Title

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ASSESSEMENT OF ACIDITY OF LAKES AND PRECIPITATION IN THE SIERRA NEVADA

by

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TECHNICAL COMPLETION REPORT

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Abstract

The east central Sierra Nevada received acid precipitation (pH 3.7 to 4.9) during convective storms interspersed through the dry seasons of 1981 and 1982. In contrast, late autumn, winter and early spring snow (1981-1982) ranged in pH from 5.2 to 6.1 (mean 5.7) and had low ammonium, nitrate and sulfate concentrations. As of 1981 most of the alpine lakes of the Sierra Nevada remain very weakly buffered, bicarbonate lakes that receive a small loading of acid precipitation and a large annual input of snowmelt uncontaminated by strong acids. These lakes contain low concentrations of orthophosphate, nitrate and ammonium and are oligotrophic. The zooplankton communities fall into two major groups, those dominated by large-bodied species in the absence of fish, and those dominated by smaller species where fish are present. If the acidity of the precipitation increases, the pH of the lakes will decrease rapidly with adverse biological impacts because the lakes and their basins have extremely low buffer capacity and the biota cannot tolerate acidic water.

Introduction

Acidic rain and snow fall on California's coast, inland valleys and Sierra Nevada. Of special and immediate concern is acidification of the Sierran lakes and streams. These waters supply San Francisco, Los Angeles and the Central Valley, and the Sierran lakes and their fish are a major recreational resource in California. Unfortunately, these waters are among the most sensitive in the world to acidic precipitation because they have almost no capacity to neutralize acids. Loss of fish and elevated levels of heavy metals are just two of the adverse effects of degraded water quality resulting from acidification. To predict and prevent severe ecological damage in the Sierran waters and elsewhere in California requires analysis of total acidic inputs to watersheds and of trends in chemical and biological parameters known to be susceptible.

The growing concern about the effect of acid rain in California is intensified by the changing prognosis for the safety and public acceptance of nuclear energy, and the resulting consideration of coal-burning power plants as alternatives. Emissions from burning coal are the major causes of the damage witnessed in Scandinavia and Canada (Overrein et al., 1980). Furthermore, emissions from automobiles and industry in California are considerable. It is not known whether the water in Sierra Nevada lakes has declined in pH to an extent causing deleterious effects on the biota.

The purpose of our research is to assess the impact or potential impact of atmospheric precipitation contaminated by strong acids on the water quality in the Sierra Nevada. To accomplish the first phase of this objective required four related activities reported here:

1. The pH and chemical composition of precipitation in all seasons was determined for two years on the eastern slopes of the Sierra Nevada.
2. The potential occurrence of a pulse of low pH water as the snowpack melts

in the spring was determined by measurement of pH and acidity in the streams and melt waters on the eastern and western Sierra slopes.

3. The pH and alkalinity of 73 alpine and subalpine lakes was measured with modern methods in the field. This survey of lakes spanned the length of the Sierra crest and the eastern and western slopes, and included lakes lying on the major rock types. To determine the chemical constituents responsible for the buffer capacity, the major solutes were also measured.
4. The zooplankton and fish present in the lakes sampled for chemistry were assessed from net casts and data records available from public agencies.

The results and significance of these activities are presented in separate sections following a review of the methodology used in the project. A final section summarizes the principal findings and recommends further research and management possibilities.

Methods

Precipitation was collected at two (winter) or three (summer) sites in the east central Sierra Nevada (Fig. 1). The primary site was located at 3000 m ASL on Mammoth Mountain; additional sites were located at 2150 m ASL in Long Valley (Sierra Nevada Aquatic Research Laboratory, SNARL) and at 2450 m ASL about four kilometers southeast of the Mammoth Mountain site (Valentine Reserve). Collections began in June 1981 and have continued through the summer of 1982.

Rain was sampled on an event basis during the summer at the Mammoth Mountain site in an Aerochemetrics wet and dry fall collector (Galloway and Likens 1976) located 6 m above the ground. Seven weekly accumulations of dry fall were collected in 1981 by rinsing the dry bucket with 100 to 300 ml of distilled water. At SNARL and Valentine Reserve (1981) plastic buckets designed for use with the Aerochemetrics collector or a large volume plexiglas collector (Lewis and Grant 1978) located only at SNARL (1982) were placed in areas away from roads, buildings or trees and opened during rain events only. The collectors and linear polyethylene sample bottles used to store the samples were cleaned with 10% HCl and rinsed at least six times with deionized, distilled water before use. Duplicate plastic, rain gauges were used at each site.

Snow samples were obtained on an event basis at Mammoth Mountain and SNARL. Integrated snow samples were collected from a calibrated snow board that was lifted to the top of the snowpack after each event. The snow was melted in a water bath at room temperature before analysis. Snow water equivalences were measured daily on Mammoth Mountain by collecting a column of snow from a snow board and weighing the snow contained in a known volume (U.S. Weather Bureau 8-inch precipitation gauge and scale calibrated in inches of water). In mid-April, when the snow depth was maximal, a snow pit was sampled at intervals from top to bottom at the Mammoth Mountain site. Occasional surface snow samples were collected in several neighboring passes and basins during the winter and spring.

Hydrogen ion activity (pH) was measured immediately after collection of the precipitation samples with a null balancing meter (Perkin Elmer Coleman 37A) equipped with a low ionic strength electrode (Jena Glass Works; Sargent Welch S-30072-15). The electrode was calibrated with pH 7 or 4 buffers, washed twice for ten minutes with stirred, distilled water and then placed in an unstirred aliquot of sample for 15 minutes. This aliquot was then discarded and the pH determination made on a fresh, unstirred sample. Occasional calibration with dilute solutions of strong acid verified the validity of this procedure (Galloway et al. 1979). Electrical conductance of unfiltered samples was measured with a null balancing meter (LectroMho) and corrected to 25°C based on a 2.5%/°C temperature coefficient determined for Sierran waters.

Major cation and anion analyses were performed on samples filtered through Gelman A/E glass fiber filters. Ammonium and phosphate were determined immediately by the indophenol blue and molybdenum blue methods (Strickland and Parsons 1972). Samples for nitrate were stored frozen and those for other solutes were stored at 4°C. Nitrate was determined as nitrite after hydrazine reduction (Kamphake et al. 1967, McColl 1980). Chloride was determined by the mercury thiocyanate method of Florence and Farrar (1971); 1 μ eq l^{-1} could be detected. Cation analyses (calcium, magnesium, sodium and potassium) were performed on an atomic absorption spectrophotometer (Varian Techtron Model AA6). Samples for calcium and magnesium were spiked with lanthanum chloride; a nitrous oxide-acetylene (1981) or air-acetylene (1982) flame was used for calcium and an air-acetylene flame for the other cations.

Sulphate was measured with the barium chloranilate method of Shafer (1967) adapted to liquid samples; the lower limit of sensitivity was ca. 5 μ eq l^{-1}. This method was insufficiently sensitive for analyses of snow, and these samples were analyzed with an ion chromatographic procedure (W. T. Frankenberger, UC Riverside, personal communication).

The HPLC (high performance liquid chromatography) separation of $SO_4^=$-S was performed on a Beckman Model 334 liquid chromatograph equipped with a Model 110 pump, Model 421 CRT microprocessor-controller, Model 210 sample injector (2-ml constant volume sample loop), and a 4.6 x 250-mm Wescan 269-001 anion column with guard column. The mode of detection was electrical conductivity (Wescan conductivity detector Model 213A). The peak area data for $SO_4^=$-S in each chromatogram was obtained on a reporting integrator (Hewlett-Packard 3390A). The eluent used was phthalic acid (4 mM) adjusted to pH 4.75 with sodium borate) pumped at a rate of 2 ml/min. An aliquot (2 ml) of each water sample was injected into the LC with a plastic syringe. The results of $SO_4^=$-S analysis were calculated from a calibration graph prepared with standard solutions containing 0, 20, 50, 100, 250, and 500 μg/l of $SO_4^=$-S. Water used for all prepared solutions was HPLC-grade water obtained from Baker (Phillipsburg, New Jersey).

Alpine lakes were usually sampled near the center of the lake from an inflatable boat. The linear polyethylene bottles used for sampling were washed with 10% HCl, rinsed four times with deionized, distilled water and three times with the lake water. pH measurements were made immediately after sampling with a digital pH meter (Markson Model 95) and combination electrode designed for low ionic strength waters (Graphic Controls PHE 52539). The electrode was calibrated daily with pH 7 buffer and thoroughly rinsed after calibration. In a laboratory comparison results were similar to those obtained with the meter and electrode used to measure precipitation pH. Alkalinity was measured within eight hours of sampling by the Gran titration procedure (Stumm and Morgan 1972, Talling 1973); 0.01 N HCl was dispensed with a micrometer buret. Samples for subsequent chemical analyses were filtered through Gelman A/E glass fiber filters at the lakeshore and stored in a cool, dark case while in transit to the laboratory. Major solutes and nutrients were determined on filtered samples with the same methods as described for precipitation. The barium chloranilate method was used for sulfate.

Crustacean plankton samples were taken with conical tow net (63 μ mesh; 30 cm mouth diameter) from near the deepest part of each lake. Two vertical tows from bottom to surface were made. Occasional samples were taken by throwing a weighted net from shore when lakes were too shallow to permit vertical hauls or when storms or mishaps made use of the boat impossible. Experience from alpine lakes elsewhere (Anderson 1971) suggests that this procedure is adequate for determining species composition in shallow lakes, but must be checked by taking vertical hauls at other times in deeper lakes, which was done in every case. Samples were preserved immediately with formalin to a final concentration of 4-5%.

Species composition was determined by examining entire samples under low magnification (40x) with a dissecting microscope; minute characteristics were determined by removing specimens to a slide and examining them at high magnification (400x) under a compound microscope. Cladoceran identifications follow the key of Brooks in Edmondson (1959) with the exception of members of the genus _Daphnia_, which were identified according to the monograph by Brooks (1957), the genus _Ceriodaphnia_, identified according to Brandlova et al. (1972), and the genus *Bosmina*, identified according to Deevey and Deevey (1971). The species *Alona* sp. has been examined by David Frey at the University of Indiana and identified as a new species but has not yet been described or classified. Copepoda identifications were all made according to Edmondson (1959). The identification of *Branchinecta dissimilis* was made according to the description in Belk (1974), and was verified by Dr. Larry Eng in the Rancho Cordoba (CA) office of Cal. Fish and Game.

Chemical Composition of Rain and Snow

Chemical composition of precipitation collected in the east central Sierra Nevada for the period June 81 to April 82 is summarized in Table 1. The period with convective, summer rain storms is listed separately from the seasons with snow derived primarily from frontal storms because of the considerable differences between these two periods. Summer rain on Mammoth Mountain had high ammonium, nitrate and sulfate concentrations and a mean pH of 4.6; pH ranged from 4.4 to 5.3. Sulfuric acid contributed about twice the acidity of nitric acid. The pH of seven summer rains at SNARL ranged from 3.7 to 4.9; six rains at Valentine Reserve ranged from 4.2 to 5.3. Rain fell infrequently during the summer as brief showers; a total of 4 cm of rain fell. Precipitation collected at SNARL and Mammoth Mountain during the summer of 1982 was similar to that from the summer of 1981 except that the nitrate and sulfate concentrations were almost equal. Volume-weighted pH, SO_4 and NO_3 were 4.7, 24 and 17 at SNARL and were 4.9, 18 and 19 on Mammoth Mountain. A total of 13.4 cm of rain fell at SNARL from 11 May until 18 September 82. A total of 15.3 cm of rain fell on Mammoth Mountain from 19 June until 19 September 82.

In contrast, late autumn, winter and early spring snow on Mammoth Mountain ranged in pH from 5.2 to 6.1 (mean 5.7) and had low ammonium, nitrate and sulfate concentrations; similar snow fell at SNARL. The water equivalence of the total precipitation from mid-October to mid-April was 142 cm; the fourteen samples collected from the end of November to mid-April constituted eighty percent of the precipitation. Snowfalls between mid-October and the end of November totalled 48 cm of water and were not sampled on an event basis but were included in the snow sampled from a pit.

A snow pit on Mammoth Mountain was sampled on 22 April 82 before significant snow melt had occurred. These collections represent an integrated sample of the total deposition of solutes since snow accumulation began in mid-October. The average concentrations (μ eq l^{-1}) of solutes are as follows: NH_4, 1.3; Na, 3.9; K, 0.8; Ca, 2.4; Mg, 0.3; NO_3, 1.3; SO_4, <7; Cl, 2. The integrated pH was 5.9. These values are quite similar to those in Table 1.

Areal atmospheric inputs of summer wet and dry deposition and as snowfall for a portion of 1981-1982 are listed in Table 2. The limited extent of these data preclude detailed evaluation but permit some general observations. With the exception of H^+, cation and anion loading by dry fall during the summer is similar to that by rain. Although considerably more precipitation fell as snow, the areal inputs of ammonium are greater during the summer, and areal inputs for the other solutes are disproportionately due to wet and dry deposition in the summer. Furthermore, the Mammoth Mountain area had about 1.6 times more precipitation than is usual during the winter of 1981-82 (California Cooperative Snow Surveys 1982). Within the general area that includes Yosemite, Mammoth Mountain and the Rock Creek basin, the long term, average water content of the snow pack on 1 April among eight routine stations at about 3000 m ASL ranges from 39 cm to 107 cm and averages 75 cm (California Department of Water Resources 1982). The long term average at Mammoth Mountain is 80 cm.

While the east central Sierra Nevada does receive some acid precipitation (pH < 5), over 90% of the precipitation falls as snow with a pH near 5.7, the expected acidity of a solution of atmospheric CO_2 and water. The acid precipitation is associated with occasional convective storms during the prolonged dry season. The strong acid contaminants most likely come from urban and agricultural sources within California (Lawson and Wendt 1982). In contrast, the majority of the precipitation in the Sierra Nevada is associated with large frontal systems that sweep across California from the Pacific Ocean. Precipitation from such storms in sparsely populated coastal regions is not contaminated with strong acids. For example, Kennedy et al. (1979) reported an average pH of 5.3 and average nitrate and sulfate concentrations of 1.6 μeq l^{-1} and < 2.7 μeq l^{-1}, respectively, in the Mattole River basin of northern California. However, these same storm systems pass over coastal and inland cities and agricultural lands that are potential sources of SO_x and NO_x. The pH of precipitation in these areas is usually less than 5 (McColl 1980). Apparently, at least in 1982, these potential contaminants were not present in the east central Sierra Nevada in sufficient quantity to produce acid snow.

Few additional analyses of the chemical composition of precipitation in the Sierra Nevada are available, and no event sampling above tree line other than that reported here for Mammoth Mountain has been accomplished. Feth, Rogers and Roberson (1964) collected snow along major east-west highways in the northern Sierra during the winters of 1958-59 and 1959-60. They judged their data to indicate that no detectable contamination from activities of man influenced the chemical composition of the snow. Their laboratory determinations of pH ranged from 4.2 to 8.3 with a median of 5.8, but these values were considered by Feth et al. not to represent the true pH of freshly melted snow. Brown and Skau (1975) collected snow from snow boards four times at twenty-six locations in the east central Sierra Nevada from January to April 1975. Snow fall was low to moderate (1.5 to 38 cm of water), and chemical concentrations varied little among these locations. Major anion and cation concentrations were similar to those reported here; pH ranged from 5.3 to 5.9. McColl (1980) reported a volume-weighted pH of 5.2 for Tahoe City, but the general applicability of this value may be questioned because of the temperature inversions and large number of automobiles in the Tahoe basin (Cahill et al. 1978). Lawson and Wendt (1982) calculated a volume-weighted mean pH of 5.0 for a full year of samples collected at the NADP site in Sequoia National Park. During the winter the pH of snow at this location is usually above 5.3 (Thomas Nichols, Sequoia-Kings Canyon National Parks, personal communication 1982).

Chemical Composition of Snowmelt

Most of the water derived from snow that enters the Sierran lakes is not melt from fresh snow that directly enters the lakes. Much of the spring snow pack has aged and accumulated solutes fom the local area and perhaps longer distances. A portion of the meltwater passes over rock and through soil before entering the lakes. To qualitatively evaluate the character of aged snow and snowmelt, relevant samples were collected from a variety of locations on the eastern and western sides of the Sierra Nevada (Table 3). The pH of these samples are usually higher than that of fresh snow. Furthermore, the solute content is elevated in comparison to the samples of snowfall collected as events at Mammoth Mountain. These results are in accord with Feth, Rogers and Roberson (1964) who emphasize that melt waters rapidly increase in solute concentration once they contact the lithosphere.

Description of the Lakes and their Basins

A survey of lakes that spanned the length of the Sierra Nevada crest was conducted in June, July, August and September 1981; four lakes were added in the summer of 1982 (Fig. 1, Appendix 1). Seventy-three lakes were visited; of these, 27 were sampled two to four times. Eighty percent of the lakes lie above 3000 m in elevation (Fig. 2) and many were headwaters. The lakes range in surface area from about 0.3 ha to 578 ha (median, 4.7 ha); watershed surface areas range from 14 ha to 8539 ha (median, 127 ha).

Most of the bedrock in the basins consists of granitic rocks, but basins were selected whose bedrocks represent a range of weatherability from calcareous metamorphic rocks to orthoclase granites (Fig. 3, 4 and 5, Appendix 1). The coverage of major rock types in each basin was determined by visually examining U.S.G.S. geologic maps (GQ series) for those quadrangles where such maps exist, and the Geologic Atlas of California (Division of Mines and Geology 1958) for those where extensive mapping has yet to be done. A estimate of the percentage of each rock type - calcareous, volcanic, plagioclase granites, orthoclase granites - in each basin was made. Calcareous bedrocks incldued all metamorphic rocks containing a substantial amount of calcium (i.e. marbles, limestone, dolcmite, calc-hornfels). Volcanic rocks consisted mostly of rhyolite, andesite and slate. The granitic rocks were divided into two groups based on their position on the gradient from plagioclase to orthoclase, with diorite, granodiorite and quartz diorite being considered plagioclase granites, and quartz monzonite, alaskite and true granite being considered orthoclase granites.

Vegetation is very sparse or lacking in the majority of the watershed, but some basins had white bark pine (*Pinus albicaulis*) and sedge-dominated turf near the lakes (Fig. 6, Appendix 2). Visitation frequency varied considerably among the lakes (Appendix 1), but very few, if any, are likely to have had their nutrient or major ion chemistry influenced by people visiting the basin. Further information about tourist use and possible impacts on Sierra lakes are provided in Silverman and Erman (1979), Ghirelli et al. (1977) and Baas et al. (1976).

Major Ion and Nutrient Chemistry of Sierra Nevada Lakes

The waters in Sierra Nevada lakes are extremely dilute, very weakly buffered and oligotrophic. Table 4 summarizes the chemical composition of the lakes sampled in this study. The charge balance of cations and anions ($^{E+}/_{E-}$) for the individual lakes are within 5 to 15% for almost all samples. Table 4 shows for comparison the chemical composition of dilute waters from other regions, some of which are experiencing acidification (eg. Southern-most Norway). The lakes of the Sierra Nevada are clearly very sensitive to acidic precipitation. The low alkalinity of the Sierran waters is especially striking (Fig. 7). Seventy per cent of the lakes sampled have summer alkalinities below 90 μ eq l^{-1}. The few lakes with alkalinities above 210 μeq l^{-1} are either located below 3000 m above sea level or in basins with calcareous rocks.

The major cation in the Sierran lakes is calcium, and bicarbonate is the major anion in most lakes. The linear regression between calcium and bicarbonate has an r^2 of 0.94 and a significance level of 0.0001. The few lakes with as much or more sulfate or chloride as bicarbonate lie in basins with considerable coverage of volcanic rocks or are especially dilute waters on granite. About 80% of the lakes have sulfate concentrations less than 40 μ eq l^{-1} (Fig. 8). Summer pH values in surface waters are usually between 6 and 8 (Fig. 9). These major ion and pH data indicate that the Sierran lakes are not acidified but instead are the expected result of weathering within their basins (see below).

Henriksen (1979, 1980) has devised several methods for predicting the acidification of lakes based on commonly measured chemical parameters. One such method is applied to data for Sierran lakes in Figure 10. Calcium concentration, assumed to represent the original alkalinity of lakes before acidification, is graphed vs. excess sulfate concentration, the measured sulfate concentration corrected for sulfate input from sea-salt spray. Based on empirical data from several hundred lakes in Scandinavia the graph delineates areas representing bicarbonate lakes ($pH > 5.3$), transition lakes ($4.7 < pH < 5.3$) and acid lakes ($pH < 4.7$). Several of the lakes sampled in midsummer of 1981 fell into the transition zone but probably because of weathering of non granitic rocks within their basins, not because of acid precipitation. The lowest scale on the graph indicates the severities of acid precipitation which have been found to push lakes into the acidic zone. Clearly the potential exists for acidification of many Sierran lakes by precipitation with pH's of 4.5 to 4.6. The temporary acidification of lakes still under winter ice cover is even more likely, and this is the pattern found in many studies of high elevation lakes whose midsummer pH's have not yet reached the acid range (Henriksen and Wright, 1977; Hultberg, 1977).

The extremely low concentrations of nutrients and the very clear waters indicate that almost all Sierran lakes are oligotrophic or ultra-oligotraphic. About 90% of the lakes sampled have nitrate values less than 4 μM (Fig. 11), ammonium values less than 0.7 μM (Fig. 12) and orthophosphate values less than 0.2 μM (Fig. 13). The few waters with elevated nitrate are clear, alpine lakes. Several lakes with pH's above 8 (Fig. 9) were shallow with abundant aquatic plants; as the plants use CO_2 for photosynthesis, they can readily raise the pH in those poorly buffered waters.

The alkalinity, pH, major solutes and nutrients of the lakes of the Sierra Nevada have been measured infrequently and in few of the thousands of lakes. Moreover, very seldom have the analyses of pH and alkalinity been performed with sufficient attention to the rapid changes that occur in these dilute, weakly buffered waters. For example, Bradford et al. (1968) surveyed 170 alpine lakes in the summer of 1965 but made their pH measurements about two weeks after collection of the samples. During a repeat sampling of many of these same lakes in the summer of 1981, Bradford et al. (1981) measured pH within about 4 hours of collection and reported a pH range of 5.6 to 6.9. Neither of these surveys included alkalinity determinations. Tonnessen and Harte (1982) sampled 26 subalpine lakes on the western sopes of the Sierra Nevada during the summers of 1980 and 1981 and reported a pH range of 6.0 to 8.5 and that about 40% of the lakes had alkalinities below 100 μeq l^{-1}. Reimers et al. (1955) reported analyses of Na, K, Mg, Ca, HCO_3, Cl, and SO_4 for ten lakes in the Convict Creek basin. Although colorimetric pH measurements were made in the field, these values are not reported for each lake because the authors found that the laboratory pH determinations were consistently higher and that the field values were too coarse to compare the lakes. Mankiewicz and Sweeney (1977) used measurements of Ca, Mg, Na, K, pH and carbon ($^{13}C/^{12}C$) ratios in an analysis of the chemical history of a lake-spring complex near the headwaters of Mammoth Creek; two alpine lakes are included. Several additional analyses of major ions in Sierran lakes are provided by Baas et al. (1976), LADWP (1972, Twin Lakes near Mammoth Lakes), and Silverman and Erman (1979, Rae Lakes). Data on fourteen additional alpine lakes were located in unpublished reports and files of the U.S. Geological Survey. Most of these analyses included only a portion of the major ions and the pH's were measured in the laboratory after excessive delay.

Because there are no reliable and representative measurements of alkalinity in high altitude lakes prior to those reported here and those of

Tonessen and Harte, it is not possible to recognize if a change through the years in the alkalinity such as that reported by Lewis (1982) for the Colorado Rockies is occurring in the Sierra Nevada. McColl (1981) presents evidence that two reservoirs in the western foothills of the Sierra Nevada (Pardee and Hetch Hetchy) have decreased slightly in pH over the period 1954-1979. During the same interval the alkalinity of Pardee appears to have decreased about 60 μeq l^{-1}. If this result is real, and not a methodological artifact, it is surprising that some of the much less buffered alpine lakes do not appear acidified.

Only a small, albeit representative, subset of Sierran lakes were sampled in this study. Although regional generalizations about the sensitivity of the lakes to acid precipitation are valuable and valid, to be able to predict the alkalinity of individual, unsampled lakes may prove useful in the future. For example, Turk and Adams (1983) were able to predict the alkalinity of lakes in the Flat Tops Wilderness Area, Colorado, from the altitude of the lakes. To determine the feasibility of predicting the alkalinity of Sierran lakes from readily obtainable information, a step wise, multiple regression was done using lake altitude, basin area and lake area as independent variables. The best single variable model uses basin area as the independent variable and explains 28% of the variance in alkalinity at a 0.0001 significance level. Adding elevation, the second best variable, and their lake area increased the r^2 value to only 29%. At least among the lakes included in this analysis, alkalinity cannot be predicted from readily available geographic criteria with sufficient certainty to be useful.

The chemical composition of natural waters is governed largely by watershed characteristics and atmospheric deposition. Feth, Roberson and Polzer (1964) provide chemical analyses of 104 springs and 34 streams located in the northern Sierra Nevada and a geochemical interpretation of solute acquisition and loss. These data include pH measurements made in the field and laboratory pH values, and illustrate the substantial changes that can occur if pH is not measured within a few minutes after collection of the sample. At the time of Feth et al.'s study, virtually the only source of inorganic acid and the major source of hydrogen ions was the reaction of carbon dioxide to form carbonic acid. Furthermore, about 95% of the total mineral content of the spring water was derived from the lithosphere. Based on the data provided by Feth et al., Garrels and MacKenzie (1967) proposed a scheme for the genesis of spring waters of the Sierra Nevada. The composition of these spring waters is consistent with a model in which high CO_2 soil waters react with igneous rocks.

Climatic factors, such as the seasonal and geographic distribution of precipitation and temperatures, as well as hydrogen ion activities and the lithosphere influence the rates of weathering and chemical character of waters. The Sierra Nevada experiences marked wet and dry seasons with most precipitation as snow in the winter (Miller, 1955); but annual evaporation ranges from less than 75 cm in the High Sierra to about 105 cm in the foothills and mean annual precipitation ranges from 180 to 40 cm. When these climatic differences are imposed on the petrologic diversity within the Sierra Nevada (e.g., Bateman, 1961, Matthes, 1930) a range of water chemistries can result. In fact, the majority of the lakes sampled are calcium-bicarbonate waters as predicted by the weathering model of Garrels and MacKenzie (1967). Exceptions do occur, however, and reflect weathering of nongranitic rocks.

To further evaluate the role of drainage basin characteristics on the chemical composition of Sierran lakes a series of statistical analyses were performed. Nitrate, sulfate, chloride, calcium, alkalinity and pH wer related to the areal coverage of rock types in the basins. The values us in this analyses are listed in Appendix 1. The statistics are summarized in Table 5. A Wilcoxon ranked sum test was evaluated for significance with the chi-squared approximation of the Kruskal-Wallis test. A significant relation indicates either a positive or negative trend over all the categories from the concentration of the chemical constituent and the areal coverage for the rock type. The most conspicuous relations are the positive trends between sulfate, calcium and alkalinity and volcanic and calcareous rocks. The negative trends between sulfate and chloride and the orthoclase granites probably indicate the importance of atmospheric deposition as the source for these two ions in basins with hard granites.

To predict the impact or potential impact of the atmospheric deposition of acidity on a lake requires measurements of the areal loading to the drainage basin and subsequently to the lake as modified by buffering within the basin and the lake. In the Sierra Nevada most of the precipitation accumulates as snow and then more or less abruptly enters the lake during snow melt. Furthermore, laboratory and field examinations of snow melt chemistry (e.g. Colbeck 1981, Jefferies et al. 1979) indicate that solutes are concentrated in the first stages of runoff.

Among the alpine lakes sampled in our survey the ratio of the surface area of the basin to the volume of the lake varied from 3 to 200. As a hypothetical exercise, if a range of snow pack depths (0.8 to 1.6 m of water) with different acidities (pHs 5.1 to 5.4) is applied to this range of basins, an estimate of the impact of spring snowmelt on the pH of the lakes can be made. The results of such a simulation for Sierra Nevada lakes indicate that most of the lakes will attain the pH of the runoff water. The model assumes that 80% of the solutes enter the runoff in the first 50% of the snowmelt, a snow alkalinity of 2 μeq l^{-1}, no buffering of the runoff before it reaches the lake, no thermal stratification in the lakes and no contribution from the sediments to the alkalinity of the lake during the brief period of snow melt. If a greater proportion of the solutes leave the snow earlier in the melt or if the lake is stratified and thus the runoff is added to a smaller volume of lake water, the acidic loading would be greater. These two possibilities are likely. The major uncertainty in this model is the extent of buffering and contributions of additional alkalinity from weathering in the basin and from the lake sediments. In the alpine basins of the Sierra Nevada thick snow packs with ice layers interspersed will tend to route some portion of the runoff through the snow itself, and the underlying ground is largely bare granites with little soil. These factors would reduce the extent of the buffering in the basin. The lake sediments can contribute to the alkalinity of the overlying water as demonstrated in laboratory microcosms by Tonnessen and Harte (1982). However, during the short period with large inflows of snow melt into a lake that may be stratified, the influence of the sediments is likely to be low.

Distribution of Zooplankton and Fish Species

The distribution of zooplankton species in the Sierra is very poorly described. Despite the potential importance of zooplankton as food organisms for fish, only one study has thus far determined the zooplankton species composition of any lakes in the Sierra (Reimers et al. 1955). The distribution of fish species is better known, but is nonetheless incomplete. Fish stocking records are irregular, and, when available, do not usually match the species present in high elevation lakes many years later. A few lake surveys, conducted by the California Department of Fish and Game, and Sequoia/Kings Canyon National Parks, provide much better data but for a more limited number of lakes. Of the 72 lakes sampled for zooplankton, we have information of the fish species present in 68.

Table 1 gives the results of the zooplankton and fish species surveys in terms of an altitudinal gradient from montane (in heavily forested basins) to alpine (above timberline) lakes. A general trend of decreasing species richness as elevation increases is apparent in both the fish and zooplankton numbers. This trend has also been noted for lakes in Canada (Anderson 1971) and Colorado (Reed and Olive 1958; Patalas 1964).

Typical fish communities can be described for each altitudinal zone. In the alpine lakes, the usual community either lacks fish, or consists of a single fish species (either Golden Trout, _Salmo aguabonita_, or Rainbow Trout, _Salmo gairdneri_). In subalpine lakes the typical community consists of two species, usually one of the above plus Eastern Brook Trout (_Salvelinus fontinalis_). In montane lakes, the community is typically made up of two or three trout species (Rainbow and Eastern Brook plus Brown Trout, (_Salmo trutta_) plus one or two other species such as sticklebacks (_Gasterosteus_ sp.) or chubs (_Gila_ sp.).

Typical zooplankton communities are less easy to describe based on altitudes largely because of the strong influence that the presence or absence of fish exerts on the zooplankton species composition. As a result, it is easier to describe the typical zooplankton community of a fishless lake than it is to describe the zooplankton of a lake of a given elevation. This influence is clear from Figure 14, where the occurrence of various zooplankton species is charted in terms of lakes with or without fish. The importance of fish presence to the size of the zooplankton species in a given lake is clear from the occurrence of large species in lakes without fish (toward the top of the figure) and smaller species in lakes with fish (toward the bottom of the figure). This pattern is not surprising and has been described in lakes all over the world (cf. Brooks and Dodson 1965; Zaret 1980). The importance of fish predation in excluding large-bodied species is well acknowledged, but some controversy exists over the reasons why fishless lakes are so universally dominated by large species rather than by small ones, or by some mixture of the two.

Sierran lakes follow the pattern described for other mountainous regions, namely, that fishless lakes are dominated by large, highly-pigmented forms (Anderson 1971, 1974, in Canada; Patalas 1964, Sprules 1972, in Colorado; Williams 1976, in Wyoming). In the Sierra, these communities are always made up of _Daphnia_ _middendorffiana_ and _Diaptomus_ _shosone_ or _Diaptomus_ _eiseni_ (but never both) and occasionally the anostracan _Branchinecta_ _dissimilis_. This large-bodied community has been shown to be maintained by invertebrate predation elsewhere (Sprules 1972; Williams 1976). An interesting difference is that no invertebrate predators of the type described in these studies (mostly _Chaoborus_ larvae) were found in our samples.

A typical community in a lake with fish in the Sierra would consist of Daphnia galeata mendotae (the most common species found), Diaptomus signicauda and Chydorus sphaericus (the two next most common species). As species richness increases (e.g. at lower elevations or in more productive lakes), species such as Bosmina longirostris, Holopedium gibberum or Alona affinis would be typical. All of these species are strongly associated with the presence of fish (in a Chi Square test, all associations with fish are significant at the $p < .05$ level), just as the large-bodied community is negatively associated with fish (all associations significant at the $p < .001$ level).

Several taxonomic points should be noted. In all samples except one, Daphnia galeata mendotae specimens lacked the helmeted carapaces typical of this species. Individuals closely resemble Daphnia rosea in some respects, but the strong likelihood that predation rates are too low in most Sierran lakes to induce helmet formation in Daphnia spp. (see O'Brien and Kettle 1979; Grant and Bayly 1981), led us to regard these specimens as unhelmeted D. galeata mendotae.

The two samples of Branchinecta dissimilis are the third and fourth descriptions of this species in California (Larry Eng, personal communication). The two other descriptions are also from high elevation lakes.

Chydorus cf. sphaericus and Alona affinis, which are described here as single species, probably consist of several species from each group.
Dr. David Frey, a chydorid expert at the University of Indiana, has examined some of these samples, and has concluded that at least one new species of the C. sphaericus group is present in these samples.

Likewise, *Alona* cf. *setulosa* has been determined to be a new species by Dr. Frey. More samples are currently being examined to determine the number of chydorid species present in these samples, and it is thought likely that several new species of the genera *Chydorus* and *Alona* will be found.

Finally, it should be noted that 4 of the lakes in our survey were previously sampled in 1950 (Reimers et al. 1955) and it is interesting to note the remarkable similarity in species composition between the two sampling dates. Although the species compositions of individual lakes are not given in the earlier study, of the six species described - *Daphnia pulex*, *D. longispina* (which has since been reclassified as *D. galeata mendotae*), *Holopedium gibberum*, *Diaptomus signicauda*, *Cyclops vernalis*, and *Eucyclops agilis* - only the last was not found in the resampled lakes.

Principal Findings and Recommendations

The major results of our study can be summarized as follows:

1. Dry season (i.e. summer-autumn) rain in the east central Sierra Nevada is acidic (pH 3.7 to 4.9). Sulfuric and nitric acids contribute to this low pH.

2. Late autumn, winter and spring snow in the east central Sierra Nevada contains low nitrate and sulfate and its pH ranges from 5.2 to 6.1.

3. This contrast between rain and snow suggests different sources for the chemical constituents.

4. Fresh snow melt collected in late spring on the eastern and western Sierran slopes ranged in pH from 5.4 to 6.3 and contained slightly more solutes than fresh snow.

5. The alpine lakes of the Sierra Nevada are very dilute and weakly buffered, bicarbonate lakes. The summer pH's range from ca. 6 to 8. The lakes do not appear to show signs of acidification but are extremely sensitive to slight increases in the acidity of precipitation.

6. The alpine lakes are oligotrophic or ultraoligotrophic based on their low orthophosphate, ammonium and nitrate concentrations and the clarity of their water.

7. The alkalinity of Sierran lakes cannot be predicted from readily available geographic information (i.e. altitude, basin area, lake area).

8. The content of sulfate, calcium and alkalinity in lake waters are positively correlated with volcanic and calcareous rocks.

9. A simulation model of the impact of snow packs of slight acidity (pH's 5.1 - 5.4) indicated that most alpine lakes wouuld attain the acidity of the snow melt.

10. Most Sierran lakes contain fish, and the presence of fish influences the species composition of the zooplankton. Assemblages with large-bodied species occur in the absence of fish while smaller species are dominant in the presence of fish.

Recommendations for future research and management derived from our study are as follows:

1. Continued monitoring of precipitation chemistry at more stations is necessary to permit evaluation of trends and to verify the generality of our findings.

2. An analysis of weather patterns and mapping of potential source areas is required to explain the contrast between summer and winter.

3. The role of dry fall as a component of atmospheric deposition must be evaluated. This requires considerable methodological development prior to a monitoring program.

4. The potential for differential melting of acidic water from the snow pack should be investigated further. This research should include specially designed traps and field collections of naturally flowing melt water.

5. Continued monitoring of selected alpine lakes should be continued on a 2-5 year cycle to determine if trends in lake acidity are occurring.

6. The aluminum chemistry of alpine waters should be investigated because of the key role of aluminum in degradation of acidified lakes.

7. A watershed-level examination of a representative alpine lake should be initiated. Such a study would integrate terrestrial, aquatic and atmospheric factors and provide the basis for a predictive model of responses to acidification.

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Table 1. Chemical composition of precipitation, east central Sierra Nevada.

Location Dates	Volume-weighted mean μ eq l^{-1}								
	pH	NH_4	Na	K	Ca	Mg	NO_3	SO_4	Cl
Mammoth Mtn.									
30 Jun 81 - 3 Oct 81	4.6	25	11.3	2.7	10.4	3	17	36	12
30 Nov 81 - 14 Apr 82	5.7	0.3	4	0.6	1.5	0.3	1.3	<6	4.1
30 Jun 81 - 14 Apr 82	5.5	2.4	4.3	0.7	1.8	0.4	2.8	<7	4.4
SNARL									
29 Nov 81 - 11 Apr 82	5.7	0.5	3.4	0.8	3	0.5	2.2	<7	3

Table 2. Precipitation loading at Mammoth Mountain, California.

Type Dates	m eq m^{-2}								
	H	NH_4	Na	K	Ca	Mg	NO_3	SO_4	Cl
Dry deposition									
30 Jun 81 - 3 Oct 81	0.1	0.6	0.5	0.2	1.0	0.2	–	0.8	0.4
Wet deposition									
30 Jun 81 - 3 Oct 81	1.0	1.0	0.5	0.1	0.4	0.1	0.7	1.4	0.5
Snow deposition									
30 Nov 81 - 14 Apr 82	2.8	0.4	5.7	0.9	2.1	0.4	1.8	8.5	5.8

Table 3. Snowmelt chemistry near Sierra Nevada alpine lakes.

Location	Date	pH	μ eq l^{-1}				
			NO_3	SO_4	Cl	Ca	Na
Tioga Pass area							
Up. Granite L.	31 May 81	5.6	0.4	17	4	73	15
Up. Gaylor L.	31 May 81	5.6	3.2	22	9	64	10
Summit L.	31 May 81	6.0	0.1	51	10	68	39
Parker Pass	31 May 81	5.9	1.6	19	6	36	34
Sequoia N.P.							
Pear L.	4 June 81	5.4	1.1	7	3	2	1
Heather L.	4 June 81	6.0	7.7	45	12	8	10
Twin L.	5 June 81	6.3	2.2	25	5	8	13
Mosquito L. #5	6 June 81	6.0	8.8	11	7	11	11
Up. Monarch L.	7 June 81	6.2	6.7	30	1	15	14
Lw. Crystal L.	7 June 81	6.1	5.1	22	3	22	11

Table 4. Chemical composition of dilute lakes (mean; median in parenthesis for Sierra Nevada only; H range for ELA and Sierra Nevada)

Region	# of lakes	µS/cm at 25°C				$\mu eq\ l^{-1}$					
			H	Na	K	Ca	Mg	HCO_3	Cl	SO_4	NO_3
Sierra Nevada, California	(73)	24 (14)	0.0004-2	26	15	164 (43)	11	108 (50)	15 (8)	38 (17)	2 (0.25)
Experimental Lakes Area, Ontario[1]	(40)	21	0.2-2	40	10	80	75	60	40	60	<1.5
West-central Norway[2]	(23)	15	6	50	3	18	16	13	46	33	5
Southern-most Norway[2]	(26)	30	18	70	5	55	41	11	71	100	4

1. Armstrong and Schindler 1971

2. Wright and Gjessing 1976

Table 5. Chi squared values as approximations of Krustal-Wallis test of significance for Wilcoxon ranked sum test.

(-) indicates trend with decreasing values of chemical constituent versus increasing rock type coverage;

(+) indicates trend with increasing value of chemical constituent versus increasing rock type coverage.

	Rock Type			
Chemical Constituent	Orthoclase Granite	Plagioclase Granite	Volcanic Rocks	Calcareous Rocks
Nitrate	0.78	0.76	0.36	0.79
Sulfate	0.024(-)	0.019(+)	0.0001(+)	0.002(+)
Chloride	0.031(-)	0.38	0.15	0.13
Calcium	0.21	0.042(+)	0.0002(+)	0.0008(+)
Alkalinity	0.93	0.07	0.006(+)	0.005(+)
pH	0.58	0.11	0.015(+)	0.032(+)

Table 6. Species richness of lakes across an altitudinal gradient.

	MONTANE (n = 10)	SUBALPINE (n = 29)	ALPINE (n = 33)
Elevation range (meters)	2150-2750	2750-3200	3200-3800
Range of zooplankton species number	3-8	1-8	0-4
Mean number of zooplankton species	5.0	4.0	1.7
Range of fish species number	1-5	0-2	0-3
Mean number of fish species	3.0	1.6	0.8

Figure Captions

Figure 1. Location of lakes sampled in summers of 1981 and 1982 (●) and of precipitation collectors sampled year round (✫). The Central Valley is on the west and the Owens Valley on the east. Shaded area lies along the Sierra Nevada crest and is over 9000 ft. (ca. 3000 m) elevation. Three lakes near Lake Tahoe are not marked.

Figure 2. Altitudes (meters above sea level) of Sierran lakes sampled.

Figure 3. Percentage areal coverage of orthoclose granites in lake basins (see text for explanation).

Figure 4. Percentage areal coverage of plagioclase granites in lake basins (see test for explanation).

Figure 5. Percentage areal coverage of volcanic rocks in lake basins (see text for explanation).

Figure 6. Dominant plant communities in lake basins (see Appendix 2 for explanation of classes).

Figure 7. Alkalinity of Sierra Nevada lakes measured during ice free period. Black section of histogram represents lakes extremely sensitive to acid inputs; cross-hatched section represents lakes very sensitive to acid input.

Figure 8. Sulfate concentrations in Sierra Nevada lakes.

Figure 9. Midsummer pH values in Sierra Nevada lakes.

Figure 10. Data for Sierra Nevada lakes fitted to nomogram developed by Henriksen (1980) to predict acidification.

Figure 11. Nitrate concentrations in surface waters of Sierran lakes.

Figure 12. Ammonium concentrations in surface waters of Sierran lakes.

Figure 13. Orthophosphate concentrations in surface waters of Sierran lakes.

Figure 14. Distribution of zooplankton species in lakes with (n = 58) and without (n = 10) fish. Species are arranged roughly from largest at top to smallest at bottom. Height of bar = percentage of lakes in each class which contain that species.

Figure 1

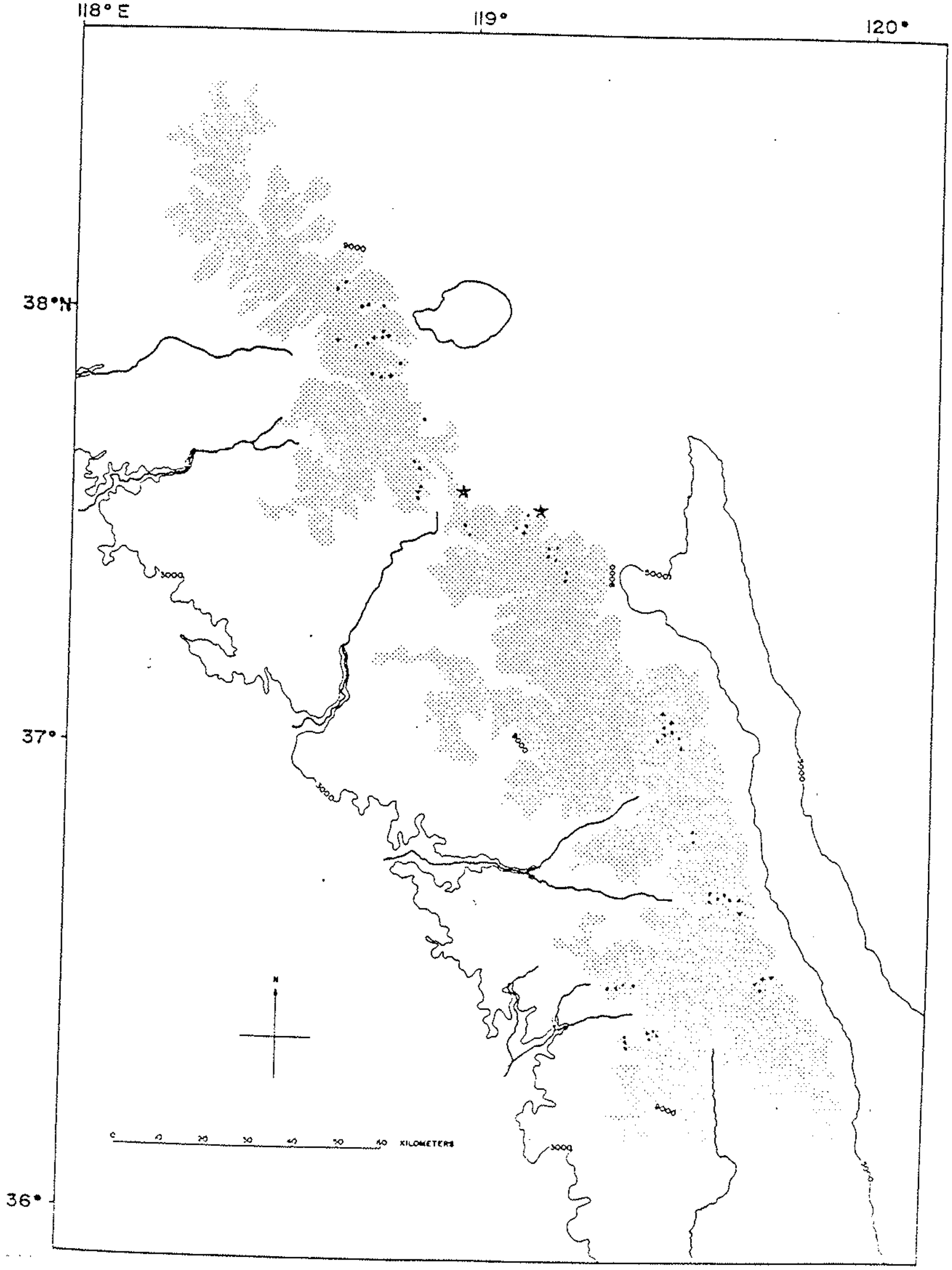
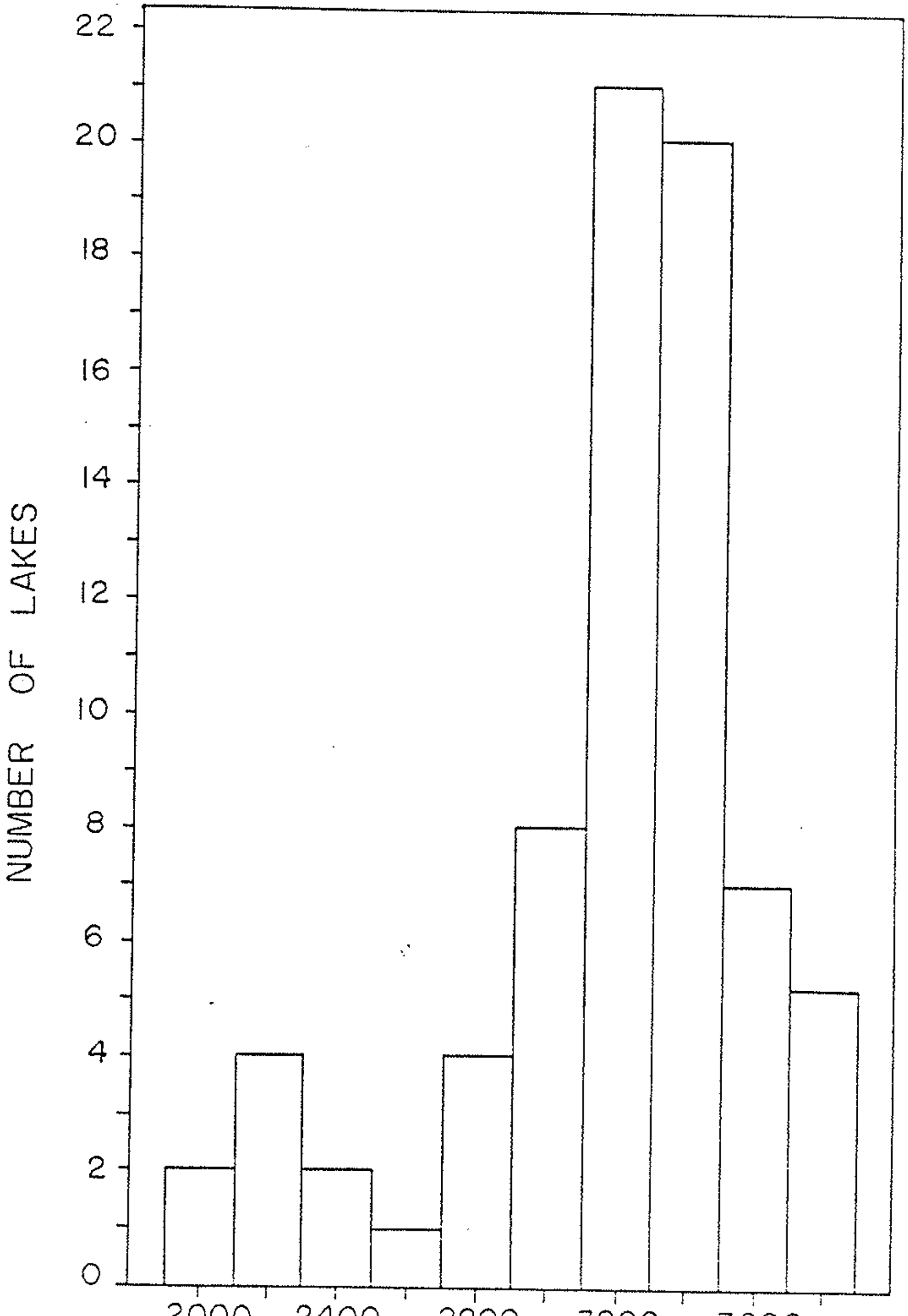
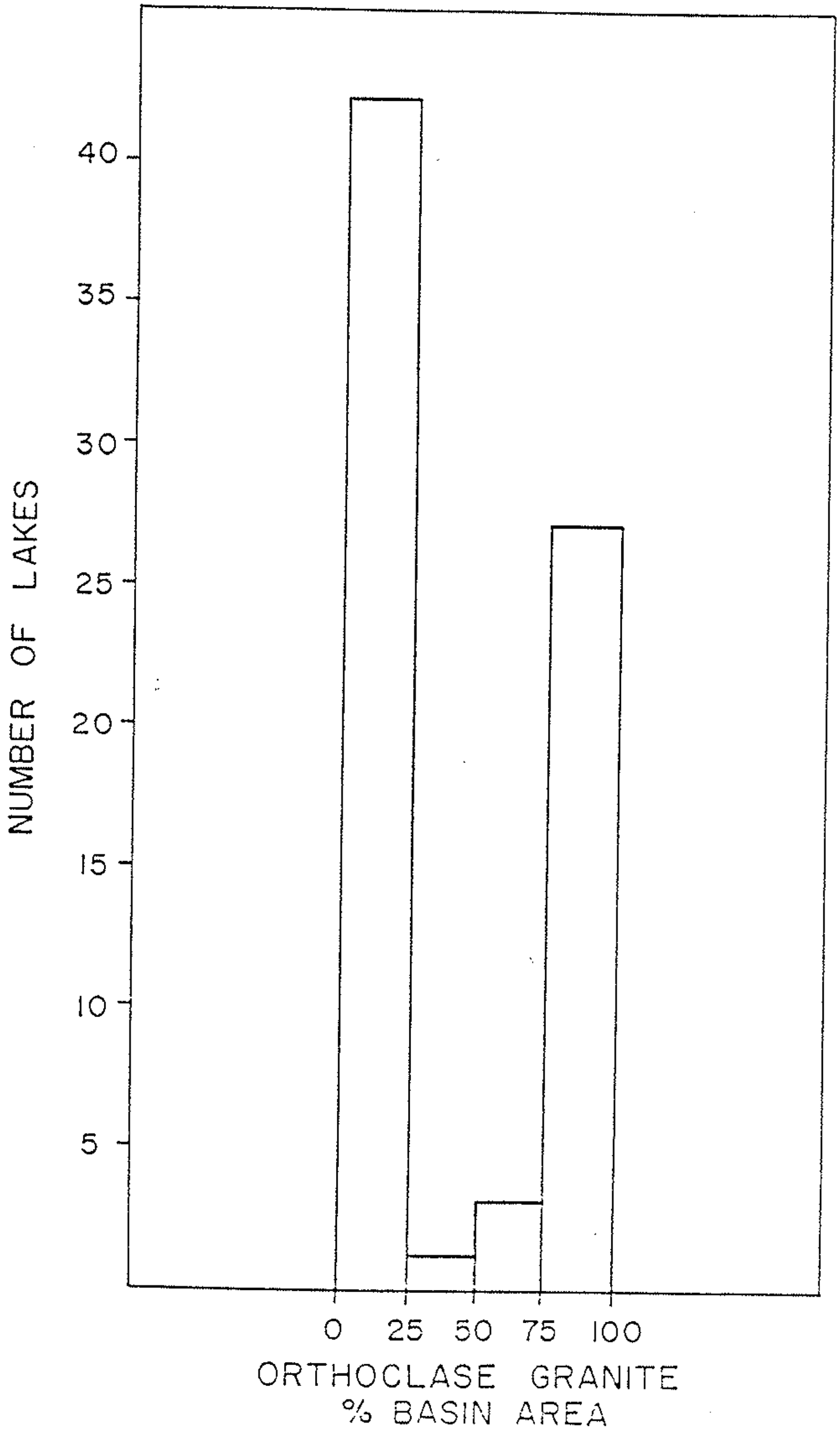

118° E
119°
120°
38°N
37°
36°
3000
3000
3000
3000
N
0 10 20 30 40 50 60 KILOMETERS

Figure 2



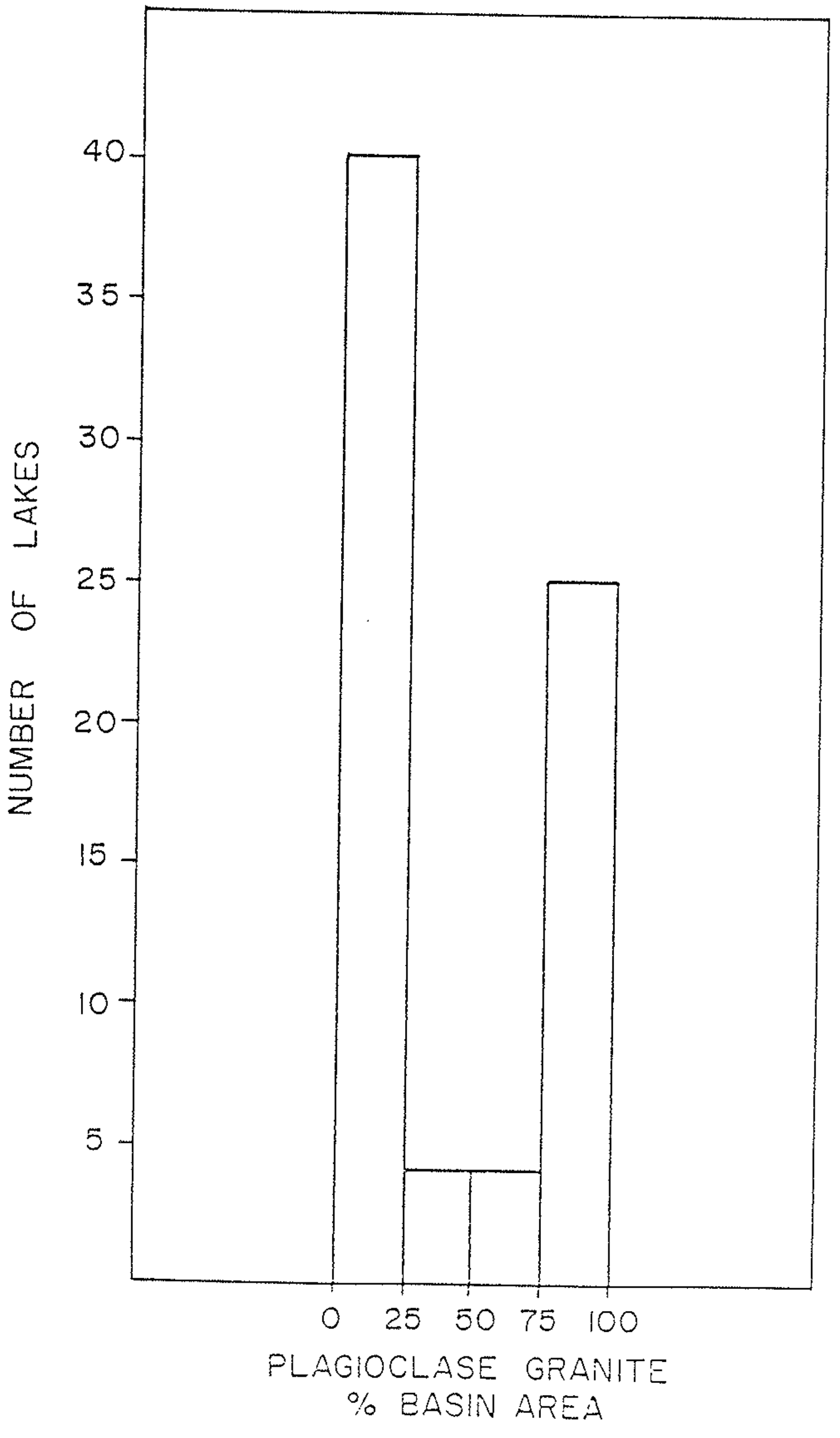
NUMBER OF LAKES
22
20
18
16
14
12
10
8
6
4
2
0
2000
2400
2800
3200
3600
ELEVATION

Figure 3



NUMBER OF LAKES
40
35
30
25
20
15
10
5
0
25
50
75
100
ORTHOCLASE GRANITE
% BASIN AREA

Figure 4



NUMBER OF LAKES
40
35
30
25
20
15
10
5
0
25
50
75
100
PLAGIOCLASE GRANITE
% BASIN AREA

Figure 5

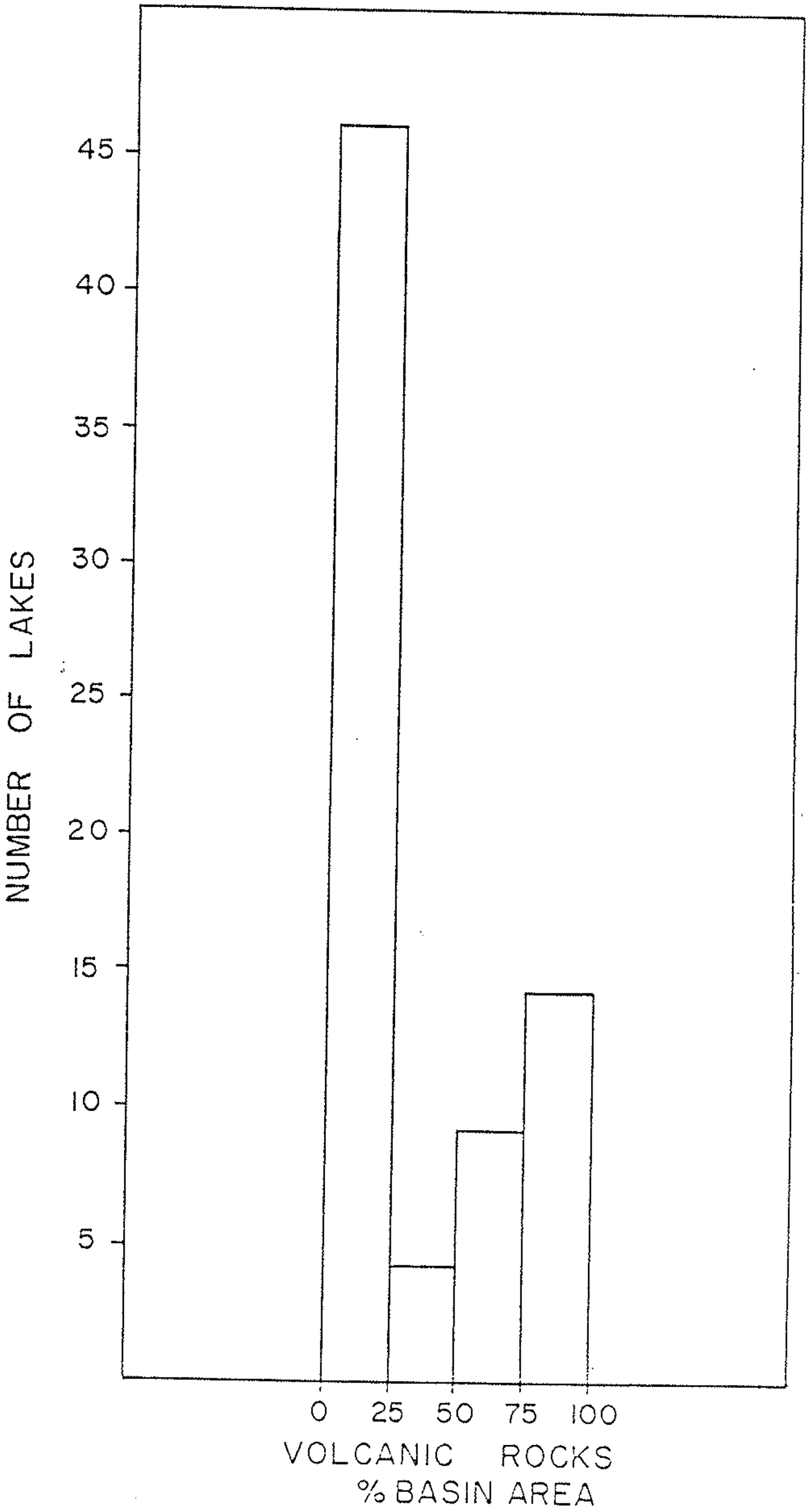
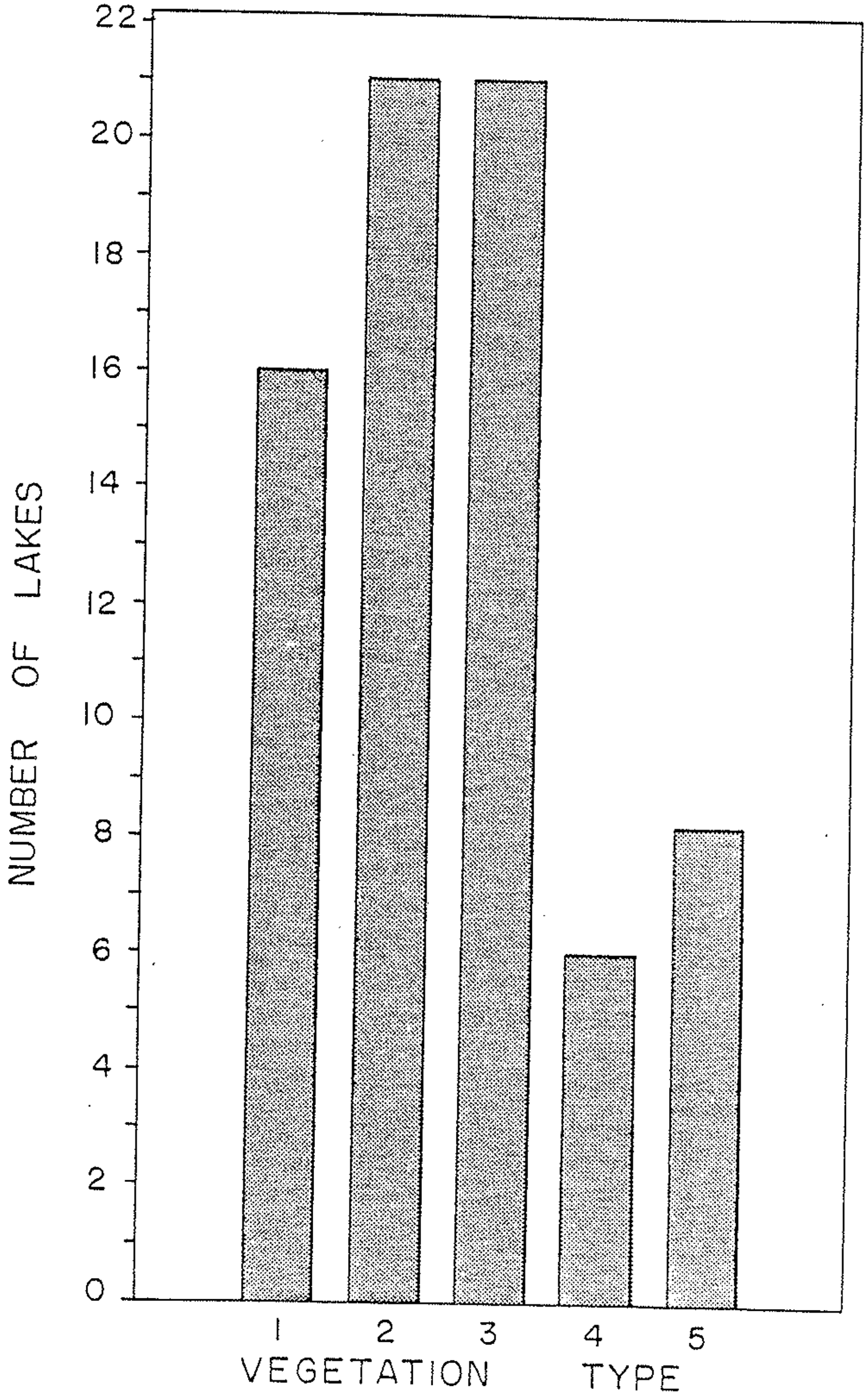
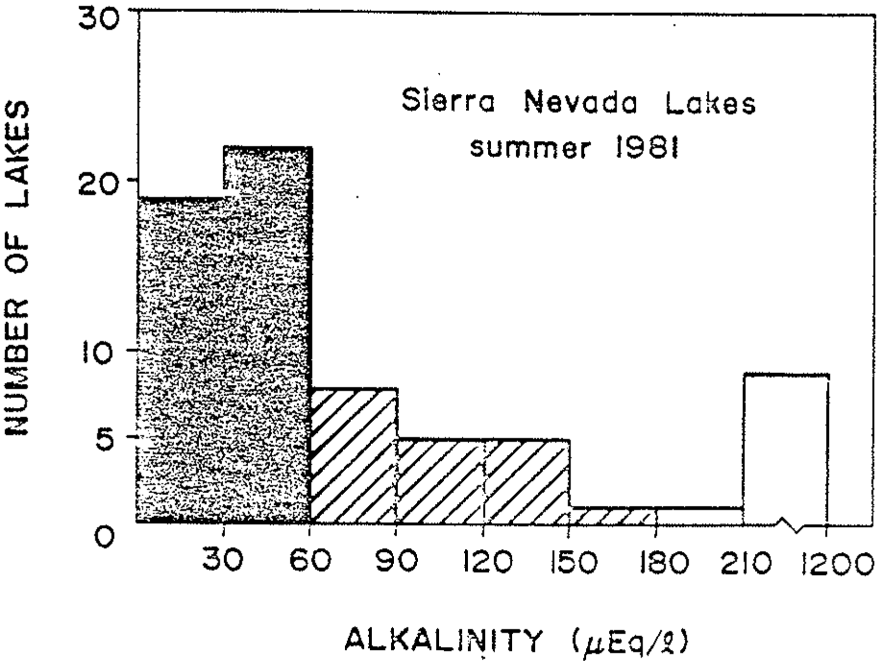

NUMBER OF LAKES
45
40
35
30
25
20
15
10
5
0
25
50
75
100
VOLCANIC ROCKS
% BASIN AREA

Figure 6



22
20
18
16
14
12
10
8
6
4
2
0
NUMBER OF LAKES
1
2
3
4
5
VEGETATION TYPE

Figure 7



Sierra Nevada Lakes
summer 1981
NUMBER OF LAKES
30
20
10
5
0
30
60
90
120
150
180
210
1200
ALKALINITY (μEq/ℓ)

Figure 8

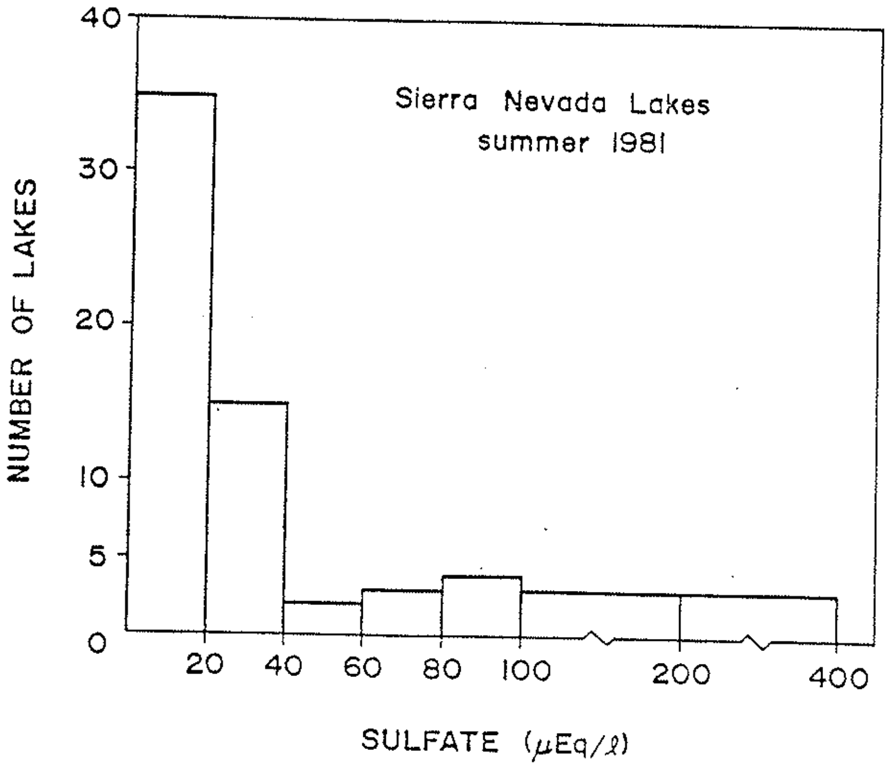

Sierra Nevada Lakes
summer 1981
NUMBER OF LAKES
0
5
10
20
30
40
20
40
60
80
100
200
400
SULFATE (μEq/ℓ)

Figure 9

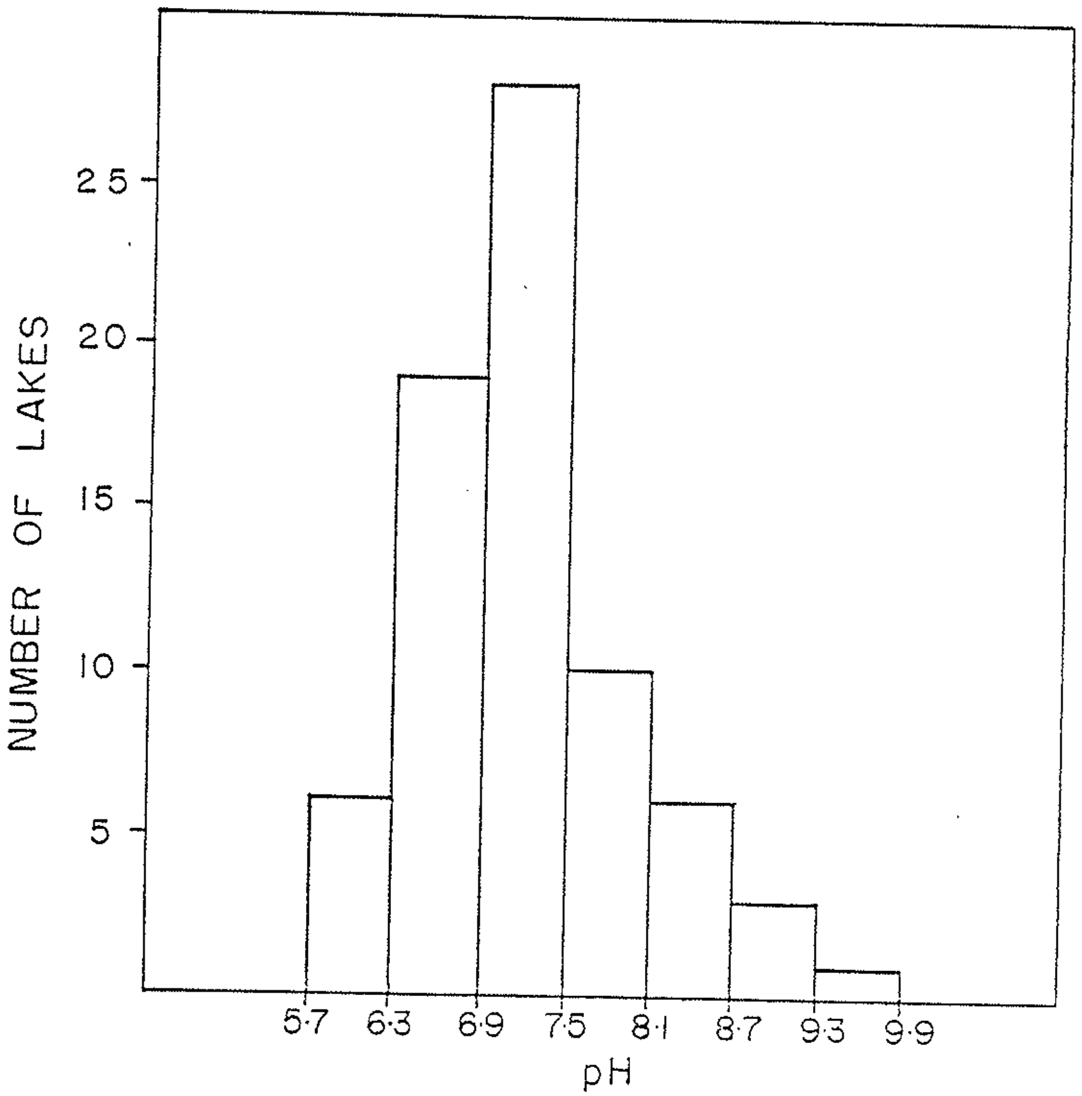
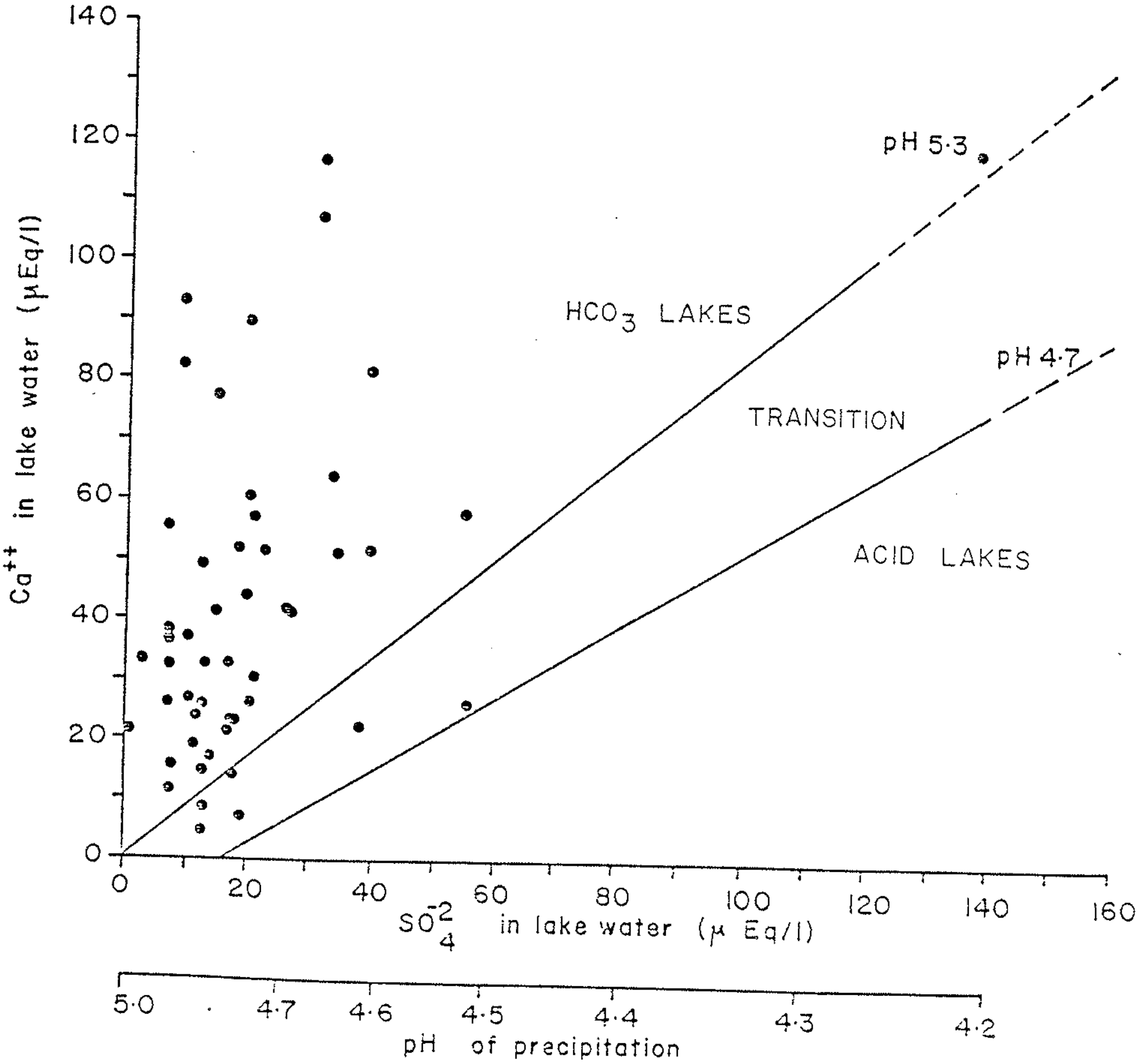


Figure 10



140
120
100
80
60
40
20
0
Ca++ in lake water (μEq/l)
0
20
40
60
80
100
120
140
160
SO4-2 in lake water (μ Eq/l)
5.0
4.7
4.6
4.5
4.4
4.3
4.2
pH of precipitation
pH 5.3
pH 4.7
HCO3 LAKES
TRANSITION
ACID LAKES

Figure 11

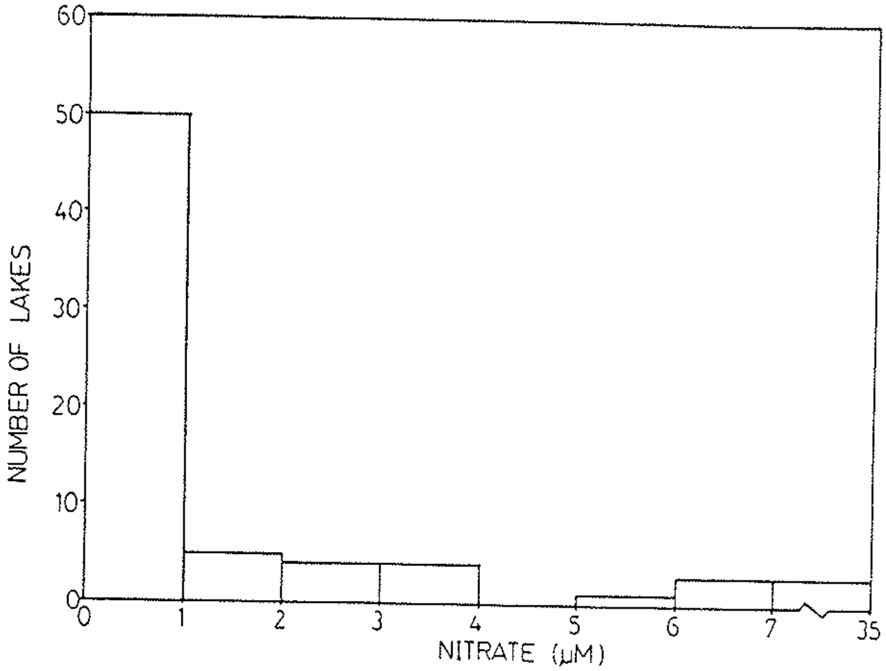


Figure 12

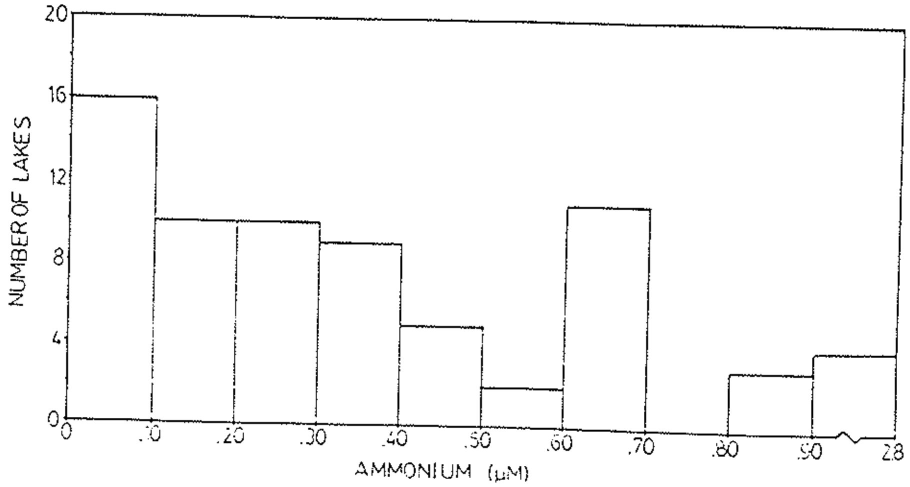
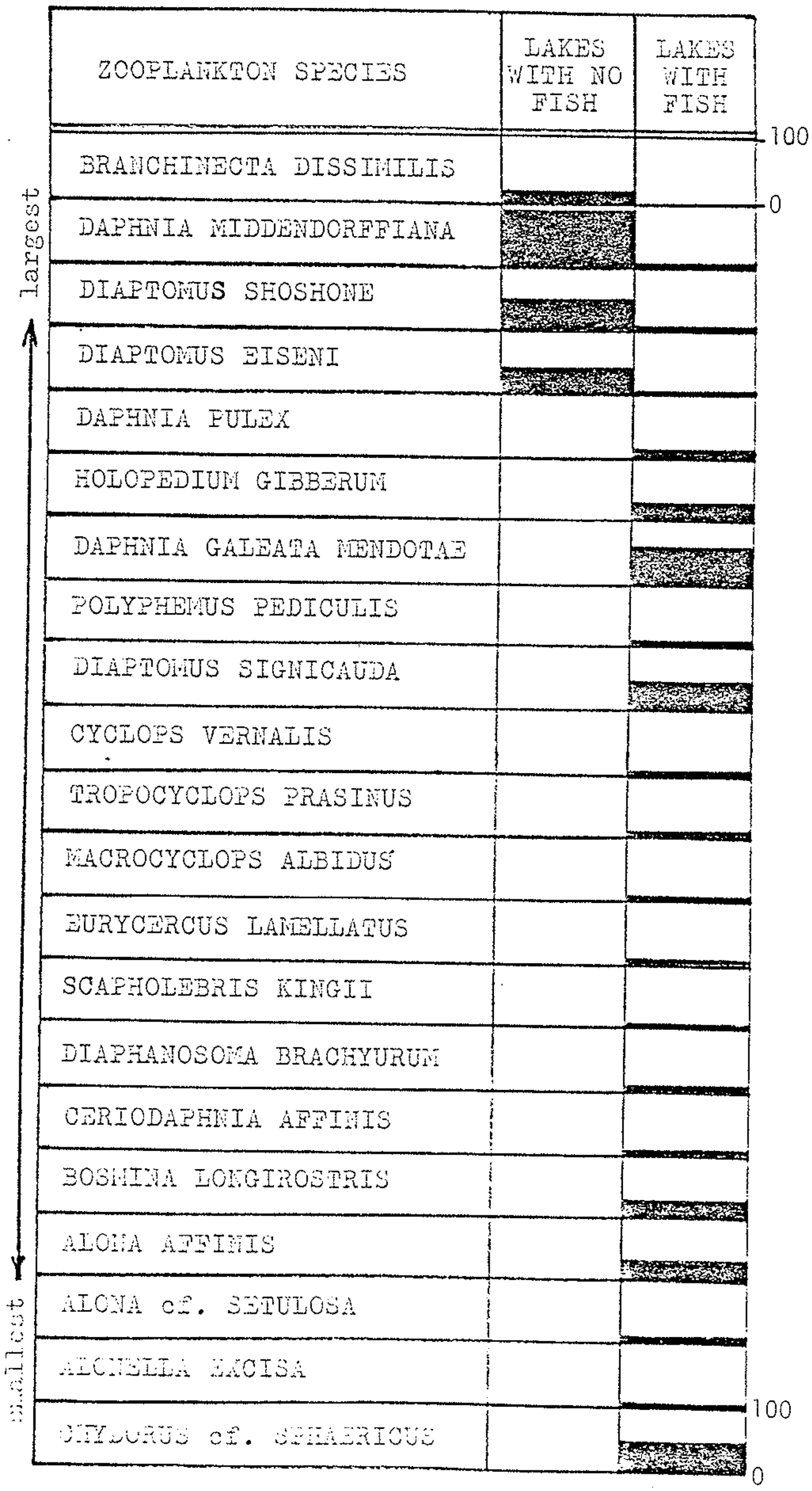


Figure 14


ZOOPLANKTON SPECIES
LAKES WITH NO FISH
LAKES WITH FISH
100
0
largest
smallest
BRANCHINECTA DISSIMILIS
DAPHNIA MIDDENDORFFIANA
DIAPTOMUS SHOSHONE
DIAPTOMUS EISENI
DAPHNIA PULEX
HOLOPEDIUM GIBBERUM
DAPHNIA GALEATA MENDOTAE
POLYPHEMUS PEDICULIS
DIAPTOMUS SIGNICAUDA
CYCLOPS VERNALIS
TROPOCYCLOPS PRASINUS
MACROCYCLOPS ALBIDUS
EURYCERCUS LAMELLATUS
SCAPHOLEBRIS KINGII
DIAPHANOSOMA BRACHYURUM
CERIODAPHNIA AFFINIS
BOSMINA LONGIROSTRIS
ALONA AFFINIS
ALONA cf. SETULOSA
ALONELLA EXCISA
CHYDORUS cf. SPHAERICUS
100
0

Appendix 1

Sierra Nevada lakes sampled in 1981 and 1982 (nos. 70, 72, 72, 73).

Conduct (= electrical conductance) is in μmho cm^{-1} at 25°C. Nitrate, sulfate, chloride, calcium and alkalinity are in μeq l^{-1}. Orthgran (= orthoclase granites), plaggran (= plagioclase granites), volcan (= volcanic rocks) as described in text are divided into areal coverage classes as follows: 1, 0-25%; 2, 25-50%; 3, 50-75% and 4, greater than 75%. Calcers (= calcareous rocks) is divided into classes as follows: 1, 0-trace; 2, 1-10%; 3, 10-50% and 4, greater than 50%. Elev is elevation in meters above sea level. Lake area and basin areas (basarea) are in hectares. Veget (= vegetation classes) are described in Appendix 2. Impact is a ranking based on the amount of visitor impact a lake receives. Ranks were made on a scale from zero to five, with the value zero being given to lakes with no campsites and little or no day use, and the value five being given to lakes accessible by roads or backcountry lakes with more than 20 campsites in heavy use.

Appendix 1.

OBS	LAKE	CONDUCT	PH	NITRATE	SULFATE	CHLORIDE	CALCIUM	ALKAN	ORTHGRAN	PLGGRAN	VOLCAN	CALCERS	ELEV	LAKEAREA	BASAREA	VEGET	IMPACT
1	UPTREASURE	6.0	6.4	3.80	10.3	6.1	24.8	19	1	4	1	1	3389	2.850	184.0	3	1
2	DADE	6.3	6.2	7.50	12.5	10.5	30.0	22	1	4	1	1	3511	3.110	130.0	1	0
3	DUCK	15.0	7.1	0.80	20.0	5.5	89.5	103	1	2	4	1	3178	95.100	588.0	3	4
4	BARNEY	73.0	9.4	1.20	155.0	14.0	549.0	403	1	1	4	1	3097	3.110	98.4	3	3
5	PARKERPASS	26.7	6.1	6.30	138.0	66.0	118.0	5	1	1	4	1	3316	2.850	101.0	2	2
6	KUNA11600	4.3	6.3	3.30	14.0	7.2	14.7	15	1	4	1	1	3536	4.920	23.3	1	0
7	HELEN	13.8	7.2	0.70	40.0	20.0	53.0	52	1	3	3	1	3316	21.500	293.0	3	2
8	DANA	15.0	6.6	8.60	61.0	8.5	58.0	9	3	1	3	2	3365	5.180	189.0	1	0
9	UPGRANITE	17.0	7.2	0.40	12.8	18.3	56.0	74	1	4	1	1	3170	6.730	119.0	3	2
10	UPGAYLOR	25.0	7.1	0.10	31.0	13.5	107.0	91	1	1	4	1	3121	4.665	41.2	2	3
11	CONVICT	158.0	8.5	0.10	242.0	34.0	1240.0	1137	1	3	3	3	2310	74.600	4999.0	5	5
12	SILVER	38.0	7.5	0.20	57.0	70.0	208.0	245	3	1	3	3	2202	45.300	8539.0	5	5
13	DUSYS10800	33.0	7.6	2.50	32.0	23.0	116.0	146	1	4	1	1	3292	1.810	172.0	3	0
14	DUSY11393	4.9	7.0	0.20	13.0	23.0	32.0	30	1	4	1	1	3473	16.100	34.7	1	2
15	ISOSELES	7.0	7.2	0.20	11.0	17.0	27.0	20	1	4	1	1	3389	4.400	55.7	2	3
16	DUSYN112890	6.0	6.8	0.10	12.0	10.0	23.0	27	1	4	1	1	3438	5.180	174.0	2	3
17	BISHOPPASS	12.0	6.9	0.40	17.0	34.0	21.0	12	1	4	1	1	3609	1.040	174.0	1	0
18	UPPERBISHOP	29.0	8.1	1.10	33.0	14.0	155.0	200	1	4	1	1	3333	2.590	58.0	2	1
19	FIFTH	20.0	7.5	2.10	20.0	3.0	60.0	60	2	4	1	1	3424	9.070	750.0	4	4
20	ABOVESAMMACK	6.8	6.3	5.80	8.0	5.0	15.3	10	1	4	1	1	3731	1.040	146.0	1	0
21	SUMMIT	7.0	6.2	6.10	12.0	9.0	15.0	10	4	1	1	1	3609	1.810	82.9	1	3
22	NEEDLE	20.0	7.1	0.70	20.0	20.0	43.0	71	4	1	1	1	3438	0.780	46.6	2	1
23	TRAIL	16.0	7.4	0.10	12.0	11.0	86.0	122	4	1	1	1	3402	2.590	77.7	3	2
24	FAIRYSHRIMP	5.3	5.7	0.90	14.0	8.0	16.0	15	4	1	1	1	3517	1.300	15.5	2	0
25	RUBY	6.8	5.9	0.90	10.0	3.0	46.0	52	4	1	1	1	3365	14.500	202.0	3	4
26	HEATHER	5.6	6.4	0.02	9.0	7.0	23.0	52	1	4	1	1	2804	2.070	57.0	4	4
27	PEAR	5.3	6.4	0.05	7.5	12.8	15.0	31	4	2	1	1	2899	7.550	157.0	4	4
28	TABLELAND	21.5	6.3	0.03	13.0	13.0	8.5	9	1	4	1	1	3261	1.040	15.8	2	0
29	TABLEMDWS	4.3	6.4	0.04	7.5	3.5	11.7	14	1	4	1	1	3139	1.550	25.1	2	1
30	MOSQUITO5	11.2	6.8	0.50	18.3	9.0	52.0	57	1	4	1	1	3139	1.550	25.1	3	4
31	MOSQUITO3	6.8	6.6	0.10	22.0	2.0	44.0	44	1	4	1	1	2999	0.780	132.0	4	4
32	MOSQUITO1	9.0	6.8	0.10	14.0	8.0	60.0	71	1	4	1	2	2926	2.070	127.0	4	4
33	UPPERCOLUMBINE	34.1	7.1	0.03	7.0	5.0	38.0	50	4	1	1	1	3365	1.300	13.5	1	1
34	COLUMBINE	15.7	7.0	0.30	7.0	5.0	32.0	42	4	1	1	1	3255	16.600	103.0	1	1
35	UPPERMONARCH	7.3	6.9	0.90	17.0	2.3	32.2	39	4	1	3	1	3292	5.700	63.7	2	1
36	LCWERMONARCH	10.0	6.9	0.60	22.0	6.0	51.0	54	4	1	3	2	3146	1.040	28.7	2	3
37	GRANITE	22.0	6.9	0.00	7.0	8.0	26.0	31	4	1	1	1	3097	20.700	262.0	3	4
38	VOLCANIC	6.7	7.1	0.00	7.0	8.0	26.0	31	4	1	1	1	3170	8.550	121.0	2	1
39	DRAGON	22.0	7.7	0.03	56.0	17.0	100.0	65	1	4	1	1	3389	9.840	877.0	2	3
40	GARDINERS11400	9.5	7.5	2.20	7.0	7.0	36.0	37	4	1	1	1	3475	3.630	66.3	1	0
41	GARDINER11394	23.0	6.8	1.60	10.0	18.0	37.0	43	4	1	1	1	3473	27.500	130.0	1	0
42	SIXTYS11280	10.0	7.0	2.00	7.0	6.5	55.0	50	4	2	1	1	3438	6.220	93.0	1	0
43	FINDOME	23.2	7.2	0.00	9.0	10.0	93.0	114	4	1	1	1	3414	1.300	23.3	2	3
44	UPPERRAE	59.0	7.8	0.09	96.0	38.0	159.0	133	3	4	1	1	3524	24.600	544.0	3	5
45	KEARSARGE	51.0	7.5	0.10	39.0	56.0	83.0	98	4	1	1	1	3365	1.040	211.0	3	4
46	TWINWEST	66.0	8.3	0.20	68.0	14.0	308.0	372	4	1	2	2	2162	120.000	5284.0	5	5
47	TWINEAST	76.0	9.0	0.20	91.0	8.0	358.0	422	4	1	2	2	2158	161.000	6786.0	5	5
48	LUNDY	71.0	7.8	0.20	207.0	7.0	423.0	301	1	3	3	2	2390	42.700	4507.0	5	5
49	MOAT	11.6	7.5	0.20	25.0	4.0	32.0	41	1	1	4	1	3194	2.590	59.1	2	1

Appendix 1 (continued)

OBS	LAKE	CONDUCT	PH	NITRATE	SULFATE	CHLORIDE	CALCIUM	ALKAN	ORTHGRAN	PLAGGRAN	VOLCAN	CALCERS	ELEV	LAKEAREA	BASAREA	VEGET	IMPACT
50	UPFROG	133.0	8.2	0.90	386.0	12.0	675.0	393	1	1	4	1	3231	0.78	57.2	2	2
51	TEN2	4.5	6.3	0.00	1.0	5.0	22.0	42	4	1	1	1	2634	8.29	335.0	-	-
52	LOWCATHEDRAL	3.2	6.1	0.10	0.0	3.5	13.5	21	4	1	1	1	2902	4.66	148.0	-	-
53	ZLAKE	8.6	7.2	0.00	17.5	8.5	33.5	26	1	1	4	1	3146	2.07	20.7	3	1
54	PNDABVSPULLER	6.0	6.5	2.70	16.0	7.0	33.0	48	1	1	4	1	3146	0.30	70.7	2	1
55	CECILE	10.4	7.1	0.20	21.0	74.0	30.0	33	1	1	4	1	3152	17.90	95.3	2	2
56	EDIZA	33.0	7.0	1.30	13.0	8.0	42.0	43	1	1	4	1	2853	10.10	945.0	3	3
57	ICEBERG	4.9	7.0	0.90	21.0	51.0	26.0	22	1	1	4	1	2999	14.20	239.0	2	2
58	GARNET	19.2	7.2	0.04	21.0	44.0	59.0	50	1	1	4	1	2975	90.70	621.0	3	4
59	THOUSANDISLAND	7.7	7.0	0.00	3.0	6.0	33.0	37	1	1	4	1	2997	130.00	1196.0	3	4
60	BRIGHTDOT	105.0	8.7	0.20	72.0	12.0	788.0	756	1	1	3	3	3194	11.40	140.0	3	2
61	DOROTHY	18.1	7.4	0.06	91.0	24.0	193.0	149	1	3	3	1	3121	61.60	396.0	3	3
62	CONSTANCE	64.0	8.1	0.50	110.0	21.0	336.0	258	1	1	4	1	3292	14.00	207.0	1	1
63	UPBENCHMARK	17.2	6.9	3.10	19.0	6.0	7.0	129	4	1	1	1	3629	1.81	161.0	2	1
64	ARCTIC6	16.4	8.7	34.20	34.0	5.0	51.0	40	4	1	1	1	3804	0.52	84.4	1	0
65	ARCTIC4	20.7	7.2	18.70	27.0	6.0	42.0	59	4	1	1	1	3792	0.78	43.0	1	0
66	ARCTIC2	9.8	6.6	3.10	15.0	6.0	42.0	60	4	1	1	1	3731	4.14	86.5	1	1
67	FALNLEAF	26.9	6.8	0.00	37.0	14.0	137.0	173	4	2	2	1	1932	578.00	3082.0	5	4
68	UPANGORA	7.4	8.2	0.20	11.0	6.2	30.0	64	1	4	1	1	2292	5.44	65.3	4	4
69	CASCADE	15.0	7.8	0.00	15.0	5.0	70.0	107	1	4	2	1	1970	85.70	837.0	5	4
70	CRYSTAL	14.0	7.0	.	32.0	5.1	43.0	50	4	1	1	1	3267	4.14	60.6	2	2
71	GEM	5.7	6.5	7.00	19.1	2.3	38.0	38	1	4	1	1	3438	1.04	80.8	3	3
72	EMERALD	3.4	6.3	0.70	11.2	1.7	17.0	31	1	4	1	1	2780	2.85	122.0	3	4
73	EBROOK	10.0	6.9	0.00	7.6	5.1	77.0	90	1	4	1	1	3146	4.66	225.0	3	4

Appendix 2

Classification of predominant vegetation types found around Sierra Nevada lakes.

1. Alpine fell-field. Elevation: above 3,200 m.

Representative plants: *Carex helleri*, *C. breweri*, *Festuca brachyphylla*, *Poa rupicola*, *P. suksdorfii*, *Luzula spicata*, *Eriogonum ovalifolium*, *Oxyria digyna*, *Draba densiflora*, *D. breweri*, *D. lemmonii*, *D. oligosperma*, *Phoenicaulis eurycarpa*, *Ivesia shockleyi*, *Potentilla diversifolia*, *Astragalus tegetarius*, *Epilobium obcordatum*, *Podistera nevadensis*, *Polemonium eximium*, *Cryptantha nubigena*, *Castilleja nana*, *Penstemon davidsonii*, *Haplopappus macronema*, *Hulsea algida*.

Comments: Although all of these perennial plants occur in fell-fields, the most notable characteristic of this region is the extreme scarcity of vegetation, and the lack or thinness of the soil.

2. Alpine meadow and meadow-like vegetation above timberline (often at lakeside) . Elevation: Above 3,200 m.

Representative plants: Sedges (*Carex* spp.), rushes (*Juncus* spp.), grasses (*Poa* spp., *Deschampsia caespitosa*, *Calamagrostis* spp.), *Antennaria alpina*, *Vaccinium nivictum*, *Saxifraga aprica*, *Kalmia polifolia* var. *microphylla*, *Aster alpigenus* ssp. *andersonii*, and specifically at lake edge, *Salix* spp.

Comments: Similar vegetation can occur in meadows of lower elevations, but mostly with different species.

3. Whitebark pine forest. Elevation: 3000-3350 m.

Representative plants: *Pinus albicaulis*

Comments: The whitebark pine forest is not generally considered a separate community, but rather the highest portion of the subalpine forest (Rundel et al. 1977). This is the timberline zone, where often the only tree occurring is the whitebark pine. It often grows as krummholz at this elevation. Many understory species are shared with Mixed Subalpine Forest.

4. Mixed subalpine forest. Elevation: 2800-3350 m.

Representative plants: *Pinus albicaulis*, *P. balfouriana*, *P. flexilis*, *P. contorta*, ssp. *murrayama*, *Tsuga mertensiana*, *Salix petrophila*, *Eriogonum incanum*, *Ribes cereum*, *R. montigenum*, *Sedum obtusatum*, *Potentilla fruticosa*, *Cassiope mertensiana*, *Phyllodoce breweri*, *Penstemon heterodoxus*.

Comments: Normally, this classification would include all forest vegetation from about 2800 m to timberline but, as noted above, the whitebark pine has been placed in its own category.

5. Upper montane - red fir forest. Elevation: 1800-2800 m.

Representative plants: *Abies magnifica*, *Abies concolor*, *Pinus contorta* ssp. *murrayana*, *P. monticola*, *P. jeffreyi*; *Castanopsis sempervirens*, *Ceanothus cordulatus*, *C. velutinus*, *Ipomopsis aggregata*, *Populus tremuloides*, a'd *Quercus vaccinifolia*.

Sources

References: Bennett 1965, Burke 1977, Chabot and Billings 1972, Klikoff 1965, Major and Taylor 1977, Munz and Keck 1959 and Rundel, Parsons and Gordon 1977.

Personal observations: John L. Stoddard, Cliff A. Ochs and Ann Howald.