown: 1=rare, 2=common, 3=abundant. Within each group, lakes are ranked from left to right by pH, and the number of lakes represented by the samples is indicated.

Lake Number	14	24	13	11	28	12	17	19	10	4	3	22	1	29	23	20	16	5	15	18	27	26	8	2	6	7	9	21	30	25	"45"	Lost	Spull	Ruby	Crys
Estimated Number of Lakes	5	27	112	59	85	37	27	11	75	16	21	16	5	5	16	37	5	16	5	5	21	21	80	32	123	53	5	32	37	11					
pH	5.98	6.00	6.02	6.04	6.10	6.11	6.11	6.17	6.20	6.29	6.36	6.38	6.40	6.65	6.67	6.68	6.69	6.87	6.97	7.49	8.34	9.56	5.23	6.00	6.04	6.11	6.11	6.32	6.34	6.42	4.7	6.13	6.4	6.56	6.68
	FISH PRESENT																						FISH ABSENT								EXTRA				
TAXA																																			
Phylum Annelida																																			
Class Oligochaeta																																			
Class Hirudinea		2					3					2						1				2													
Phylum Arthropoda																																			
Class Crustacea																																			
Order Anostraca																																			
Family Streptocephalidae																																			
g. Streptocephalus																												3							
Order Podocopa																					1														
Order Amphipoda																																			
Family Talitridae																																			
g. Hyallela azteca								2	1							2		2																	
Class Aracnida																																			
Order Aciformes											1				1				1										2						
Class Insecta																																			
Order Ephemeroptera																																			
Family Baetidae																																			
g. Callibaetis								2										1	1		3	2				3	2	2	2	2					
g. Cinygmula													2																						
Family Siphloneuridae																																			
g. Ameletus																								2	3										
g. Siphloneuris																			1																
Family Leptophlebiidae																																			
g. Paraleptophlebia		1																																	
Order Odonata																																			
Family Aeshnidae																																			
g. Aeshna		2					1					1				3		1			3						1	3	2			2			

APPENDIX B. (continued). Aquatic invertebrates collected from 35 sample lakes during the summers of 1990 and 1991. Qualitative densities are shown: 1=rare, 2=common, 3=abundant. Within each group, lakes are ranked from left to right by pH, and the number of lakes represented by the samples is indicated.

FISH PRESENT

Lake Number	14	24	13	11	28	12	17	19	10	4	3	22	1	29	23	20	16	5	15	18	27	26
Estimated Number of Lakes	5	27	112	59	85	37	27	11	75	16	21	16	5	5	16	37	5	16	5	5	21	21
pH	5.98	6.00	6.02	6.04	6.10	6.11	6.11	6.17	6.20	6.29	6.36	6.38	6.40	6.65	6.67	6.68	6.69	6.87	6.97	7.49	8.34	9.56
TAXA																						
g. Anax	1							3														
g. Triacanthagyna								1														
Family Libellulidae																						
g. Pachydiplex longipennis																						
g. Pseudolon																						3
g. Sympetrum																						
Family Lestidae																						
g. Lestes	2																					
Family Coenagrionidae																						
g. Enallagma																		2				1
g. Coenagrion/Enallagma																3						
g. Ischnura	3																					
g. Zoniagrion																		1				
Order Plecoptera																						
Family Nemouridae																						
g. Nemoura																					2	
Order Hemiptera																						
Family Gerridae																						
g. Gerris	3	2			1		1					3		1	1			2			2	
Family Corixidae																						
g. Graptocorixa	3							2				3				2					2	2
Family Notonectidae																						
g. Notonecta		1												2					2		3	3
Order Megaloptera																						
Family Sialidae																						
g. Sialis					1			1				2		1	1							
Order Trichoptera																						

FISH ABSENT

Lake Number	8	2	6	7	9	21	30	25
Estimated Number of Lakes	80	32	123	53	5	32	37	11
pH	5.23	6.00	6.04	6.11	6.11	6.32	6.34	6.42
TAXA								
g. Anax								
g. Triacanthagyna								
Family Libellulidae								
g. Pachydiplex longipennis							1	
g. Pseudolon								
g. Sympetrum					1			
Family Lestidae								
g. Lestes								
Family Coenagrionidae								
g. Enallagma						1		
g. Coenagrion/Enallagma					2			
g. Ischnura								
g. Zoniagrion								
Order Plecoptera								
Family Nemouridae								
g. Nemoura								
Order Hemiptera								
Family Gerridae								
g. Gerris						1	2	
Family Corixidae								
g. Graptocorixa					2	1	2	
Family Notonectidae								
g. Notonecta					2	1		2
Order Megaloptera								
Family Sialidae								
g. Sialis						3	2	
Order Trichoptera								

EXTRA

Lake Number	"45"	Lost	Spull	Ruby	Crys
Estimated Number of Lakes					
pH	4.7	6.13	6.4	6.56	6.68
TAXA					
g. Anax					
g. Triacanthagyna					
Family Libellulidae					
g. Pachydiplex longipennis					
g. Pseudolon		1			
g. Sympetrum					
Family Lestidae					
g. Lestes					
Family Coenagrionidae					
g. Enallagma					
g. Coenagrion/Enallagma					
g. Ischnura					
g. Zoniagrion					
Order Plecoptera					
Family Nemouridae					
g. Nemoura					
Order Hemiptera					
Family Gerridae					
g. Gerris			1		2
Family Corixidae					
g. Graptocorixa					
Family Notonectidae					
g. Notonecta					
Order Megaloptera					
Family Sialidae					
g. Sialis		2			2
Order Trichoptera					

APPENDIX B. (continued). Aquatic invertebrates collected from 35 sample lakes during the summers of 1990 and 1991. Qualitative densities are shown: 1=rare, 2=common, 3=abundant. Within each group, lakes are ranked from left to right by pH, and the number of lakes represented by the samples is indicated.

Lake Number	14	24	13	11	28	12	17	19	10	4	3	22	1	29	23	20	16	5	15	18	27	26	8	2	6	7	9	21	30	25	"45"	Lost	Spull	Ruby	Crys
Estimated Number of Lakes	5	27	112	59	85	37	27	11	75	16	21	16	5	5	16	37	5	16	5	5	21	21	80	32	123	53	5	32	37	11					
pH	5.98	6.00	6.02	6.04	6.10	6.11	6.11	6.17	6.20	6.29	6.36	6.38	6.40	6.65	6.67	6.68	6.69	6.87	6.97	7.49	8.34	9.56	5.23	6.00	6.04	6.11	6.11	6.32	6.34	6.42	4.7	6.13	6.4	6.56	6.68
	FISH PRESENT																						FISH ABSENT								EXTRA				
TAXA																																			
Family Limnephilidae																																			
cases only	2	2						3	1			1	2					1	3									3							3
g. Dicosmoecus				2						3																2									
g. Ecclisomyia											3			3	3									2	1									1	
g. Limnephilus												1										3													
g. Onocosmoecus										3																									
g. Psychoglypha			1																										1				3		
Family Leptoceridae																																			
g. Oecetis																3																			
g. Triaenodes																											1								
Order Coleoptera																																			
Family Gyrinidae																																			
g. Gyrinus																												3	3						
Family Dytiscidae																																			
g. Agabus					1														2			1						3							
g. Deronectes		1										3				2																			
g. Hydaticus modestus																					1														
g. Hydrovatus																																	1		
g. Hygrotus										1					1							1					1	1							
g. Laccophilus aristernalis																										1									
g. Oreodytes							1																												
Family Noteridae																																			
g. Hydrocanthus																									1										
Family Haliplidae																																			
g. Haliplus																					2														
Order Diptera																																			
Family Tabanidae																																			
g. Tabanus												1																							

APPENDIX B. (concluded). Aquatic invertebrates collected from 35 sample lakes during the summers of 1990 and 1991. Qualitative densities are shown: 1=rare, 2=common, 3=abundant. Within each group, lakes are ranked from left to right by pH, and the number of lakes represented by the samples is indicated.

Lake Number	14	24	13	11	28	12	17	19	10	4	3	22	1	29	23	20	16	5	15	18	27	26	8	2	6	7	9	21	30	25	"45"	Lost	Spull	Ruby	Crys
Estimated Number of Lakes	5	27	112	59	85	37	27	11	75	16	21	16	5	5	16	37	5	16	5	5	21	21	80	32	123	53	5	32	37	11					
pH	5.98	6.00	6.02	6.04	6.10	6.11	6.11	6.17	6.20	6.29	6.36	6.38	6.40	6.65	6.67	6.68	6.69	6.87	6.97	7.49	8.34	9.56	5.23	6.00	6.04	6.11	6.11	6.32	6.34	6.42	4.7	6.13	6.4	6.56	6.68
	FISH PRESENT																						FISH ABSENT								EXTRA				
TAXA																																			
Family Tipulidae																																			
g. Prionoera																					3														
Family Chironomidae	2		1		2	2	3	3	2		1	3		2				2	3		3	3				3	1	1	2	3		1			
Family Dixidae																																			
g. Dixella																		1																	
Phylum Mollusca																																			
Class Gastropoda																																			
Order Basommatophora																																			
Family Lymnaeidae																																			
g. Lymnaea																			3		3														
Family Physidae																																			
g. Physa																			2																
Family Planorbidae																																			
g. Gyraulus																			3			2													
Class Pelycypoda																																			
Order Heterodonta																																			
Family Sphaeridae																																			
g. Pisidium	2	2			2			2	2		3			2	1	2		3			3	2				2		2	2	2		1	2		1

APPENDIX B. Aquatic invertebrates collected from 24 sample outlet streams during the summers of 1990 and 1991. Qualitative densities are shown: 1=rare, 2=common, 3=abundant. Within each group, streams are ranked from left to right by pH.

Lake Number	7	30	25	13	11	28	12	10	4	3	22	23	1	29	17	16	5	15	18	27	Lost	Spull	Ruby	Crys
pH	6.11	6.34	6.42	6.02	6.04	6.10	6.11	6.20	6.29	6.32	6.38	6.38	6.40	6.65	6.66	6.69	6.87	6.97	7.49	8.34	6.13	6.4	6.56	6.68
	FISH			FISH ABSENT																	EXTRA			
TAXA																								
Phylum Annelida																								
Class Oligochaeta		3												3		1				2				
Class Hirudinea								3					1									3		
Phylum Arthropoda																								
Class Crustacea																								
Order Amphipoda																								
Family Talitridae																								
g. Hyallela azteca																			3					
Class Aracnida																								
Order Aciformes												2				1								
Class Insecta																								
Order Ephemeroptera																								
Family Baetidae																								
g. Baetis	3						1						1		1		1			3		2	1	
g. Callibaetis		3																						
g. Cinygmula													3											
Family Heptageniidae																								
g. Epeorus													1											
Family Leptophlebiidae																								
g. Paraleptophlebia																						3		
Order Odonata																								
Family Aeshnidae																								
g. Aeshna		1																			1			
Family Libellulidae																								
g. Libellula																			1					
Family Coenagrionidae																								
g. Coenagrion																								
g. Enallagma											2													
g. Coenagrion/Enallagma																								
g. Ischnura																								
g. Zoniagrion																			2					
Order Plecoptera																								
Family Nemouridae																								
g. Malenka																				2				
g. Zapada												1												
Family Perlodidae																								
g. Isoperla	2																			1				
Family Chloroperlidae																								
g. Suwallia/Sweltsa												2		3								2		

APPENDIX B (continued). Aquatic invertebrates collected from 24 sample outlet streams during the summers 1990 and 1991. Qualitative densities are shown: 1=rare, 2=common, 3=abundant. Within each group, streams are ranked from left to right by pH.

	FISH			FISH ABSENT																	EXTRA			
Lake Number	7	30	25	13	11	28	12	10	4	3	22	23	1	29	17	16	5	15	18	27	Lost	Spull	Ruby	Crys
pH	6.11	6.34	6.42	6.02	6.04	6.10	6.11	6.20	6.29	6.32	6.38	6.38	6.40	6.65	6.66	6.69	6.87	6.97	7.49	8.34	6.13	6.4	6.56	6.68
TAXA																								
Order Hemiptera																								
Family Gerridae																								
g. Gerris																1								
Family Corixidae																								
g. Graptocorixa		2																						
Family Notonectidae																								
g. Notonecta														1										
Order Megaloptera																								
Family Sialidae																								
g. Sialis												2								2	3			
Order Trichoptera																								
Family Rhyacophilidae																								
g. Himalopsyche							1																	3
g. Rhyacophila							1		3				1	1								3		
Family Brachycentridae																								
g. Amiocentrus							1																	
Family Limnephilidae																								
cases only																1	1							
g. Desmona														3			2							
g. Dicosmoecus					3			1																
g. Ecclisomyia						1						2			1					2				3
g. Psychoglypha			2			1												2						
Order Coleoptera																								
Family Gyrinidae																								
g. Gyrinus																								
Family Dytiscidae																								
g. Agabus										1														
g. Dytiscus														1										
g. Hygrotus						1																		
g. Oreodytes						1					3				1									
Family Elmidae																								
g. Narpus																				1				
Order Diptera																								
Family Tabanidae																								
g. Chrysops							2																	
Family Tipulidae																								
g. Pedicia									1															
Family Simuliidae																								
g. Prosimulium																	3							
g. Simulium			3			3	3			2					3		3	3		3	2	3	2	3
Family Chironomidae		3	3	3	3	3	3	3	3	3	3	3	1	3	3		2	3			3	3		3
Family Empididae																								
g. Clinocera																				1				

APPENDIX B (concluded). Aquatic invertebrates collected from 24 sample outlet streams during the summers of 1990 and 1991. Qualitative densities are shown: 1=rare, 2=common, 3=abundant. Within each group, streams are ranked from left to right by pH.

Lake Number	7	30	25	13	11	28	12	10	4	3	22	23	1	29	17	16	5	15	18	27	Lost	Spull	Ruby	Crys
pH	6.11	6.34	6.42	6.02	6.04	6.10	6.11	6.20	6.29	6.32	6.38	6.38	6.40	6.65	6.66	6.69	6.87	6.97	7.49	8.34	6.13	6.4	6.56	6.68
	FISH			FISH ABSENT																	EXTRA			
TAXA																								
Family Muscidae																								
g. Limnophora												2												
Phylum Mollusca																								
Class Gastropoda																								
Order Basommatophora																								
Family Lymnaeidae																								
g. Lymnaea																				3				
Class Pelycypoda																								
Order Heterodonta																								
Family Sphaeridae																								
g. Pisidium		3			3	3	2	3			2	2		3				3	2	3	3	3	2	

APPENDIX C. Results of analysis on 10% field duplicate pairs. CV is coefficient of variation (SD/mean). CV was not used for pH due to its narrow limits. RMS% is the root mean square of the coefficients of variation (or root mean square of standard deviations in the case of pH).

			CATIONS(µeq/L)						ANIONS(µeq/l)		
LAKE	pH	COND(µs)	Ca	Mg	Na	K	Al	ANC(µeq/L)	Cl	Nitrate	Sulfate
8A	5.23	33.0	135.0	42.0	25.0	14.0	7.0	3.9	4.0	16.5	215.0
8B	5.33	33.7	130.0	39.0	24.0	13.0	13.8	4.4	3.2	16.4	212.0
SD	0.08	0.49	3.54	2.12	0.71	0.71	4.82	0.35	0.57	0.07	2.12
CV(%)	-	1.5	2.7	5.2	2.9	5.2	46.5	8.5	15.7	0.4	1.0
12A	6.11	8.2	28.8	5.3	18.2	6.5	1.4	53.5	2.4	2.2	7.4
12B	6.04	7.5	29.6	5.5	19.7	7.4	2.1	52.7	3.4	2.4	7.7
SD	0.05	0.49	0.57	0.14	1.06	0.64	0.49	0.57	0.71	0.14	0.21
CV(%)	-	6.3	1.9	2.6	5.6	9.2	28.1	1.1	24.4	6.1	2.8
19A	6.17	10.9	49.0	9.4	20.6	5.9	5.5	85.1	3.5	0.1	3.5
19B	6.13	10.9	48.4	9.4	20.8	5.8	6.1	85.6	3.7	0.1	3.6
SD	0.03	0.00	0.42	0.00	0.14	0.07	0.47	0.35	0.14	0.00	0.07
CV(%)	-	0.0	0.9	0.0	0.7	1.2	8.1	0.4	3.9	0.0	2.0
RMS%	0.06	5.98	2.35	5.01	5.05	8.32	41.77	8.07	22.28	6.02	2.44