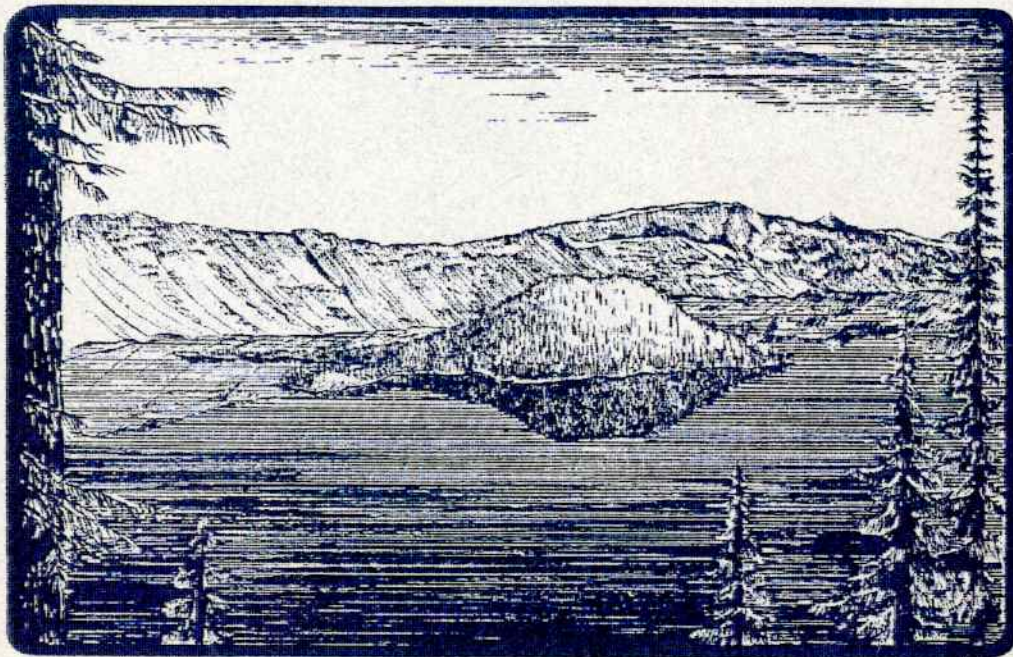


# CRATER LAKE

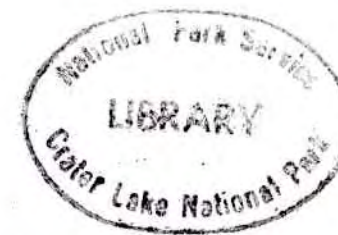
## LIMNOLOGICAL STUDIES FINAL REPORT

Gary L. Larson • C. David McIntire • Ruth W. Jacobs, Editors  
Technical Report NPS/PNROSU/NRTR-93/03

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UNITED STATES DEPARTMENT OF THE INTERIOR  
NATIONAL PARK SERVICE • PACIFIC NORTHWEST REGION



## Crater Lake Limnological Studies Final Report

Gary L. Larson, C. David McIntire, and Ruth W. Jacobs  
Editors

Technical Report NPS/PNROSU/NRTR-93/03

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Pacific Northwest Region  
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## **Crater Lake Limnological Studies**

### **Executive Summary**

The National Park Service began a study of Crater Lake in 1982 because of indications that lake clarity might be declining. Later the same year, Congress passed Public Law 97-250, which authorized and directed the Secretary of the Interior to promptly initiate a 10-year program to assess the status of the water quality of the lake. Little was known about the ecology of the lake in 1982. Consequently, the National Park Service adopted the following major goals for the study of this unique lake: (1) develop a data base to compare present and future conditions of the lake, (2) develop an understanding of lake components and processes, (3) develop a long-term program for monitoring changes, (4) determine if the lake had experienced recent changes, and if so, (5) identify causes and recommend mitigation procedures if the changes were related to human activity.

Looking at the data in its entirety, researchers concluded at the end of the study that Crater Lake was a complex and dynamic system with considerable seasonal and annual variability. Although fish, which were introduced into the lake between 1888 and 1941, affected the lake's food web, no other changes caused by human activities could be specifically identified or separated from those caused by natural phenomena. Although the possibility of long-term changes in the lake could not be dismissed, researchers regarded such changes to be too subtle for detection over a time scale represented by the available data.

Original concerns about changes in lake clarity were prompted by measurements of clarity with a Secchi disk. Measurements of lake clarity with a 20-cm (8 in) Secchi

disk with black and white quadrants were included in the 10-year study in order to gain data for comparison with historical data. Analysis of the Secchi disk data revealed that clarity was now generally greater than 25 m (82 ft) but less than 35 m (115 ft). The shallowest reading during this study (21.9 m; 72 ft) was recorded in August of 1982, and the deepest reading (39.2 m; 129 ft) was recorded in June of 1988. This deepest reading was 0.8 m (3 ft) short of the maximum Secchi reading on record for the lake using the 20-cm disk. August Secchi disk readings in the range of 39-40 m (128-131 ft), a range that encompassed the maximum Secchi depths recorded in August of 1937 and 1969, were not observed between 1982 and 1992. In addition to measurements with a Secchi disk, changes in the composition and depth of penetration of surface light were measured with a photometer, and changes in the spatial distribution of particles in the water column were measured with a transmissometer. Natural variabilities were apparent using all three measurements of clarity, but as a whole, the data did not support the hypothesis that clarity of Crater Lake had undergone long-term change.

Extensive measurements were taken of temperature, alkalinity, conductivity, pH, and other chemical and physical properties of water in the lake. No long-term changes in these measures of water quality were evident during the duration of the study nor through a comparison of current and historical data. Concentrations of phosphorus and nitrate, two very important nutrients for growth of algae, were low. An estimated 90% of the nitrogen and 30% of the phosphorus brought into the lake each year came from the atmosphere. The remaining fractions entered the lake from other sources associated with the caldera, including springs flowing from the walls of the caldera into the lake. Contribution of nitrates to the lake from the springs was specifically studied because of

concerns about a sewage drain field for visitor facilities located just outside the caldera wall. One spring located on the caldera wall near the sewage drain field exhibited relatively high nitrate concentrations but contributed less than 1% of the total annual input of new nitrate into the lake. Although an analysis of the water chemistry of the spring could not confirm the source of the nitrates, the drain field was removed in 1991 as a precautionary measure.

Hydrothermal fluids, discovered on the lake bottom, contributed to the lake's *relatively* high salt content and were, in part, responsible for the long-term stability in water chemistry of the lake. The hydrothermal inputs were determined to be highly significant in maintaining the lake's natural biological, chemical, and physical processes.

Phytoplankton and zooplankton communities were sparse, diverse, and complex. Seasonal and annual changes in chlorophyll, primary production, phytoplankton abundance, and zooplankton abundance were observed. The abundance of the largest species of zooplankton was markedly cyclic and appeared to respond to changes in lake productivity and fish predation. Kokanee salmon and rainbow trout continue to persist in the lake beyond the last stocking in 1941. Kokanee salmon were cyclic in abundance, lived both near the shore and in open deep water, and fed on zooplankton and small bottom-dwelling insects. Rainbow trout lived along the edges of the lake and fed on terrestrial insects, large-bodied bottom fauna, and kokanee. Fish clearly exhibited the potential both to alter the food webs within open-water and near-shore habitats and to affect nutrient cycling within the lake.

In general, the Crater Lake ecosystem was extremely responsive and sensitive to environmental change and was judged to be pristine, except for the consequences of fish

introductions. The study documented many of the components and processes important to lake clarity and the lake system as a whole. The study also identified many questions needing further study. Long-term change could not be fully evaluated because very little historical data were available to compare with the detailed data base assembled during this study. This situation underscored the need for a long-term monitoring program to evaluate future change against the benchmark set in the 10-year study. Global climate change, air pollution, on-site auto and boat use, and non-native fish present the greatest potential human-related threats to the pristine nature of Crater Lake. Additional studies would refine knowledge of the components and dynamic processes of the lake system as well as separate changing lake conditions caused by natural phenomena from those caused by human-related activities.

## Abstract

Limnological studies of Crater Lake were initiated by the National Park Service in 1982 in response to an apparent decline in lake clarity and possible changes in characteristics of the algal community. Congress passed Public Law 97-250 in the fall of 1982, which authorized and directed the Secretary of the Interior to conduct a 10-year limnological study of Crater Lake and to immediately implement such actions as may be necessary to retain the lake's natural pristine water quality. The broad project goals adopted for the study included: (1) develop a limnological data base to be used for comparisons of future conditions of the lake; (2) develop a better understanding of physical, chemical and biological components of the lake system; (3) develop a long-term monitoring program; (4) determine if the lake had experienced recent changes, and if changes were present and human related; (5) identify the causes and recommend ways of mitigating the changes.

An ecosystem approach was used to develop the program. Conceptual models of the lake ecosystem were developed and used to guide research and analyses. Studies included quantity and chemistry of precipitation, lake-level fluctuations, solar radiation, chemistry of intra-caldera springs, lake clarity, lake color, lake chemistry, particle flux, chlorophyll, primary production, phytoplankton, zooplankton, bottom fauna and flora, and fish. An extensive data base was assembled for each aspect of the study.

Crater Lake was found to be a complex, dynamic, and oligotrophic (nutrient-poor) system. The volume of the lake responded quickly to changes in precipitation because the basin has no surface outlet. Water leaves the lake through seepage and evaporation. Although the lake level normally fluctuates about 0.5 m annually, the lake surface

dropped about 3 m in elevation between 1984 and 1992. The lake was relatively high in dissolved salts, total alkalinity, and conductivity; pH ranged between 7 and 8. Hydrothermal fluids from the lake bottom contributed to the relatively high salt content of the lake. Phosphorus and nitrate were low in concentration, although the concentration of the latter increased substantially below a depth of 200 m. On an annual basis, atmospheric bulk deposition accounted for about 90% of the nitrogen and 30% of the phosphorus input to the lake. Recycling of nutrients was important to the internal nutrient budget of the lake.

Wind-driven circulation mixed the lake in winter and spring to a depth of about 200 m. Some deep-water mixing was indicated by high concentrations of dissolved oxygen at the lake bottom. The lake was thermally stratified in summer and fall. The interface between the warmed surface waters and the cold waters of the deep lake was at a depth of about 80 m.

Secchi disk clarity generally was in the high-20-m to mid-30-m range. The depth of 1% of the incident surface light generally was between 80 and 100 m. Seasonal changes in Secchi disk readings and the depth of 1% incident light were observed. In summer, a layer of near-surface turbidity was associated with changes in Secchi disk clarity. Lake color measurements indicated that the near-surface water was very blue.

Water chemistry of the caldera inlet springs exhibited a wide range of chemical concentrations and total ionic compositions over short distances around the perimeter of the lake. Calcium, magnesium, and sodium were the major cations; bicarbonate was the major anion. Contribution of nitrates to the lake from the springs was specifically studied because of concerns about a sewage drain field for visitor facilities located just

outside the caldera wall. One spring located on the caldera wall near the drain field system exhibited relatively high nitrate concentrations but contributed less than 1% of the total annual input of new nitrate into the lake. Although an analysis of the water chemistry of the spring could not confirm the source of the nitrates, the drain field was removed in 1991 as a precautionary measure.

Chlorophyll, phytoplankton, and zooplankton were uniformly distributed in winter and spring from the lake surface to the depth of mixing (maximum depth about 200 m), and maximum primary production occurred between 40 and 60 m. A deep-water chlorophyll maximum developed between 100 and 140 m in summer and fall, and maximum primary production typically occurred between 40 and 80 m. About 96% of total primary production was associated with nutrients recycled in the euphotic zone. A sparse but complex phytoplankton community partitioned the water column to a depth of 200 m. A high density of phytoplankton typically developed in the warm near-surface waters. Cyclic seasonal and annual changes in chlorophyll, primary production, and phytoplankton density were observed. Periods of upwelling of nutrient-rich waters from the deep lake were thought to influence the productivity of the lake.

In summer and fall the zooplankton community, which was comprised of eight rotifer species and two species of crustaceans, partitioned the water column to a depth of 200 m. Zooplankton abundance in the upper 20 m of the water column was very low. Highest densities of zooplankton were located in the depth interval of 80 to 180 m. Closely related or competing species were found in different portions of the water column. The largest crustacean species was cyclic in abundance, and its abundance was

related to lake productivity and fish predation. When it was abundant, rotifer abundances declined, and changes in the distribution of the other crustacean species were observed.

Two species of fish, rainbow trout and kokanee salmon, continued to persist in the lake. Both species were stocked many years ago, continued to reproduce in the lake, and had long-term effects on the lake system. Kokanee salmon mostly were pelagic and fed primarily on crustacean zooplankton and small-bodied bottom fauna. Abundance of kokanee was cyclic owing to the numerical dominance of one year class. Rainbow trout were found along the littoral zone of the lake and fed on terrestrial insects at the lake surface, large-bodied bottom fauna, and kokanee.

Benthic macroinvertebrate richness was moderate in Crater Lake and comparable to the richness found in other large, cold, oligotrophic lakes in the northern hemisphere. Densities of epibenthic macroinvertebrates on rocky substrates in the littoral zone were relatively high. Most taxa in the littoral zone were types common to streams and rivers in montane areas of western North America. Snails were common to a depth of 100 m. Oligochaeta worms and chironomid midges were common in the deep lake.

A new species of aquatic mite, *Algophagopsis* sp., was found in the lake. Crater Lake remains the only known local for this species. The mite was abundant on rock surfaces in association with aquatic lichen and *Nostoc* in the main lake, on filamentous algae in Emerald pool located on Wizard Island, and on the deep-water moss, *Drepanocladus aduncus*, with the deepest collection from 118 m.

Beds of macrophytes were found on some of the sand-gravel benches around the perimeter of the lake. *Drepanocladus aduncus* was present in dense beds in the lake in

the depth interval of 30 to 120 m. Several species of diatoms were associated with the moss. Periphyton was collected from many sites around the margin of the lake, as well as from depths of 120 m or more.

Comparisons of limnological data collected prior to the study with data collected during the study did not reveal any major long-term changes in the near-surface water quality of the lake. Hydrothermal inputs were responsible for the stable concentrations of dissolved salts through time. The analysis of Secchi disk records collected between two time intervals, 1913-1969 and 1978-1991, suggested that the data sets were fairly comparable. However, this finding was insufficient to summarily dismiss the possibility of subtle long-term change to the lake. Changes in nutrient input from the atmosphere and potential local sources of nutrients may have some long-term roles to play in the productivity and clarity of Crater Lake. It remained difficult to separate the natural variability of the Secchi disk readings from any changes that may have resulted from human-related activities. Disk readings in the range of 39-40 m, which were recorded in August of 1937 and 1969, were not repeated in readings taken in August from 1978 through 1991. However, readings of 37 m and 39 m were recorded in July of 1985 and June of 1988, respectively. The absence of extremely deep Secchi disk readings during this study may have been a sign of change, but a 33.5 m reading in August 1954, the only bona-fide August Secchi disk reading between 1937 and the late 1960's, illustrated the problem of separating the natural dynamics of lake clarity from any long-term decreases in clarity.

In general, the Crater Lake ecosystem was extremely responsive and sensitive to environmental change and was judged to be pristine, except for the consequences of fish

introductions. The study documented many of the components and processes important to lake clarity and the lake system as a whole. Knowledge of the relative importance of these components and processes was high in many instances, although the level of knowledge of any one of the complex features tended to be low to moderate. The study also identified many questions needing further study. Long-term change could not be fully evaluated because very little historical data was available to compare with the detailed data base assembled during this study. This situation underscored the need for a long-term monitoring program to evaluate future change against the benchmark set in the 10-year study. Global climate change, air pollution, on-site auto and boat use, and non-native fish present the greatest potential human-related threats to the pristine nature of Crater Lake. Additional studies would refine knowledge of the components and dynamic processes of the lake system as well as separate changing lake conditions caused by natural phenomena from those caused by human-related activities.

## Acknowledgments

The Crater Lake Limnological Study was a cooperative effort among individuals representing both management and science. The editors of this report thank the authors of the various sections for their dedication and contributions to the study. Personnel of the National Park Service who made important contributions to the study included Dennis Fenn, Ray Herrmann, Bob Stottlemeyer, Daniel Tobin, Jr. (deceased), Charles Odegaard, Richard Winters, Jim Larson, Shirley Clark, Ed Starkey, Jim Rouse, Bob Benton, Ben Ladd, Dave Morris, George Phillips, George Buckingham, Peter Thompson, Mark Forbes, Jon Jarvis, Jim Milestone, Ken Stahlnecker, Jerry McCrea, Kent Taylor, Roger Andrasik, Jim Webster, Fred VanHorn, Tim Olivarias, Steve Underwood, Bill Holda, Douglas Raeburn, and Sean McGuinness. Many other National Park Service personnel in the Washington Office, the Pacific Northwest Regional Office, and Crater Lake National Park contributed as well, and their efforts are appreciated. The efforts of the scientific peer review panel, chaired by Stanford Loeb, and the support of Charles Goldman are appreciated. The support and efforts of numerous research assistants, especially John Salinas and Scott Stonum, and volunteers who worked on the study are also appreciated. Many thanks are extended to Charles Bacon, C. Hans Nelson, Manuel Nathenson, Richard Kraus, Silvia Earl, and Jim English for their assistance with several aspects of the study, to Douglas Larson for his contribution of unpublished data, and to the reviewers of various sections of the final report. Many thanks are also extended to the faculty and staff of Oregon State University, especially those in the College of Forestry and the College of Oceanic and Atmospheric Sciences, for their support and assistance.

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lake; (3) establish a long-term monitoring program to examine limnological characteristics of the lake; and (4) investigate the possibility of long-term changes in lake conditions, and if such changes were found and human related, identify the causal factor(s) and recommend ways of mitigating the change(s).

The 10-year study of Crater Lake began in the summer of 1983 with emphasis on establishment of a monitoring program (Larson 1990). Much of the preliminary work was done by 1985, and two conceptual models were developed to guide additional monitoring and research (Figs. 1 and 2). The first model identified the various components involved in the functioning of the Crater Lake ecosystem and their interrelationships, whereas the second model focused on ecosystem components within the lake. A set of working objectives was developed based on these models, and a format for the monitoring program was completed (Tables 1 and 2). The working objectives were divided into three subdivisions: (1) baseline; (2) lake structure and organization; and (3) examination of changing lake conditions through the analysis of baseline data, lake color, optical properties, and paleolimnology. All components listed in Table 1 were addressed in the program. The optical study by Smith et al. (1973) was repeated, and lake cores were obtained to evaluate historic lake conditions from the physical, chemical, and diatom fossil records in the sediments. However, analyses of the new optical data and lake cores were not completed in time to be included in this report.

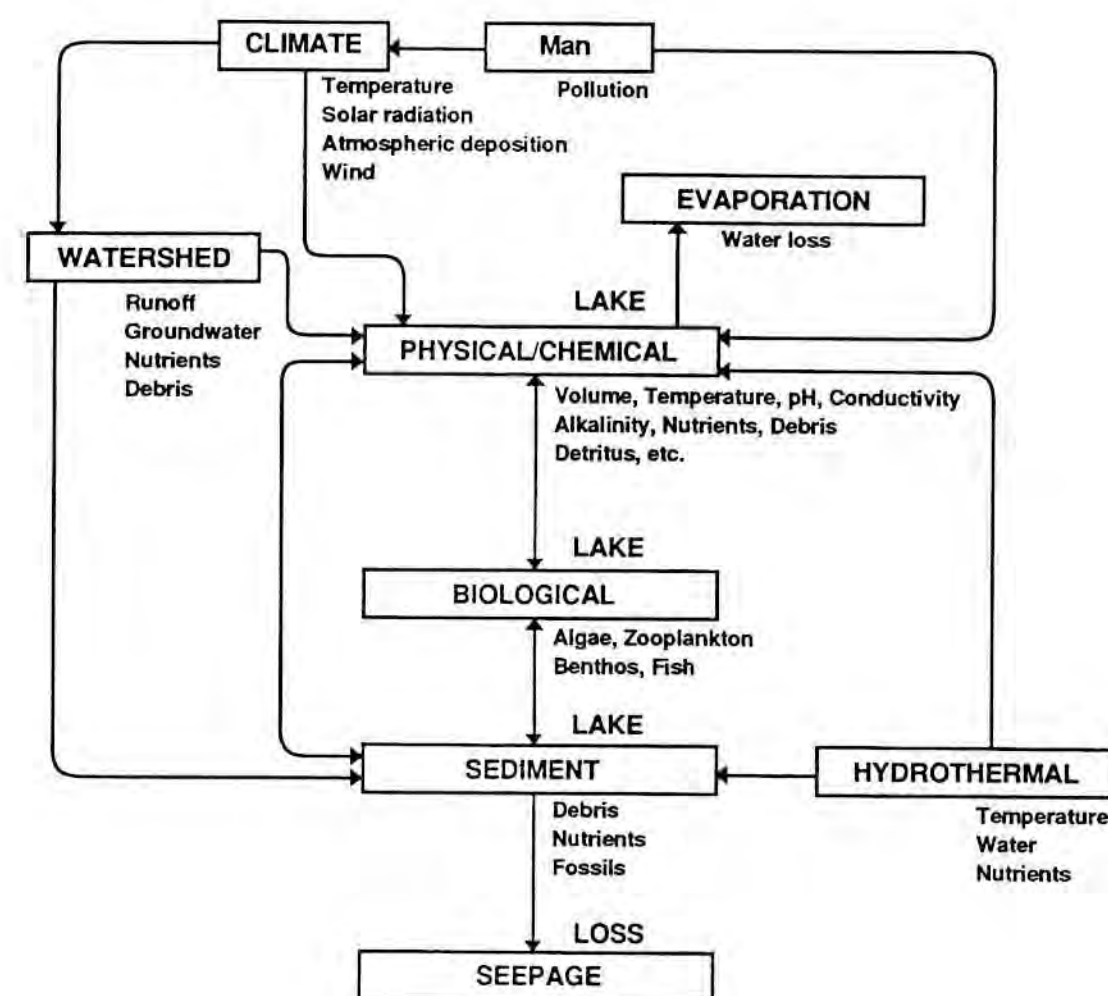


Figure 1. Conceptual model of the Crater Lake ecosystem (after Larson 1990).

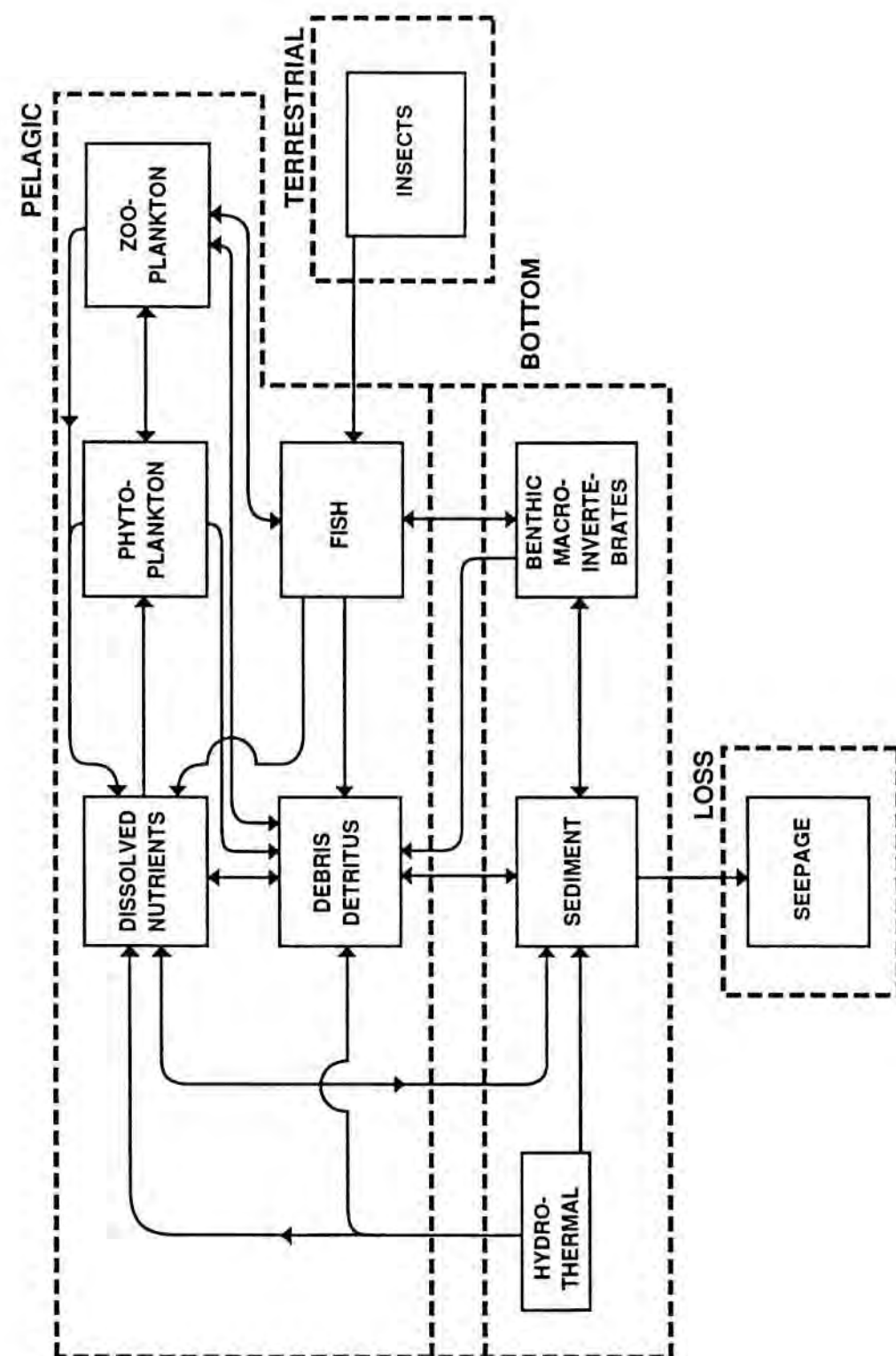


Figure 2. Details of the lake aspects of the conceptual model shown in Figure 1 (after Larson 1990).

Table 1. Working objectives of the Crater Lake limnological studies (after Larson 1990).

1. Baseline data base.
  - A. Describe the general physical, chemical, and biological characteristics of the lake for the period 1983-1992.
    1. Determine the amount of seasonal and annual variation of each variable.
    2. Determine how each variable varies with depth.
    3. Determine the amount of spatial (horizontal) variation of each variable.
    4. Evaluate the lake clarity data relative to the physical, chemical, and biological conditions of the lake.
2. Lake organization and structure.
  - A. Lake volume, stratification and circulation.
    1. Estimate water input into the caldera.
    2. Document relationships between input and changing lake levels.
    3. Evaluate conditions necessary for the development of thermal stratification.
    4. Describe the circulation patterns and processes of the lake.
  - B. Nutrients.
    1. Estimate nutrient loading of the lake from atmospheric sources and caldera springs.
    2. Estimate loss of nutrients by sedimentation.
    3. Evaluate nutrient concentrations in the lake through time relative to inputs, losses, and recycling.

(continued)

Table 1. (continued).

|    |                                                                                                                                                                                                        |
|----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| C. | Biological features.                                                                                                                                                                                   |
| 1. | Describe the relationships of phytoplankton species, abundance biovolume, distribution, and production relative to physical and chemical lake features and zooplankton.                                |
| 2. | Describe the relationships of zooplankton species, abundance, biomass, and distribution relative to physical and chemical lake features, phytoplankton, and fish.                                      |
| 3. | Describe the relationships of benthic macro-invertebrate species, distribution, and abundance relative to physical and chemical lake features.                                                         |
| 4. | Describe the relationships of fish species, abundance, biomass, and distribution relative to physical and chemical lake features and zooplankton, benthic macro-invertebrates and terrestrial insects. |
| 3. | Optical characteristics, lake color, and paleolimnology.                                                                                                                                               |
| A. | Color and optical properties.                                                                                                                                                                          |
| 1. | Determine color, and optical properties of the lake as measured by Secchi disk, photometer, and transmissometer.                                                                                       |
| a. | Compare data with Pettit's 1935 lake color study.                                                                                                                                                      |
| b. | Compare data with Smith et al., 1969 optical study.                                                                                                                                                    |
| c. | Compare data with pre-1983 Secchi disk data.                                                                                                                                                           |
| d. | Compare data with pre-1983 photometer data.                                                                                                                                                            |
| e. | Compare Secchi disk data with photometer and transmissometer data.                                                                                                                                     |
| 2. | If changes are observed, (3.A1), interpret these relative to modern lake clarity conditions (1.A4).                                                                                                    |
| B. | Paleolimnology.                                                                                                                                                                                        |
| 1. | Evaluate historic lake conditions from analyses of sediment cores from the lake.                                                                                                                       |
| a. | Determine how selected physical characteristics changed through time.                                                                                                                                  |

(continued)

Table 1. (continued).

|    |                                                                                                                                    |
|----|------------------------------------------------------------------------------------------------------------------------------------|
| b. | Determine how selected chemical characteristics changed through time.                                                              |
| c. | Examine the fossil record through time.                                                                                            |
| 2. | Determine relationships between the characteristics of surface sediments and settling materials.                                   |
| 4. | Evaluate long-term system dynamics (from 1, 2, and 3).                                                                             |
| A. | Determine if any variable under study shows signs of change that are greater than would be expected from modern annual variations. |
| B. | Determine if any detected changes were related to a loss of lake clarity.                                                          |
| C. | To the extent necessary, identify and conduct special studies to evaluate factors that may be impacting lake water quality.        |

Table 2. Baseline limnological monitoring of Crater Lake and at intra-caldera springs (after Larson 1990).

|    |                                                                        |
|----|------------------------------------------------------------------------|
| 1. | Lake Program.                                                          |
| A. | Temperature.                                                           |
| 1. | Temperature profiles to 250 m (maximum length of thermistor cable) at: |
|    | 1-m intervals from 0 to 20 m                                           |
|    | 5-m intervals from 20 to 100 m                                         |
|    | 20-m intervals from 100 to 200 m, and                                  |
|    | 25-m intervals from 200 to 250 m                                       |
| 2. | Conductivity, temperature and depth probe (CTD) to 550 m.              |
| B. | Optical properties.                                                    |
| 1. | 20-cm Secchi disk                                                      |
| 2. | Photometer (to 150 m)                                                  |
| 3. | Transmissometer (to 550 m)                                             |

(continued)

Table 2. (continued).

## C. Chemical properties.

Total alkalinity, pH, specific conductance, and the concentrations of dissolved oxygen, total phosphorus, orthophosphate, nitrate-nitrogen, total Kjeldahl-nitrogen, ammonia-nitrogen, silica, and trace elements at all or selected depths from the following depth sequence: 0, 5, 10, 20, 60, 100, 200, 300, 400, 500, and 550 m.

## D. Biological properties.

1. Chlorophyll *a*.

In vitro chlorophyll concentration according to the following depth sequence:

5-m intervals from 0 to 10 m.

20-m intervals from 20 to 200 m.

25-m intervals from 200 to 300 m.

## 2. Primary production (carbon-14 light/dark bottle).

C-14 Primary production at the chlorophyll sampling depths to 180 m.

## 3. Phytoplankton.

Species, density, and biovolumes at all chlorophyll sampling depths.

## 4. Zooplankton.

Species, density, and biomass in samples obtained by a vertical tow of a .5 m diameter, number 25 closing net.

## 5. Fish.

Species, abundance, and biomass, spatial distribution, age, sex, growth and food habits. Samples collected with gill nets, hook and line, and down rigger. Pelagic distributions estimated using an echosounder.

(continued)

Table 2. (continued).

## 2. Springs.

## A. Location.

Each spring identified by a numbered tag.

## B. Physical and chemical water quality and bacteria.

Record temperature and take samples for pH, conductivity, alkalinity, nutrients, trace elements, and bacteria (total coliforms, fecal coliforms, and fecal streptococcus).

References

- Larson, D.W. 1984. The Crater Lake study: Detection of possible optical deterioration of a rare unusually deep caldera lake in Oregon, U.S.A. *Verh. Internat. Verein. Limnol.* 22:513-517.
- Larson, G.L. 1985. Crater Lake limnological studies: 1984 annual report. National Park Service, Cooperative Park Studies Unit, Oregon State University, Corvallis. 73 pp.
- Larson, G.L. 1987. A review of the Crater Lake limnological programs. Pages 58-69. *in* T.P. Boyle, ed., *New Approaches to Monitoring Aquatic Ecosystems*. ASTMSTP 940, American Society for Testing and Materials, Philadelphia, Penn.
- Larson, G.L. 1990. Status of the ten-year limnological study of Crater Lake, Crater Lake National Park. Pages 7-18 *in* E.T. Drake, G. L. Larson, J. Dymond, and R. Collier, eds., *Crater Lake: An Ecosystem Study*. Pacific Division, American Association for the Advancement of Science, San Francisco, Calif.
- Pettit, E. 1936. On the color of Crater Lake water. *Proceedings, National Academy of Science* 22:139-146.
- Smith, R.C., J.E. Tyler, and C.R. Goldman. 1973. Optical properties and color of Lake Tahoe and Crater Lake. *Limnology and Oceanography* 18:189-199.

## Study Area and Facilities

Gary L. Larson, C. David McIntire, and Mark Buktenica

Crater Lake is within Crater Lake National Park in the Cascade Mountain Range. This southern Oregon lake basin (caldera) was formed by catastrophic collapse of the sides of Mount Mazama following a violent eruption about 6,850 years ago (Bacon and Lanphere 1990). Walls of the caldera have been enlarged by caving and sliding to form a scalloped outline between 8 and 10 km in diameter. Post-caldera volcanism inside the caldera formed the central platform, Merrium Cone, and Wizard Island (Fig. 1). The lake was filled to nearly its present level before the end of andesitic postcaldera volcanism about 6,000 years before present. A small rhyodacite dome east of Wizard Island was extruded about 4,000 years before present (Bacon and Lanphere 1990). The rim of the caldera averages about 2,100 m in elevation, with some peaks reaching about 2,500 m.

Crater Lake occupies 79% of the caldera of Mount Mazama. The lake has a surface area of 53.2 km<sup>2</sup>, maximum depth of 589 m, a mean depth of 325 m, and a shoreline length of 31 km (Fig. 1; Byrne 1965, Phillips 1968). The average elevation of the lake surface is 1,882 m (see section Climate Variability and its Effects on Water Level). There is no surface outlet, but over 40 permanent and ephemeral inlet streams (commonly referred to as springs) occur in the caldera.

The 10-year study of Crater lake began in the summer of 1983 and continued through the summer of 1993. From 1983 through 1985, field studies of the lake were conducted only from late June through September because researchers could not gain access to the lake during many months of the year due to inclement weather. During

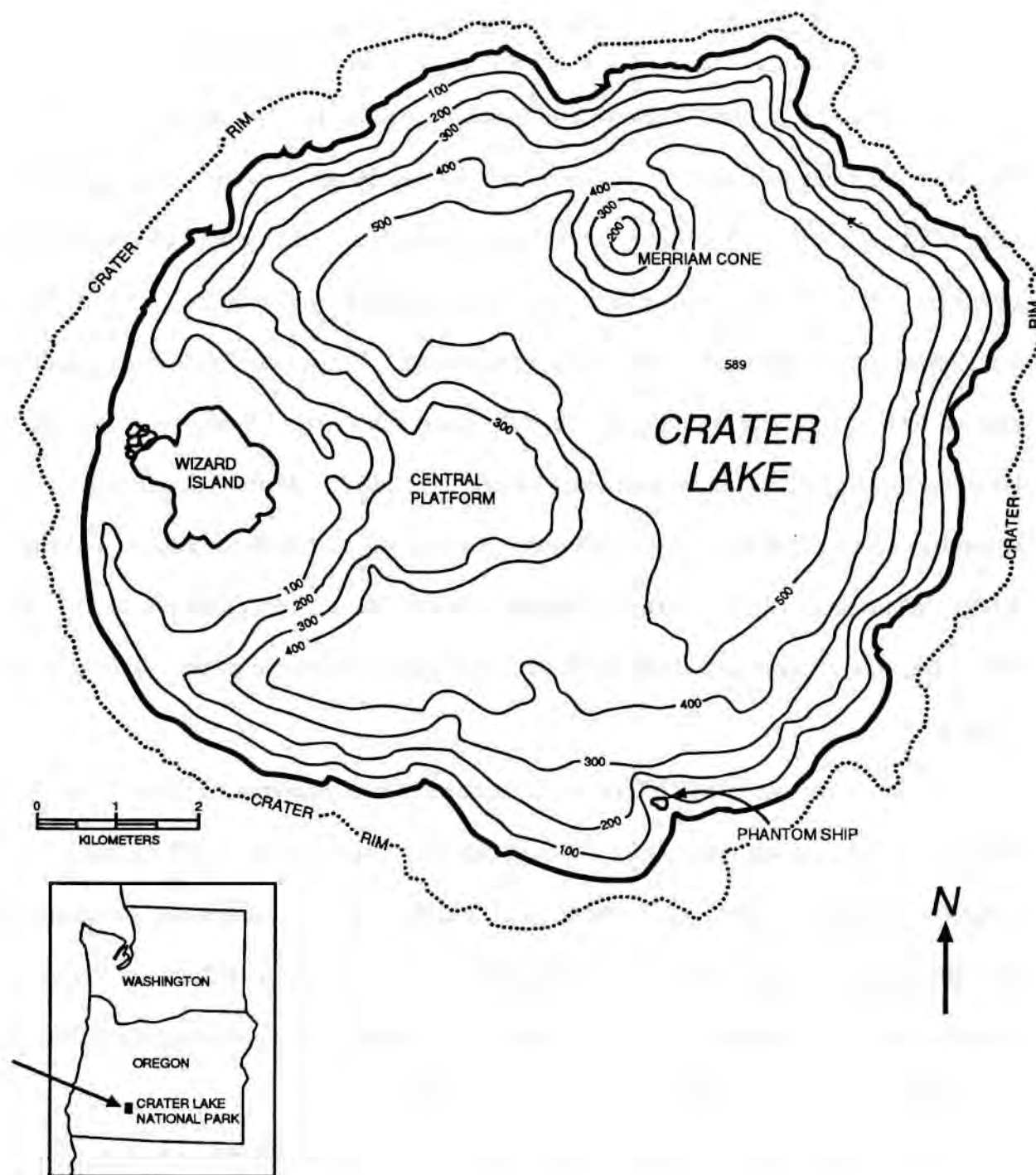


Figure 1. Bathymetry and important morphological features of Crater Lake (after Barber and Nelson 1990).

this period, research vessels were flown to the lake by helicopter or winched down the side of the caldera in the early summer and removed from the lake by helicopter in the fall. A boat house with storage space and living quarters was constructed in 1985 on Wizard Island. From then on, research vessels were stored in the boat house using a dolly and rail system. This arrangement allowed for sampling during spring and winter months in addition to the sampling from June through September. However, research personnel, sampling equipment, and support equipment still required helicopter assistance or winching to get to and from the lake. In summer, research staff reached the lake via a 1.6-km trail on the north side of the caldera (Fig. 2). A four-wheel-drive trail tractor was used to transport equipment and supplies.

Monitoring occurred in the deepest basin of the lake at a site designated as Station 13 (Fig. 2). Much of the historical data had been collected at this site. Furthermore, limnological conditions at Station 13 were known to be similar to conditions at Station 23, a site located in the south basin (Larson 1985).

Two research boats were used during the study, a 5.5-m-long Boston Whaler and an 8-m-long double-pontoon vessel with a flat deck and open center well. The Boston Whaler was usually reserved for winter and fall sampling. Water samples were collected to a depth of 300 m from the Boston Whaler using a hand-cranked winch with a meter wheel. The pontoon boat was covered by a canopy and equipped with a gasoline-powered winch. A meter wheel was used on the pontoon boat to determine sampling depths from 0 to 550 m. Both boats were powered by gasoline outboard engines.

Dissolved oxygen analyses, water filtering, and processing of biological samples were conducted in a laboratory at Crater Lake National Park. For information about

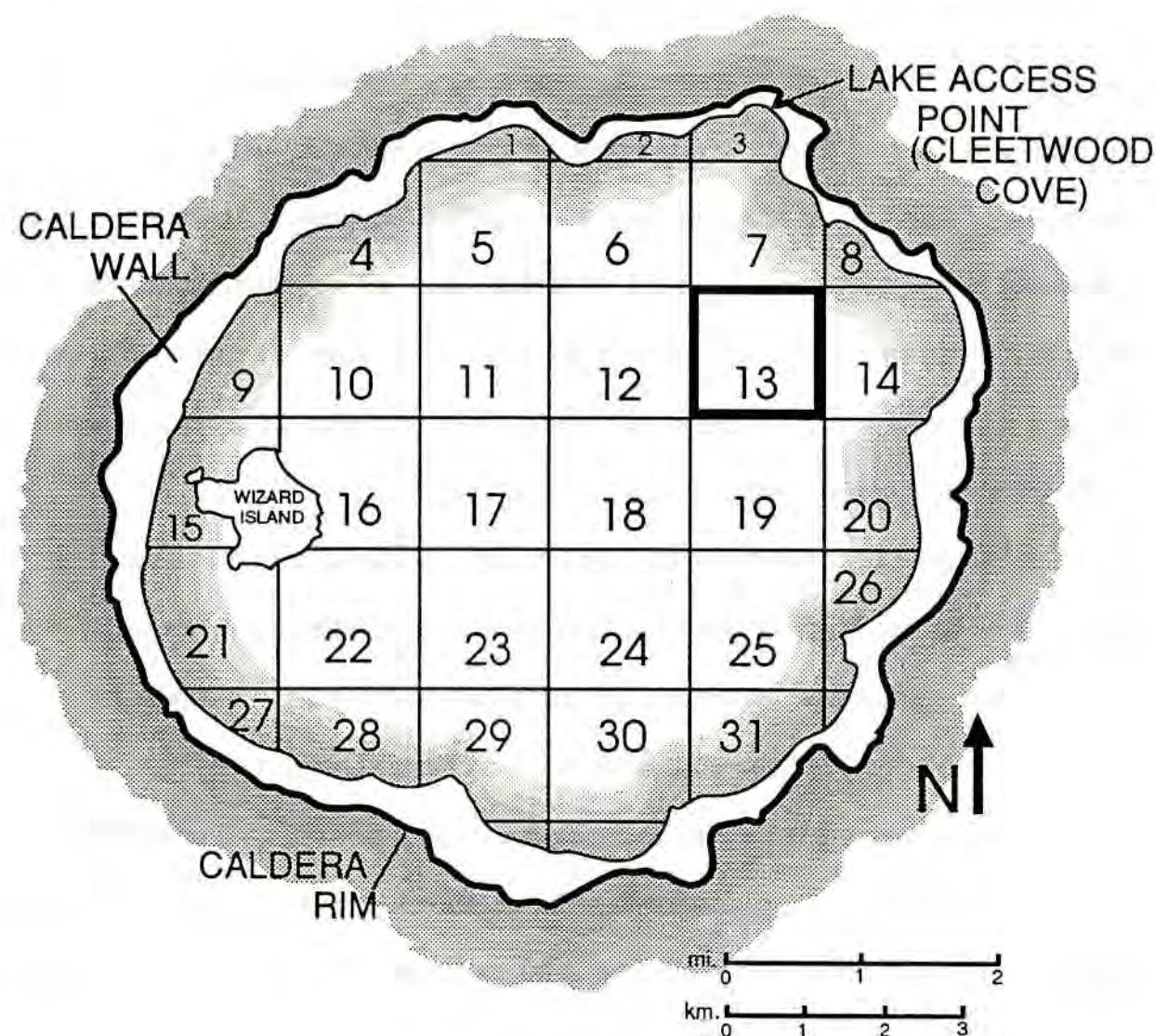


Figure 2. Grid system of Crater Lake stations established by Hoffman (1969). The main monitoring station (13) is 589 m deep.

other analyses of the water samples, see the section Procedures of the Cooperative Chemical Analytical Laboratory. The processing and analyses in the park were done in a small make-shift laboratory from 1982 through 1986. In 1987, a room in a park building was converted into a chemistry laboratory and equipped with acid-proof bench tops, storage cabinets, and a fume hood. Analytical procedures used at the park's chemistry laboratory are outlined in a handbook of standard operating procedures for the Crater Lake program (Salinas 1992).

#### References

- Bacon, C.R. and M.A. Lanphere. 1990. The geologic setting of Crater Lake, Oregon. Pages 19-27 in E.T. Drake, G. L. Larson, J. Dymond, and R. Collier, eds., *Crater Lake: An Ecosystem Study*. Pacific Division, American Association for the Advancement of Science, San Francisco, Calif.
- Barber, J.H. and C.H. Nelson. 1990. Sedimentary history of Crater Lake caldera, Oregon. Pages 29-39 in E.T. Drake, G. L. Larson, J. Dymond, and R. Collier, eds., *Crater Lake: An Ecosystem Study*. Pacific Division, American Association for the Advancement of Science, San Francisco, Calif.
- Byrne, J.V. 1965. Morphometry of Crater Lake. *Limnology and Oceanography* 10:462-465.
- Hoffman, F.O. 1969. The horizontal distribution and vertical migration of the limnetic zooplankton in Crater Lake, Oregon. M.S. thesis, Oregon State University, Corvallis. 60 pp.
- Phillips, K.N., and A.S. Van Denburg. 1968. Hydrology of Crater, East and Davis lakes, Oregon. U.S. Geological Survey Water Supply Paper 1859-E.
- Salinas, J. 1992. Standard operating procedures for the monitoring program at Crater Lake, Oregon. U.S. Department of Interior, Crater Lake National Park, Crater Lake, Oreg. 43 pp.

**Quality Assurance Program of the  
Cooperative Chemical Analytical Laboratory**

Cameron Jones

The Oregon State University Pacific Northwest Cooperative Chemical Analytical Laboratory (CCAL) handled the analysis of the water samples collected from Crater Lake during the 10-year study except for a limited number of analyses performed at Crater Lake National Park (see Study Area and Facilities section). The CCAL has a rigorous quality assurance (QA) program to monitor work conducted in the laboratory. The seven elements of the program are as follows:

1. Provide sample information concerning arrival date and analysis date.
2. Provide sample data with calibration summaries in a data report.
3. Perform and monitor QA procedures and criteria for each analysis method:
  - a. Derive standard curves.
  - b. Monitor precision/accuracy within each analysis batch.
  - c. Derive level of detection for each analysis.
  - d. Compare new standard solutions to old standard solutions.
4. Compare duplicate analyses within analytical batches.
5. Analyze duplicate samples submitted by investigators.
6. Compare current results with historical data.
7. Provide a report delineating precision and accuracy of standards, blanks, and duplicates two to three times per year.

Detailed descriptions of the procedures carried out under this QA program follow.

### **Reporting Sample Arrival and Analysis Dates**

A log sheet documenting arrival date and correlating investigator sample identification with laboratory sample numbers accompanies each data report. Analysis run dates for each analysis are provided on sample data reports in the calibration summary section.

### **Sample Data Reports**

The data report contains calibration summaries for all samples analyzed. This includes the standard concentrations and response (i.e., absorbance and chart units) used to create the standard curve for that analytical batch. For TKN, TP, OP,  $\text{NO}_3\text{-N}$ ,  $\text{NH}_3\text{-N}$ , and Si, (see Appendix 1 for definition of acronyms) linear regression information from the standard curve is listed. This includes  $r^2$ , intercept, and slope. Instrument response for the reagent blank is listed. For TKN the average digest blank is listed. Individual laboratory numbers for samples analyzed with that standard curve are listed.

### **QA Procedures Used to Evaluate Sample Data**

#### **Derivation of Standard Curves**

For each analysis, a standard curve is generated using standard solutions that have been diluted from a precisely prepared stock solution of known concentration. Anhydrous chemicals used for preparation of stock solutions are oven dried for at least 24 hours and then stored in a desiccator immediately prior to use. Hydrated chemicals are dried in a desiccator for at least 48 hours immediately prior to use. All chemicals used to prepare stock solutions are weighed to a tenth of a mg. Dilutions are prepared using class "A" volumetric glassware or are measured by weight to the nearest mg. Dilutions are made to a concentration level appropriate for the range of samples

regularly analyzed by the laboratory and that give a reasonable response from the instrument detector. A reasonable response is one that is well above any signal or noise generated by a reagent blank solution. Samples are then analyzed and compared to the standard curve, and results calculated from the comparison. For most analyses, at least three concentration levels plus a reagent blank are used to generate a standard curve. The exceptions are conductivity (1 standard + deionized water (DIW)) and alkalinity (2 standards + 2 DIW).

Standard solutions are analyzed with each analysis batch and the results are examined and evaluated for linearity. Each analysis has specific criteria for evaluation that are explained below. Additionally, the detection response (i.e., absorbance) is examined for comparability with previous standards of the same concentration. Any significant deviation from historical values for these standards is cause for close examination of the entire analysis.

For some analyses (TKN, TP, and OP), a computer-calculated "r" value that relates degree of correlation is automatically generated from the analytical instrument giving the analyst precise information regarding linearity. The lab strives for  $r^2$  values of 1.000 for each analysis, and  $r^2$  values are expected to meet or exceed 0.9990. Values of  $r^2$  down to 0.9900 are acceptable, especially if no repeat analysis is feasible. If non-linearity is in evidence ( $<0.9900$   $r^2$  value), or poor linearity is in evidence ( $<0.9990$   $r^2$  value), the standard curve is examined for procedural errors (e.g., incorrectly entered standard information, reagents not prepared correctly, or reagents not added). Procedural errors, if found, are corrected and the standard curve is reevaluated. If non-linearity is still in evidence, the samples for that run are designated questionable and are repeated with a new standard set if sufficient sample volume remains. Sample

results are not reported from questionable standard sets that have had valid repeat analysis.

If insufficient sample remains to repeat the analysis, the data are carefully scrutinized and evaluated by other factors within the analysis run for validity (e.g., duplicate samples, duplicate analyses, digest blanks, digest standards, quality control check sample, and recalculation of standard curve after eliminating outlier standard values). These results, if acceptable, are reported to the investigator as valid, but with a hand-written note on the data report alerting investigators to the possibly anomalous values. If the results do not meet the secondary criteria for non-standard validity, then the data are reported as questionable on the data report. This is denoted by a lower-case letter "q" next to the questionable value. No values are reported in extreme cases where meaningful data has not been produced. In instances where the analysis is not affected by time constraints (digest time, color development), the standards are again prepared before any samples are analyzed until a linear calibration is achieved.

Other analyses ( $\text{NO}_3\text{-N}$ ,  $\text{NH}_3\text{-N}$ , and Si) are evaluated visually for linearity during sample analysis. Once the analysis is complete, a hand-calculated regression curve using the standard solution data is evaluated for linearity using the criteria stated above. When the data have met all criteria, they are digitized and entered into the laboratory data management program. This program produces a regression equation that is evaluated using the criteria from above and is then compared to the hand-calculated regression equation. Anomalies between the hand-calculated and data-program regression equations are resolved before the data report is sent to the investigator.

When the standard curve has an intercept other than zero, and sample results fall within the range between zero and the first standard, sample values are calculated using

a two-point regression using the first standard and zero. This is dependent upon the reagent blank representing zero concentration or the reagent blank being subtracted from the raw sample result before calculation. Analyses producing data values derived from a two-point regression equation are noted in the calibration summary on the data report. Any single data value falling between zero and the detection level but having a detectable response is listed on the final data report with an asterisk, denoting that the value is below the level of detection.

Each analysis has a standard operating procedure for generating a standard curve which is documented in the CCAL Chemical Analysis Procedure Manual. The following are brief descriptions of solutions analyzed to produce standard curves for these procedures and the instrumentation used for analysis.

Alkalinity. Two dilute standard solutions per analysis batch are analyzed to verify titrant concentration and proper operating conditions of the auto-titrator. Two DIW blanks are analyzed for use in calculating titrant concentration and to evaluate precision. The standard stock solution is 0.02 N sodium carbonate. Instrumentation is a Radiometer type TTT 1c auto-titrator using a glass pH electrode with a calomel reference electrode and a temperature compensator electrode. Samples are titrated to pH 4.5.

Ammonia-Nitrogen. Concentrations of 0.050 mg/l, 0.100 mg/l, and 0.200 mg/l are used. Standard stock solution is 1000 mg/l  $\text{NH}_3\text{-N}$  made from ammonium chloride. Instrumentation is a Technicon Auto-Analyzer II.

Calcium. Concentrations of 3.00 mg/l, 6.00 mg/l, and 10.00 mg/l are used. The initial standard is read in absorbance and assigned its nominal concentration value. The final two standards are read in concentration in reference to the first standard. A

calibration curve is calculated by a computer program which evaluates curve parameters for acceptance. Non-linearity, such as S-shaped curves, results in an error message, which aborts analysis of samples. Standard stock solution is a purchased prepared 1000 mg/l Ca solution.

Magnesium. Concentrations of 0.500 mg/l, 1.500 mg/l, and 3.000 mg/l are used. The initial standard is read in absorbance and assigned its nominal concentration value. The final two standards are read in concentration in reference to the first standard. A calibration curve is calculated by a computer program which evaluates curve parameters for acceptance. Non-linearity, such as S-shaped curves, results in an error message, which aborts analysis of samples. Standard stock solution is a purchased prepared 1000 mg/l Mg solution.

Nitrate-Nitrogen. Concentrations of 0.025 mg/l, 0.050 mg/l, and 0.100 mg/l are used. Standard stock solution is 1000 mg/l  $\text{NO}_3\text{-N}$  made from potassium nitrate. Instrumentation is a Technicon Auto-Analyzer II.

Ortho-Phosphate. Concentrations of 0.050 mg/l, 0.100 mg/l, and 0.200 mg/l, and a reagent blank are used. The spectrophotometer provides calibration slope, intercept, and correlation information for immediate evaluation before preceding with sample analysis. For samples high in phosphate, a 0.300 mg/l standard is also analyzed. Standard stock solution is 50 mg/l  $\text{PO}_4\text{-P}$  made from monobasic potassium phosphate. Instrumentation since March 1989 is a Milton-Roy 601 spectrophotometer with a 10 cm path length. Analysis occurs at 880 nm. Instrumentation prior to March 1989 was a Klett Summerson colorimeter, model 900-3 with a 1.5-cm-path-length cell. Analysis occurred at 660 nm with a red filter.

pH. Three buffer solutions of 7.0, 4.0, and 10.0 are used. Instrumentation is a Radiometer type TTT 1c auto-titrator pH meter using a glass pH electrode with a calomel reference electrode and a temperature compensator electrode.

Potassium. Concentrations of 2.00 mg/l, 6.00 -mg/l, and 12.00 mg/l are used. The initial standard is read in absorbance and assigned its nominal concentration value. The final two standards are read in concentration in reference to the first standard. A calibration curve is calculated by a computer program which evaluates curve parameters for acceptance. Non-linearity, such as S-shaped curves, results in an error message, which aborts sample analyses. Standard stock solution is a purchased prepared 1000 mg/l K solution.

Silica. Concentrations of 5.0 mg/l, 15.0 mg/l, 25.0 mg/l as  $\text{SiO}_2$  are used. Data are converted to Si by calculation. Standard stock solution is a purchased prepared 1000 mg/l  $\text{SiO}_2$ . Instrumentation is a Technicon Auto-Analyzer II.

Sodium. Concentrations of 1.00 mg/l, 3.00 mg/l and 6.00 mg/l are used. The initial standard is read in absorbance and assigned its nominal concentration value. The final two standards are read in concentration in reference to the first standard. A calibration curve is calculated by a computer program which evaluates curve parameters for acceptance. Non-linearity, such as S-shaped curves, results in an error message, which aborts analysis of samples. Standard stock solution is a purchased prepared 1000 mg/l Na solution.

Specific Conductance. A standard solution of 0.01 N potassium chloride is analyzed at the beginning of each analysis batch. A DIW blank is also analyzed. Instrumentation is a YSI model 31 conductivity bridge.

Total Kjeldahl Nitrogen. Concentrations of 0.20 mg/l, 0.40 mg/l, 0.80 mg/l, 1.00 mg/l, 1.50 mg/l, and a reagent blank are used. The spectrophotometer provides calibration slope, intercept, and correlation information for immediate evaluation before preceding with sample analysis. For samples high in TKN, a 2.00 mg/l standard is also analyzed. Two digested reagent blanks and at least one digested standard solution are included with each analysis batch. Digest standards are ammonium chloride solutions of the same concentration range as those used to generate the standard curve. A single concentration is analyzed (one per rack) on all 12 burner/distillation positions before rotating to the next concentration range. This assures that each burner/distillation position is checked at each concentration level. Standard stock solution is 1000 mg/l  $\text{NH}_3\text{-N}$  made from ammonium chloride. Recovery for ammonium chloride digest standards must be 85% or better to validate the analysis. Lower recoveries indicate questionable data. Analysis batches producing low-recovery data may still have to be used due to the large sample volume requirement for TKN (500 mls). Organic nitrogen digestion efficiency is checked with a 50 mg/l cystine standard solution. Recovery must be at least 85%, and for the cystine standard, recoveries are expected to exceed 90%. Certified National Bureau of Standards reference material cystine is used. Instrumentation since December 1986 is a Milton-Roy 601 spectrophotometer with a 2.54-cm-path-length cell. Analysis occurs at 425 nm. Instrumentation prior to December 1986 was a Fisher Electro spectrophotometer, model 81 with a 2.54-cm-path-length cell. Analysis occurred at 425 nm with a blue filter.

Total Phosphorous. Concentrations of 0.050 mg/l, 0.100 mg/l, 0.200 mg/l and a blank are analyzed. The spectrophotometer provides calibration slope, intercept, and correlation information for immediate evaluation before preceding with sample analysis.

All standards are digested with the sample set. Standard stock solution is 50 mg/l  $\text{PO}_4\text{-P}$  made from monobasic potassium phosphate. Instrumentation since April 1989 is a Milton-Roy 601 spectrophotometer with a 10 cm path length. Analysis occurs at 880 nm. Instrumentation prior to April 1989 was a Klett Summerson colorimeter, model 900-3 with a 1.5-cm-path-length cell. Analysis occurred at 660 nm with a red filter.

Trace Metals. The CCAL submits samples to the U.S. Environmental Protection Agency (EPA) in Corvallis, Oregon for analysis of trace metals. The abbreviated procedure for calibrating the inductively coupled plasma atomic emission spectrophotometer (ICPAES) used by the EPA.

The analysis program to be run is normalized (short version of calibration) and quality control samples from Inorganic Ventures and EPA (ICAP-19 and ICAP-7) are analyzed. If quality control samples do not fall within the established 95% confidence interval, a full calibration of the ICPAES is necessary. Samples are analyzed if quality control standards are acceptable. A replicate analysis is performed on every tenth sample. A sample is analyzed a third time if replicate analyses do not meet established precision criteria. The ICPAES is checked for problems if there is still disagreement between replicates, and the instrument is calibrated if necessary. The same replicate procedure is followed for the last sample in an analysis batch. After every tenth sample, the mid-range standard (QMX001) and the matrix blank (QMX000) are analyzed. The mid-range check standard must agree to within 10% of the listed value. The main purpose of the mid-range 23-element check standard is to monitor system drift. System drift is typically less than 5% over eight operating hours. The standard is reanalyzed after resetting the system blank if the mid-range standard varies by more than 10%. The system must be again normalized or recalibrated before additional analyses are

performed if the mid-range standard reanalysis is still not within the established tolerance. All samples that are not bracketed by conforming standards are reanalyzed. Ion concentrations used to calibrate the ICPAES are listed in Table 1.

Table 1. Ion concentrations used to calibrate the inductively coupled plasma atomic emission spectrophotometer.

|        |                                                                                       |
|--------|---------------------------------------------------------------------------------------|
| S001:  | 0.2 mg/l - Mo, Sn<br>1.0 mg/l - Si, Ti<br>2.5 mg/l - P, S, Na<br>5.0 mg/l - Ca, Mg, K |
| S002:  | 2 mg/l - Mo, Sn<br>10 mg/l - Si, Ti<br>25 mg/l - P, S, Na<br>50 mg/l - Ca, Mg, K      |
| S003:  | 20 mg/l - Mo, Sn<br>100 mg/l - Si, Ti<br>250 mg/l - P, S, Na<br>500 mg/l - Ca, Mg, K  |
| S004:  | 0.2 mg/l - Mn, Sr<br>0.5 mg/l - Zn<br>1.0 mg/l - Al, B, Cd, Cu, Cr, Fe, Ni            |
| S005:  | 2 mg/l - Mn, Sr<br>5 mg/l - Zn<br>10 mg/l - Al, B, Cd, Cu, Cr, Fe, Ni                 |
| S006:  | 20 mg/l - Mn, Sr<br>50 mg/l - Zn<br>100 mg/l - Al, B, Cd, Cu, Cr, Fe, Ni              |
| S0007: | 1.0 mg/l - As, Sb                                                                     |
| S008:  | 10 mg/l - As, Sb                                                                      |
| S009:  | 100 mg/l - As, Sb                                                                     |

## Precision and Accuracy of Analyses

Accuracy is defined as a comparison of a measured value with that of a true value. True values are established for well-characterized reference standards or certified reference materials (i.e., obtained from the National Institute of Standards and Technology, formerly the National Bureau of Standards). Accuracy can also be monitored by repeated measurements of a quality control check sample (QCCS) to determine a true value based on a 95% confidence interval around a mean value. The CCAL evaluates accuracy by a combination of comparing standard curves, QCCS, and analyzing performance evaluation samples. These three measures of accuracy provide a context with which to evaluate accuracy on a batch-by-batch basis. As delineated in the Derivation of Standard Curves section, data are reported only if they meet specific analytical criteria. If analysis batches deviate from established accuracy parameters, the data are flagged as being of lesser accuracy than is expected.

Accuracy is evaluated with each analysis batch by comparing instrument response measurements of the standard solutions used for that run with historical values generated by standard solutions for that analysis. With large sample sets (>20 samples), standard solutions are analyzed within the run at regular intervals to check for continued validity of results. These check standards are evaluated as they are analyzed, and the continuation of the analysis of further samples is dependent upon good correlation (+/-10%) of the theoretical value of the check standard with the measured response. If response is low, action is taken to uncover the cause and correct it before analyzing samples. Sample results from low-response analysis batches are inspected for validity and are repeated when necessary if there is sufficient sample remaining. Analyses using check standards are: NO<sub>3</sub>-N, NH<sub>3</sub>-N, and Si, Ca, Mg, Na, and K.

An overall assessment of analytical accuracy is made by analyzing blind QA samples from the U.S. Geological Survey Standard Reference Water Survey Program twice a year. Depending upon the selection of check samples available, one, two, three, or four samples are analyzed during each check period. Concentration ranges vary from dilute (precipitation) to relatively high concentration samples (2500  $\mu\text{S}/\text{cm}$ ). These blind standards allow the laboratory to compare results with other participating laboratories to gauge analytic accuracy and comparability. The U.S. Geological Survey reports the results to the laboratory as variation from the mean of all laboratories analyzing that sample, with extreme outlier values disregarded in calculating a mean value for any particular parameter. These check samples test for the following nutrients and/or physical properties: total phosphorous, ortho-phosphate, ammonia-nitrogen, nitrate + nitrite-nitrogen, organic nitrogen (Kjeldahl), silica, pH, alkalinity, and specific conductance.

Once a year EPA Water Pollution Quality Control Samples are analyzed. These standards come as sealed ampuls that are diluted according to directions. The analyzed values can then be checked against the nominal values supplied with the check standard. The following nutrients are analyzed using this standard: total Kjeldahl nitrogen, ortho-phosphate, total phosphorous, nitrate, and ammonia. Between the two check standard programs, all analyses are validated at least once a year by outside programs.

Precision is measured by determining the variance among repeated analyses of a sample, standard solution, or QCCS. Precision is evaluated for each analysis batch by analyzing duplicate samples and comparing the raw and calculated values generated from the analysis. Duplicate samples are analyzed at least once per analysis batch to determine precision, with the exception of TKN where digest blanks are duplicated with

each run). Duplicate samples are chosen randomly. If duplicate analyses do not produce acceptable results within the precision limits established for that particular analysis (Table 2), the sample is repeated for further comparison. In such instances the entire analysis batch is examined for validity and possible error sources (e.g., instrument malfunction, analyst error, inhomogeneous sample, unfiltered analyses, or contaminated glassware).

If conforming results are produced by additional in-batch replication, then the entire analysis batch is evaluated for obvious outlier sample results. Samples with outlier results are repeated when sufficient sample remains. All other sample data in such sets is closely examined and evaluated for validity.

If anomalous duplicate data are present and replication produces additional nonconforming data, then the entire analysis batch is repeated when sufficient sample remains. Repeating the entire analysis batch occurs only if there is more than one questionable circumstance associated with that particular analysis batch. Samples with insufficient volume for repeat analysis are examined and reported above in the section Derivation of Standard Curves.

For some analyses, standard solutions that are analyzed as an accuracy check are also evaluated for repeatability to establish within-batch precision. Precision has been evaluated at low concentrations for those analyses for which detection levels have been determined.

Whenever the laboratory changes analytical methods and/or instrumentation, investigators will be informed of the resulting new precision and accuracy for that analysis. A hand-written note on data reports will alert investigators to changes in

Table 2. Analytical detection levels and precision limits of the Cooperative Chemical Analytical Laboratory.

| Analysis                      | Level of Detection       | Precision <sup>1</sup>        |
|-------------------------------|--------------------------|-------------------------------|
| Alkalinity                    | 0.2 mg/l                 | +/- 0.02 mg/l <sup>2</sup>    |
| Ammonia-nitrogen <sup>3</sup> | 0.010 mg/l               | +/- 0.002 mg/l <sup>4</sup>   |
| Calcium                       | 0.06 mg/l                | +/-0.065 mg/l <sup>5</sup>    |
| Chloride                      | 0.10 mg/l <sup>6</sup>   | +/- 0.06 mg/l @ 0.25 mg/l     |
|                               |                          | +/- 0.03 mg/l @ 5.00 mg/l     |
|                               | 0.02 mg/l <sup>7</sup>   | not available                 |
|                               | 0.20 mg/l <sup>8</sup>   | not available                 |
| Magnesium                     | 0.001 mg/l               | +/-0.0006 mg/l <sup>5</sup>   |
| Nitrate-nitrogen              | 0.001 mg/l               | +/- 0.001 mg/l <sup>4</sup>   |
| Phosphate, ortho              | 0.001 mg/l <sup>9</sup>  | +/- 0.001 mg/l <sup>5</sup>   |
|                               | 0.002 mg/l <sup>10</sup> | +/- 0.001 mg/l <sup>5</sup>   |
| pH                            | 0-14 pH units            | +/- 0.1 pH unit <sup>11</sup> |
| Potassium                     | 0.03 mg/l                | +/- 0.015 mg/l <sup>5</sup>   |
| Silica                        | 0.20 mg/l                | +/- 0.05 mg/l <sup>4</sup>    |
| Sodium                        | 0.01 mg/l                | +/- 0.005 mg/l <sup>5</sup>   |
| Specific conductance          | 0.4 $\mu$ s/cm           | +/- 2% <sup>12</sup>          |
| Sulfate                       | 0.10 mg/l <sup>6</sup>   | +/- 0.005 mg/l @ 0.10 mg/l    |
|                               |                          | +/- 0.2 mg/l @ 1.00 mg/l      |
|                               | 0.01 mg/l <sup>7</sup>   | not available                 |
|                               | 0.20 mg/l <sup>8</sup>   | not available                 |
| Nitrogen, total               | 0.010 mg/l <sup>13</sup> | +/- 0.006 mg/l <sup>15</sup>  |
| Kjeldahl nitrogen             | 0.010 mg/l <sup>14</sup> | +/- 0.007 mg/l <sup>15</sup>  |
| Total phosphorus              | 0.001 mg/l <sup>16</sup> | +/- 0.002 mg/l <sup>5</sup>   |
|                               | 0.004 mg/l <sup>17</sup> | +/- 0.002 mg/l <sup>5</sup>   |

<sup>1</sup>Precision was evaluated by repeated analysis of standard solutions near the level of detection.

<sup>2</sup>Evaluation of titration precision and accuracy by comparison with Gran titration results.

<sup>3</sup>For ammonia-nitrogen, the laboratory has been able to produce data with the same precision as stated above at a DL of 0.005 mg/l.

<sup>4</sup>Method specified detection level as yet unconfirmed, but evaluated as reasonable by monitoring sample response at this concentration level.

<sup>5</sup>Evaluated by low concentration detection level analysis.

<sup>6</sup> $\geq$  sample number 1083.

<sup>7</sup>sample numbers 1052, 1073 - 1080.

<sup>8</sup> $\leq$  sample number 1072 (except sample number 1052).

<sup>9</sup>March 1989 - present.

<sup>10</sup>1983 - February 1989.

<sup>11</sup>Limitation of analog instrument currently in use.

<sup>12</sup>Limitation of instrument scale on instrument currently in use.

<sup>13</sup>December 1986 - present.

<sup>14</sup>Through November 1986.

<sup>15</sup>Estimate based on low concentration standards analyzed on a continuing basis.

<sup>16</sup>April 1989 - present.

<sup>17</sup>1983 - March 1989.

methods/instrumentation and a formal notification will accompany the data.

Comparability between methods is evaluated by analyzing standard solutions and quantifying any differences.

Quality control check standards (QCCS) are used to monitor batch to batch accuracy and precision. QCCS are selected and prepared to be within the actual concentration range of submitted samples. A large volume of naturally occurring surface water is collected and brought to the laboratory. It is filtered through a GF/F filter (0.7  $\mu$ m retention) and allowed to stabilize for a period of time ranging from 1 to 20 weeks. The sample is selected for specific target analyses dependent on expected nutrient concentration. Water from Crater Lake, Oregon is used as a QCCS for all phosphorous analyses. Water from Mack Creek, a stream located in the H.J. Andrews Experimental Forest in western Oregon, is used for Kjeldahl-nitrogen analyses. After allowing a sample to stabilize, the QCCS is analyzed repeatedly to develop a mean concentration value and standard error range. For phosphorous QCCS, a minimum of 30 replicates are analyzed to characterize the water. For Kjeldahl-nitrogen QCCS, a minimum of 16 replicates are analyzed to characterize the water. All accuracy and precision criteria are applied to the QCCS characterization analyses. Error ranges of plus or minus one, two and three standard deviations are developed from a statistical analysis of the replicate analyses. QCCS characterization data must conform with expected QA population distribution before it is accepted (68.3%  $\pm$  1 SD, 95.5%  $\pm$  2SD, and 99.7%  $\pm$  3SD). Once a QCCS has been characterized and is accepted, it is analyzed with each batch of samples for the phosphorous analyses. Due to the time and labor intensive nature of the Kjeldahl nitrogen analysis, the QCCS is analyzed once for every six batches of analyses. QCCS data from individual analysis batches must fall within the expected concentration

range developed from the characterization analyses. If QCCS data do not fall within the expected concentration range, then the entire analysis is examined for analytical problems.

QCCS are closely monitored for degradation. When QCCS degradation becomes evident, a new QCCS is characterized and established before sufficient degradation occurs to the previous QCCS that would produce results varying greater than the  $\pm 3SD$  error range initially established.

QCCS have been attempted to be developed for the ammonia-nitrogen and nitrate-nitrogen analyses, but these QCCS degrade too quickly to be of any use as a QA check. Eventually the laboratory will either develop synthetic QCCS for these analyses or will purchase QCCS for these analyses from an outside source.

#### **Level of Detection**

Detection level (DL) of analysis has been determined methodologically for ortho-phosphate and total phosphorous. For these analyses, low-concentration standard solutions were analyzed along with reagent blanks to determine what concentration level produces a quantifiable instrument response. A detection level is set at the concentration level that produces a repeatable response with a demonstrated degree of accuracy. The degree of accuracy at low concentration levels can vary widely on a percent recovery basis, and precision must be very good at those levels before qualifying as a legitimate detection level. Once a detection level has been determined, no regular detection level standard is analyzed on a batch by batch basis. Instead, operating conditions are monitored closely in conjunction with the range of samples being analyzed.

For the remainder of analyses, the detection levels have been assigned as those specified by the standard method from which the analysis is derived. Assigned DL's are evaluated for each analysis by examining instrument response from sample data that approach the DL. For all analyses, the proscribed DL has been met or improved.

#### **Comparison of Standard Solutions**

Whenever a new stock standard solution (the solution from which further serial dilutions are prepared) is prepared, it is compared to the old stock solution before the new stock solution is used for calibration standards in an analysis. Serial dilutions of the new solution are compared directly to serial dilutions of the old solution. There must be good correlation ( $>95\%$ ) between standards before the new calibration standards are used in analysis. The only exception to this comparison method is for stock solutions that tend to degrade over time. For this situation a comparison is still made, with a greater concentration value expected for the new stock standards in comparison to the old. Low concentration standard solutions of ammonia are most prone to this tendency. Great care is taken to make stock solutions and calibration standards for ammonia well before any degradation occurs, but experience has shown that some degradation occurs regardless. The above procedure also checks comparability for intermediate working solutions (solutions made on an as needed basis from the stock solution that facilitate the preparation of calibration standards). Calibration standards are subjected to comparison as part of either the stock or working solution comparisons.

New stock solutions are prepared at least once a year regardless of the continued validity of calibration standards made from the solution. Comparisons are also made of prepared stock solutions purchased from chemical suppliers. Reagent preparation is

documented by date, technician preparing the solution, and chemical lot number for all analyses. Preparation date appears both on the reagent bottle and on a reagent tracking chart. Notation is made on data sheets whenever new reagent solutions are used.

#### **Duplicate Analyses**

Duplicate laboratory analyses are reported on the data reports and are designated by a "D" following the laboratory sample number. These duplicates are used to monitor precision on a within-batch basis. No statistical information regarding duplicate laboratory analyses is currently provided in the final data report. Duplicate values are checked for acceptable correlation before data is sent to the investigator. If duplicate correlation does not conform to expected precision levels, the data are reported according to the guidelines outlined in Derivation of Standard Curves.

#### **Field Duplicates**

Statistical information concerning field duplicate sample results (co-submitted split samples) is not provided. The laboratory will perform analyses on field duplicate samples -- termed analytical duplicates -- at no additional charge (1 duplicate for every 10 samples submitted). To receive the blind duplicate sample analyses at no charge investigators must identify the blind duplicates after receiving the data report. Blind duplicates cannot be positively identified prior to data reporting thus preventing any statistical comparison. Known duplicate samples are examined for precision as part of the data quality check before data are sent to the investigator.

The laboratory encourages all investigators to evaluate collection variation by submitting field blanks and field replicate samples for analysis. However, information of

this nature goes beyond assessing conditions controllable by the laboratory because sample splitting is essentially limited by field procedures.

#### **Comparison of Current Data with Historic Data**

Comparison of current laboratory results to results of historically analyzed samples from the same site is done on a rudimentary level. If the laboratory has analyzed enough samples to give an indication of expected results, the current data are evaluated in a broad sense by confirming that the samples fall within the same general concentration range. However, the validity of analysis results are based solely on analytical criteria for calibration, accuracy, and precision and not on producing a result that fits the study plan or conforms to historical norms. Historical comparisons of this type can lead to a bias of dynamic sample monitoring.

#### **QA Report**

The laboratory compiles all data from individual analysis batches to statistically evaluate the data. The data have been gathered and filed since 1983. The compiled information includes: reagent blank values, calibration standard values, standard curve information, check standard values, digest standard values, and digest blank values. These data have been monitored and evaluated on a batch-by-batch basis as they have been collected. This has lead to a generalized overview for expected ranges and deviations for each analytical parameter. No summary report has been issued or compiled to date.

## Appendix 1. Definition of acronyms and abbreviations used in this section.

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|                    |   |                                                                   |
|--------------------|---|-------------------------------------------------------------------|
| CCAL               | - | Cooperative Chemical Analytical Laboratory                        |
| DIW                | - | Deionized Water                                                   |
| DL                 | - | Detection Level                                                   |
| EPA                | - | U.S. Environmental Protection Agency                              |
| mg/l               | - | Milligrams per Liter                                              |
| NH <sub>3</sub> -N | - | Ammonia Nitrogen                                                  |
| NO <sub>3</sub> -N | - | Nitrate + Nitrite Nitrogen                                        |
| OP                 | - | Ortho Phosphate                                                   |
| OSU                | - | Oregon State University                                           |
| PNW                | - | USDA Forest Service Pacific Northwest Forestry Science Laboratory |
| PO <sub>4</sub> -P | - | Phosphate Phosphorous                                             |
| QA                 | - | Quality Assurance                                                 |
| QC                 | - | Quality Control                                                   |
| QCCS               | - | Quality Control Check Sample                                      |
| Si                 | - | Silica                                                            |
| TKN                | - | Total Kjeldahl Nitrogen                                           |
| TP                 | - | Total Phosphorous                                                 |
| USGS               | - | U.S. Geological Survey                                            |

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## Appendix 2. Analytical methodology of the Cooperative Chemical Analytical Laboratory.

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| Analysis                 | Method # with Specifications and Modifications <sup>1</sup>                                                                                                                                  |
|--------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Alkalinity               | 403, procedure 4c, titrate to pH 4.5. Modifications: Use 0.02N N a <sub>2</sub> CO <sub>3</sub> and 0.02N H <sub>2</sub> SO <sub>4</sub> .                                                   |
| Ammonia                  | 417F.                                                                                                                                                                                        |
| Calcium                  | 303A; flame atomic absorption spectroscopy. Modifications: nitrous oxide/acetylene flame since May 1987; addition of 1 ml 50,000 mg/l lanthanum oxide to 10 ml sample to control ionization. |
| Chloride                 | Technicon industrial method 99-70W, <sup>2</sup><br>4110B. <sup>3</sup>                                                                                                                      |
| Specific Conductance     | 205; Wheatstone bridge.                                                                                                                                                                      |
| Magnesium                | 303A; Flame atomic absorption spectroscopy.                                                                                                                                                  |
| Metals-Trace             | USEPA 200.7; Induction coupled plasma emission spectroscopy.                                                                                                                                 |
| Nitrate                  | 418F. Technicon industrial method 100-70W; different formulations for color and ammonium chloride reagents.                                                                                  |
| Nitrogen, Total Kjeldahl | Kjeldahl digestion: H <sub>2</sub> SO <sub>4</sub> , CuSO <sub>4</sub> /KCl, Nessler finish.                                                                                                 |
| pH                       | 423; Calomel reference electrode, glass pH electrode, temperature compensator.                                                                                                               |
| Phosphate-Ortho          | 424F. Modifications: Ascorbic acid reagent 2g/100 ml.                                                                                                                                        |
| Phosphorous-Total        | 424C, 424F. Modifications: microwave digestion 60 minutes, 50 ml analysis volume, ascorbic acid reagent 2g/100 ml.                                                                           |
| Potassium                | 303A; Flame atomic absorption spectroscopy.                                                                                                                                                  |
| Silica                   | Technicon industrial method 105-71W/B.                                                                                                                                                       |
| Sodium                   | 303A; Flame atomic absorption spectroscopy.                                                                                                                                                  |
| Sulfate                  | Technicon industrial method 105-72W. <sup>2</sup><br>4110B. <sup>3</sup>                                                                                                                     |

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<sup>1</sup> Method numbers refer to Standard Methods For the Examination of Water and Wastewater 15th Edition, 1980, except sulfate and chloride Standard Methods For the Examination of Water and Wastewater 17th Edition, 1989.

<sup>2</sup> For sample number ≤ 1072 except sample number 1052.

<sup>3</sup> Sample numbers 1052, ≥ 1073.

| Analysis                 | Instrumentation                                                                                                                                                                                                                 |
|--------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Alkalinity               | Radiometer type TTT 1c auto-titrator with glass pH electrode, calomel reference electrode and temperature compensator electrode.                                                                                                |
| Ammonia                  | Technicon Auto-Analyzer II.                                                                                                                                                                                                     |
| Calcium                  | Perkin-Elmer 500 atomic absorption spectrophotometer. <sup>1</sup>                                                                                                                                                              |
| Chloride                 | Technicon Auto-Analyzer II. <sup>2</sup><br>Dionex 4000i Ion Chromatograph. <sup>3</sup>                                                                                                                                        |
| Specific Conductance     | YSI model 31 conductivity bridge.                                                                                                                                                                                               |
| Magnesium                | Perkin-Elmer 500 atomic absorption spectrophotometer. <sup>1</sup>                                                                                                                                                              |
| Metals-Trace             | Bausch and Lomb Model 3580 ICPAES <sup>4</sup>                                                                                                                                                                                  |
| Nitrate                  | Technicon Auto-Analyzer II.                                                                                                                                                                                                     |
| Nitrogen, Total Kjeldahl | Milton-Roy 601 spectrophotometer with 2.54-cm-path-length cell. Analyze at 425 nm. <sup>5</sup><br>Fisher Electro spectrophotometer, model 81 with 2.54-cm-path-length cell. Analyze at 425 nm with a blue filter. <sup>6</sup> |
| pH                       | Radiometer type TTT 1c auto-titrator with glass pH electrode, calomel reference electrode and temperature compensator electrode.                                                                                                |
| Phosphate-Ortho          | Milton-Roy 601 spectrophotometer with 10-cm-path length. <sup>7</sup><br>Klett Summerson colorimeter, model 900-3 with 1.5-cm-path-length cell. Analyze at 660 nm with a red filter. <sup>8</sup>                               |
| Phosphorous-Total        | Milton-Roy 601 spectrophotometer with 10-cm-path length. <sup>9</sup><br>Klett Summerson colorimeter, model 900-3 with 1.5-cm-path-length cell. Analyze at 660 nm with a red filter. <sup>10</sup>                              |
| Potassium                | Perkin-Elmer 500 atomic absorption spectrophotometer. <sup>1</sup>                                                                                                                                                              |
| Silica                   | Technicon Auto-Analyzer II.                                                                                                                                                                                                     |
| Sodium                   | Perkin-Elmer 500 atomic absorption spectrophotometer. <sup>1</sup>                                                                                                                                                              |
| Sulfate                  | Technicon Auto-Analyzer II. <sup>2</sup><br>Dionex 4000i Ion Chromatograph. <sup>3</sup>                                                                                                                                        |

<sup>1</sup> Sample numbers 586-595.<sup>2</sup> ≤ sample number 1072 (except sample number 1052)<sup>3</sup> sample numbers 1052, ≥ 1073<sup>4</sup> All cations/trace metals except as noted in footnote 1.<sup>5</sup> December 1986 - present<sup>6</sup> 1983 - November 1986<sup>7</sup> March 1989 - present<sup>8</sup> 1983 - February 1989<sup>9</sup> April 1989 - present<sup>10</sup> 1983 - March 1989

## Climate Variability at Crater Lake National Park and its Effect on Water Level

Kelly Redmond

Knowledge of climate variations in Crater Lake National Park is essential for understanding the behavior of the natural physical and biological systems in the park. Such knowledge is also needed for practical applications in planning and maintaining facilities and services for the visiting public. Studies of climate and effects of climate on lake levels were initially motivated by a desire to explain the substantial changes in lake level over this century (Fig. 1). The most notable feature of the record of lake levels was a rapid decrease in lake elevation in the 1920's, which culminated in a decade (1931-1942) of low water levels 4-5 m below those recorded before or since. An understanding of these and other lake-level variations in turn required knowledge of variations in components of the lake's water budget.

The lake's water budget was first considered by Diller (1902). Harding (MS, 1953) later re-examined these figures. Phillips (1968) investigated the hydrology of Crater Lake and two other lakes in Oregon. Simpson (1970) performed another analysis of the water budget of Crater Lake to understand the mixing of tritium from atmospheric testing to depths in the lake. Nathensen (1992) investigated aspects of the water budget for the purpose of interpreting data pertinent to fluxes of dissolved constituents in the lake.

The objectives of the present study were to:

- 1) describe important features of the long-term climate of Crater Lake, and assemble this information for use by other researchers,

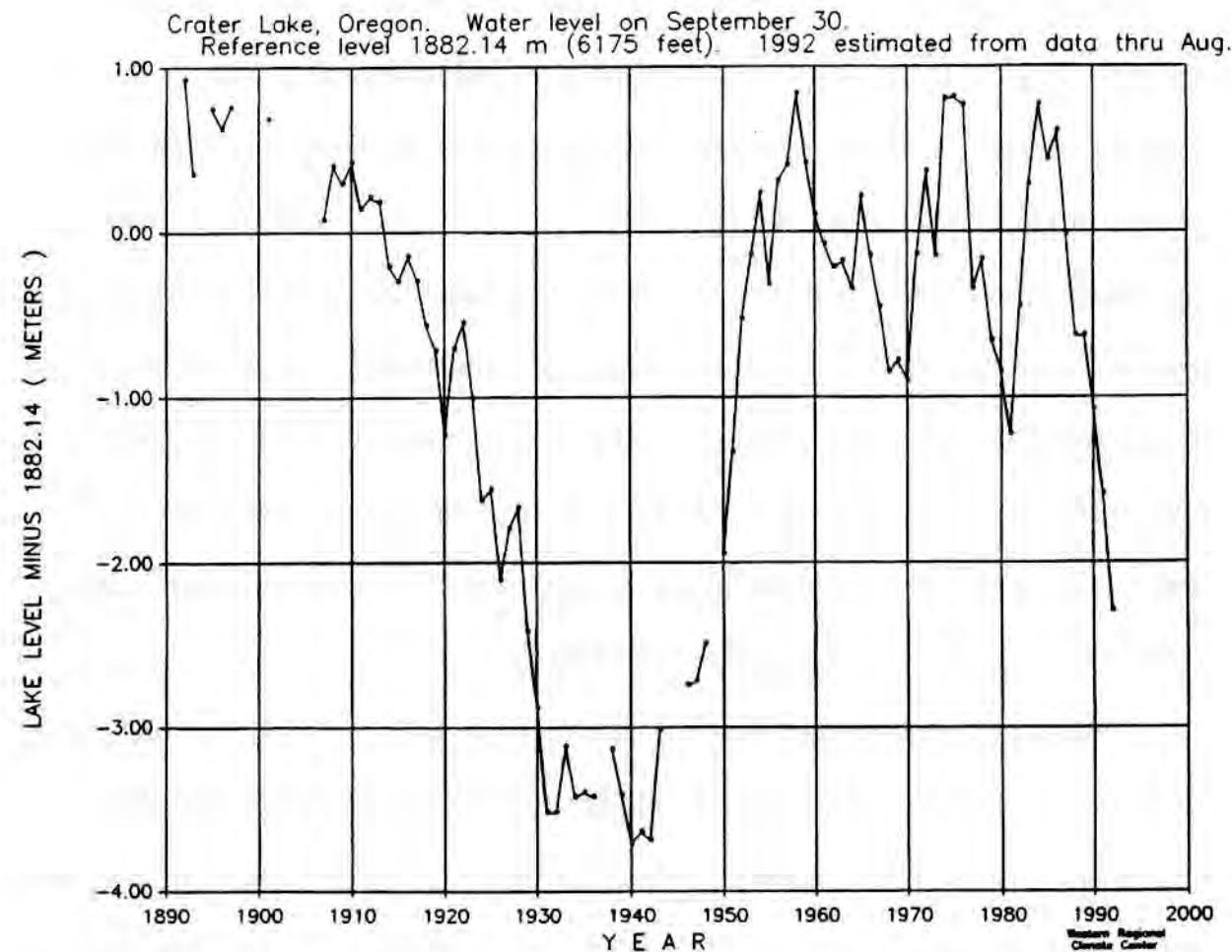


Figure 1. Observed elevation of the lake surface this century, expressed as a departure from the nominal elevation of 1,882.14 m (6,175 ft). The 1992 value is based on an observation on Aug. 28 plus normal decline to Sept. 30.

- 2) describe variations of principal climate elements about their long-term mean values,
- 3) explain the observed variation in lake level during this century.
- 4) develop estimates of annual values of the principal elements of the water budget of Crater Lake,
- 5) begin the development of methods to model daily variations in the level of Crater Lake, and
- 6) describe the relation of climate in Crater Lake National Park to global scale climate, particularly the El Niño/Southern Oscillation (ENSO).

### The Physical Setting

Several aspects of the physical setting (see Study Area and Facilities section) are relevant to the water budget of the lake. The water surface, itself about 300 m below the caldera rim, has a mean elevation of 1,882 m, which is considerably above the surrounding landscape. The mean annual temperature at the weather station at park headquarters (1,973 m) is about 3°C. Thus, the water in the lake is quite cold but not as cold as the air. Except for a brief period in mid-summer, the mean daily air temperature is lower than the water temperature (Redmond 1990). Prevailing south to west winds during winter months are forced to rise and deposit heavy precipitation near the Cascade crest. Crater Lake straddles a sharp east-west gradient in annual precipitation. The southwest rim receives approximately twice the precipitation (about 200 cm) that falls on the northeast rim (about 100 cm), although these two locations are only 10 km apart. The lake occupies about 78 percent of its own drainage basin, which has steep, nearly cliff-like sides. A substantial part of the water budget, therefore, consists of vertical fluxes directly onto or away from the lake surface. Most of the copious annual precipitation falls in winter as snow, and in the small part of the basin that is land

surface, snow melt does not occur until spring or early summer. This delayed runoff keeps the lake high well into early summer even when precipitation is low (Redmond 1990). In mid- to late summer the level of the lake begins to fall because diminishing snowmelt and ground water runoff cannot compensate for lack of precipitation. On average the lake drops about 0.5 m during summer. Thus, the lake appears to evaporate at the highest rate in summer. Water level begins to rise in late October with the onset of the next precipitation season. However, winter evaporation may be substantial but hidden by effects of abundant precipitation.

### **Methods**

The general approach of this study was to assemble and use historical climate information from standard sources, supplemented by additional available data. Much of the historical climate data were maintained as part of the archives of the Oregon Office of State Climatologist. These data are also now available at the Western Regional Climate Center of the Desert Research Institute in Reno.

Statistical relations were developed between data sets expected to possess physical linkages. As much advantage as possible was made of the availability of relatively long, systematic and regular observations. For example, through the end of 1991, 22,280 daily measurements of precipitation had been recorded at park headquarters. For other portions of the work, stratified samples were utilized (such as for studies of daily evaporation and the relation to ENSO). Procedures were developed to adjust non-concurrent measurements to either standard time intervals or dates.

Climate measurements have been made at a consistent location at park headquarters since 1931. This site is about 2 km to the southwest of Rim Village and

200 m below the village. These readings include daily maximum and minimum temperature, precipitation, snowfall, and snow depth. Lake elevation has been measured daily with a resolution of 0.01 foot (3 mm) at a USGS gaging station at Cleetwood Cove since 1961. These readings were reasonably continuous with occasional gaps of a few months. Seasonal precipitation totals were measured using a storage gage on the rim above Cleetwood Cove since October 1964. Storage gages were placed on Wizard Island in 1987 and on the southwest rim near Rim Village in 1986.

In the summer of 1991, a floating weather station was anchored at Station 13, south of Cleetwood Cove. This device measures hourly temperature, humidity, wind speed and direction and near-surface water temperature. A chain of thermistors below the water surface measures changes in the vertical water temperature profile. Another station was installed on the rim a few hundred meters northwest of Rim Village, also with the capability to measure temperature, humidity, and wind at hourly intervals. Data from neither platform were available in time to analyze for this report, but in the future these will be valuable sources of information.

### **Results and Discussion**

#### **Climate**

The park experienced a wide range of climatic conditions during the course of the 10-year study. Successive wet winters occurred in the early 1980's, followed by a succession of very dry winters in the later 1980's and early 1990's (Fig. 2 and Appendix I). Despite such extreme variability, precipitation for this decade was about equal to the average for the period 1931-1990. At this writing, the Crater Lake region is experiencing one of the most significant droughts in its recorded history. Total

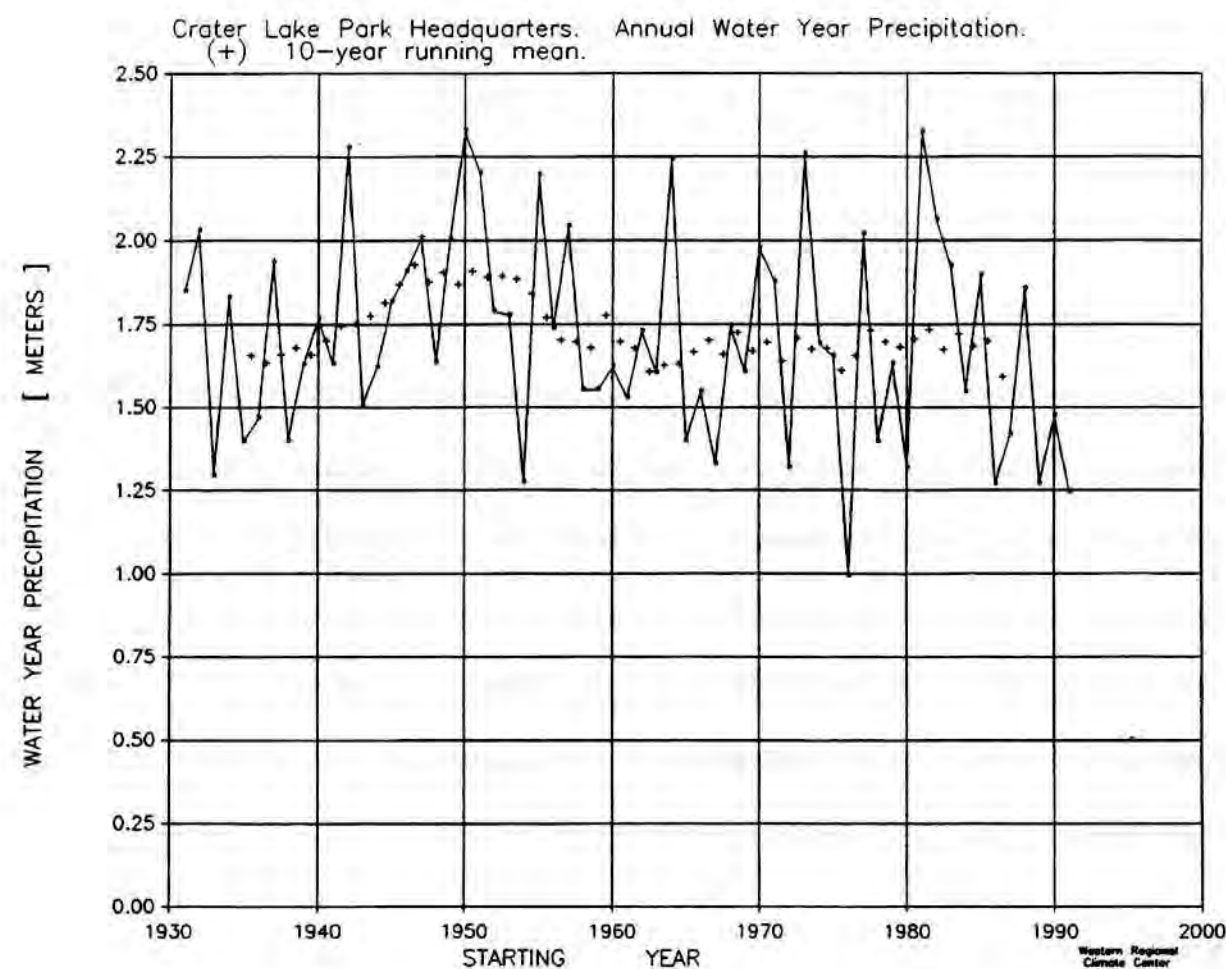


Figure 2. Annual precipitation for the water year (October through September) at Park Headquarters, plotted in the starting year, expressed in meters. Some values during 1943-46 are estimated. (+) is a 10-year running mean.

precipitation during the past three water years (October-September) is the lowest three-year total since records began at Park Headquarters in 1931.

Data from the park weather station has been collected at 8 am since January 1, 1982 (observation time affects the reported mean temperature). Cool years in the early 1980's have given way to warmer years. The water year just ended, 1991-1992, was by far the warmest in recent decades (Fig. 3 and Appendix I). Through August 1992, Crater Lake has experienced 14 consecutive warmer-than-average months. Because of its high altitude and similarity to free-air conditions, there is no particular reason for annual temperature fluctuations at Crater Lake to mimic those at lower elevations to the west or east. Indeed, the correlation between annual mean air temperature at Medford and Sexton Summit (a similar exposure to Crater Lake) over several decades is only 0.57. Data from the Crater Lake station show no sign of long-term warming.

#### Water Budget Elements

Four principal factors affect the water budget. The lake gains water from precipitation, from immediate and delayed runoff from the caldera sides and ground water inflow. The lake loses water upward by evaporation and downward by seepage from the bottom (Fig. 4). In an interesting departure from the usual situation in hydrology, the easiest of these four quantities to measure appears to be seepage.

The surface of Crater Lake almost never freezes entirely across. The surface was solidly frozen in 1949, and then not again until during the study period-once in January and again in December, 1985. In both instances, another rare event occurred simultaneously - an extended winter period with almost no precipitation. During these situations, with evaporation effectively shut off by a lid of ice and runoff at a minimum

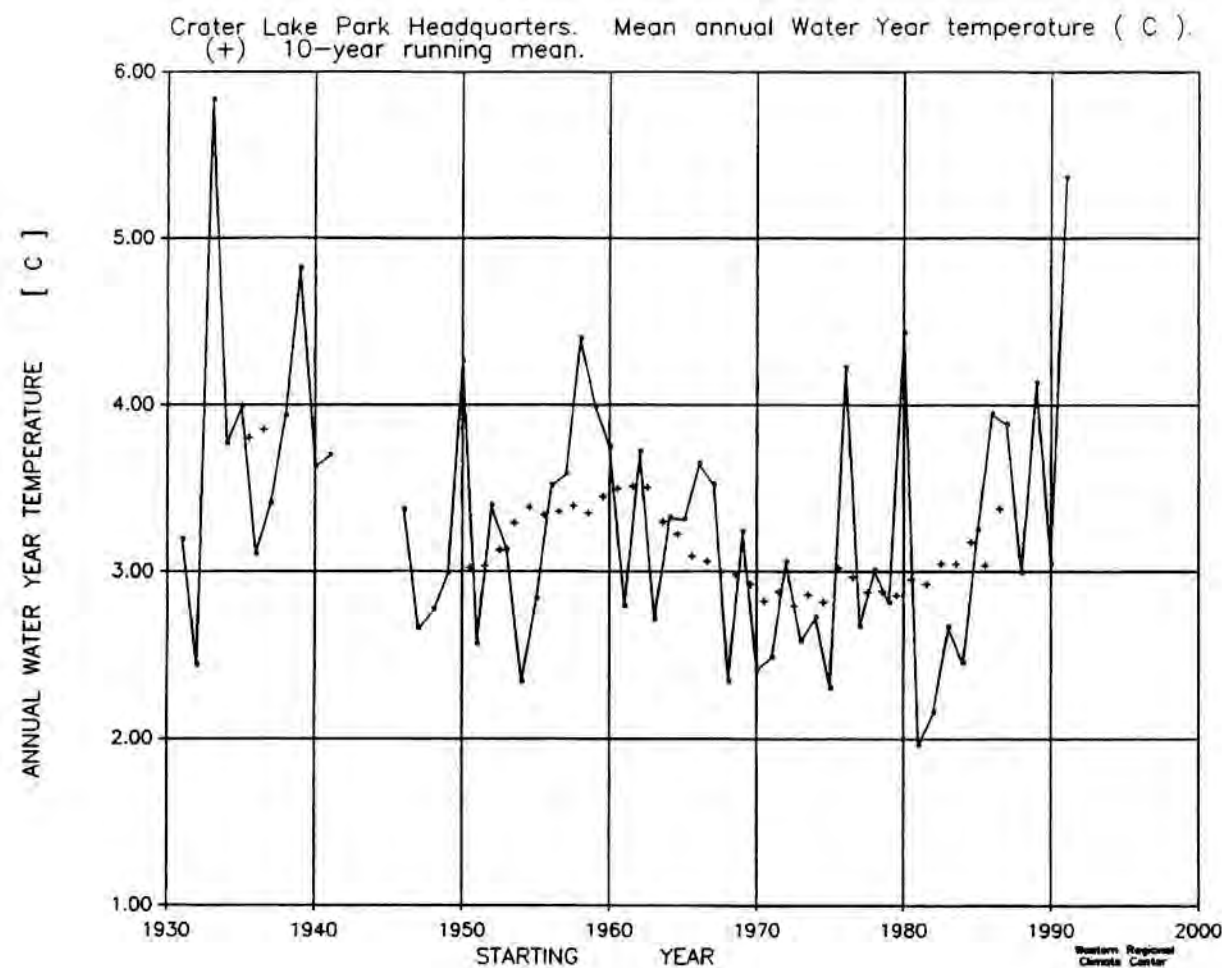


Figure 3. Annual mean temperature for the water year (October-September) at Park Headquarters, plotted in the starting year, expressed in degrees C. (+) is a 10-year running mean.

because of the cold, the lake level continued to fall at a steady rate through seepage over about 40 days, at an average rate of 3.47 mm/day.

Average precipitation for the basin is not known well enough to establish its relation to the time rate of change of lake volume with high accuracy. It is well established that in this region there is significant spatial correlation of annual and monthly precipitation. Thus, basin-average precipitation should be proportional to that at any nearby upwind site, in particular park headquarters. As evidence of this, the 1964-1988 correlation of July-June precipitation at Cleetwood Cove to that at park headquarters is 0.90 even though Cleetwood receives only 72% as much precipitation as park headquarters. However, the mean ratio of 0.715 had a standard deviation of 0.074 over these 24 years, and varied from 0.62 to 0.92. The relation between the two sites is

$$P_{CC} = -1.9 + 0.730 P_{HQ} \text{ (cm)},$$

where  $P_{CC}$  is precipitation at Cleetwood Cove and  $P_{HQ}$  is precipitation at park headquarters.

The relation between water year (October through September) precipitation and lake level change was established using data from park headquarters. The relationship from 1961-1988 was:

$$LLC = -246.5 + 1.457 P_{HQ} \text{ (cm)},$$

( $r = .96$ ), where  $P_{HQ}$  is the precipitation at park headquarters. Nathanson (1992) observed that use of multiple gages generally improves the reliability of regressions. The use of combined Cleetwood and headquarters precipitation data changes the constant to about -210 to -220. Also, the Cleetwood gage is emptied around July 1 rather than October 1. The use of a different definition for the precipitation year affects this constant (Nathanson, 1992). The October-September definition may be preferable,

because even though snowmelt is often nearly finished by July 1, subsurface runoff probably persists after that. An increase in the value of this constant implies that evaporation is reduced (see below). For this study, park headquarters precipitation was used because the record there extends back to 1931. This period of records is much larger than the period of records collected at Cleetwood Cove and, therefore, is more useful for reconstruction purposes. Missing precipitation values for winter months during 1943-1946 were estimated from data collected at a nearby climate station at Prospect, Oregon. These estimates of the missing data points are better than previous estimates based on observations at Roseburg, Oregon.

The relation since 1961 between precipitation at park headquarters and lake level change can be used to reconstruct the annual lake level changes back to 1931. The reconstruction can be extended further back in time by estimating precipitation at park headquarters, using data from two towns within 120 km of the lake, Grants Pass and Roseburg, Oregon. These reconstructions indicate that a precipitation minimum in the 1910's and 1920's led to a lower lake until a period of high precipitation rapidly raised the lake around 1950 (Fig. 4). An improved estimate of Crater lake precipitation during World War II has modified this reconstruction from those published earlier. In summary, precipitation variations in large measure account for fluctuations in lake level, and variations in evaporation or seepage are less influential. An analysis in Redmond (1990) showed that seepage did not appear to be a function of stage.

During colder portions of the year when runoff is low, variations in the day-to-day change of lake level are primarily controlled by precipitation and evaporation directly over the lake. An analysis of daily lake-level changes can provide a number of insights into the evaporation process at the lake.

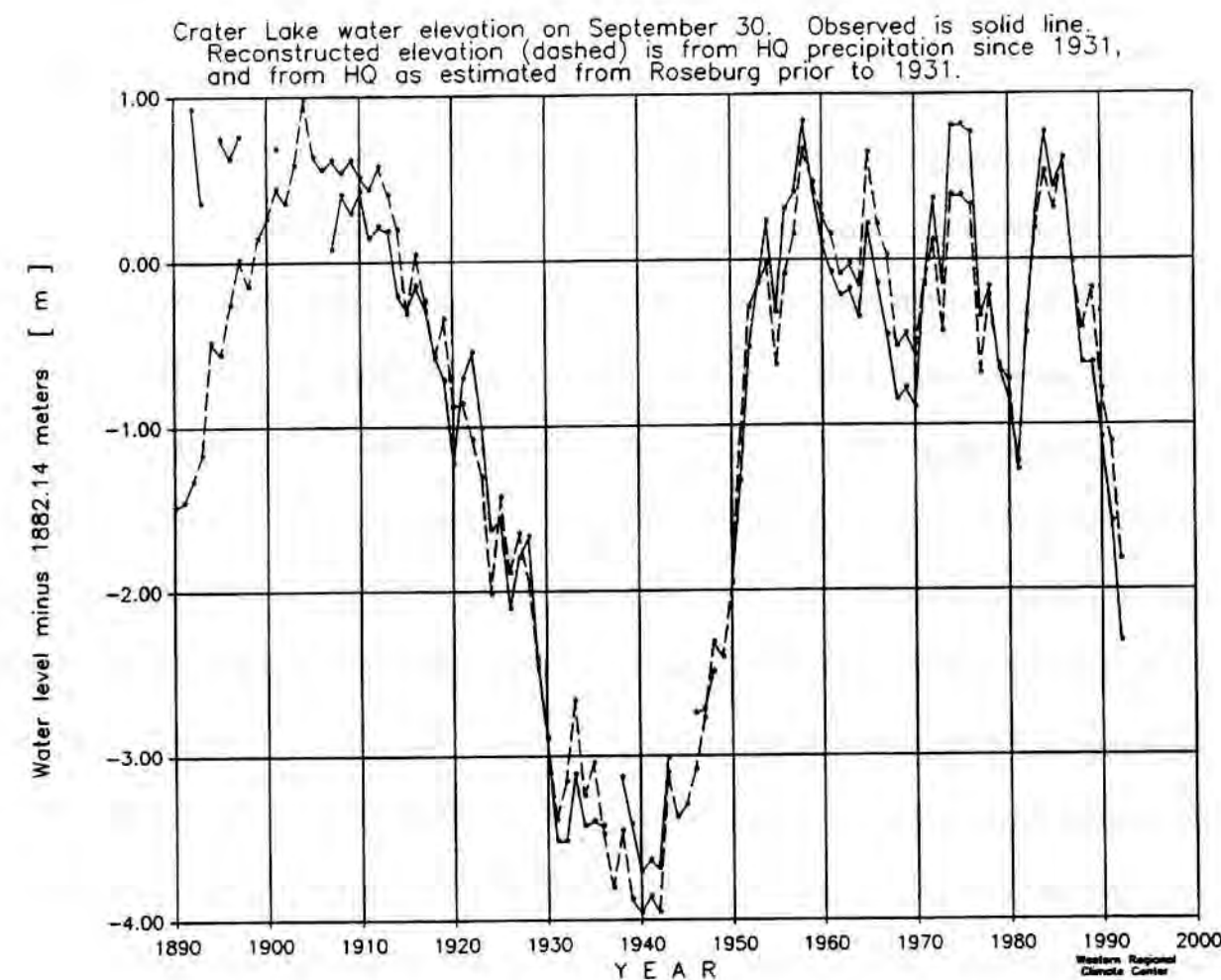


Figure 4. Lake level as reconstructed from park headquarters precipitation. Park headquarters participation prior to 1931 is estimated from Grants Pass. Solid line = observed lake level. Dashed lines = reconstructed lake level. Agreement is forced on September 30, 1986.



average daily decrease in lake level is at a minimum in summer, when runoff is contributing to the lake. The largest decreases are noted in the autumn months. During autumn, winter snowmelt runoff will have been completed, and subsurface runoff should be near the lowest value for the year. At this time the lake is still warm, but the air above the lake has begun its seasonal cooling. Daily decreases of 0.04 foot or more (1.22 cm, or 0.48 inch) occur on 5.3 percent of non-precipitation days in September, and have reached as high as 2.4 cm in one day in October and February.

In addition, the average daily change in lake level for non-participation days was determined for January-February, July-August, August-September, and October-November, and stratified according to the air-minus-water temperature differences. Air temperature is the mean daily temperature. Values are shown in Table 2. In both winter and summer, the cooler the day, the greater the lake level decrease. A constant seepage (-0.347 cm/day) can be subtracted from these values if desired. In both winter and late summer, when runoff should be near a minimum, the values should be affected mainly by evaporation. In all cases, the colder the air, the greater the evaporation.

#### Relation to El Niño/Southern Oscillation

Interest has greatly increased in El Niño and its effects on global climate change since the large El Niño event of 1982-1983. Although the term is often used rather carelessly (Aceituno 1992), El Niño refers to the anomalous warming of the ocean to the west of Peru along the equator. El Niño is just one phase of a phenomenon having a longer time scale (usually four to nine years) known as the Southern Oscillation. A cold phase (sometimes called "anti-El Niño" or "La Niña") of the same oscillation is often overlooked. The relation between the phases of the Southern Oscillation, and El Niño

Table 2. Average daily change in lake level on days with no precipitation, stratified according to air-minus-water temperature difference ("TA-TW", in Degrees F). "#" is number of cases (days). Values are in cm, negative values imply a decrease from the previous day. Seepage (-0.347) is included in the averages. Days are from the period 1961-1986.

| TA-TW   | Jan-Feb | #  | Jul-Aug | #   | Aug-Sep | #   | Oct-Nov | #   |
|---------|---------|----|---------|-----|---------|-----|---------|-----|
| 29:35   |         | 0  | -0.085  | 32  |         | 0   |         | 0   |
| 22:28   |         | 0  | -0.378  | 143 | -0.439  | 61  | -0.304  | 6   |
| 15:21   | -0.411  | 20 | -0.418  | 365 | -0.469  | 236 | -0.317  | 66  |
| 8:14    | -0.417  | 57 | -0.527  | 291 | -0.576  | 299 | -0.491  | 152 |
| 1:7     | -0.482  | 91 | -0.573  | 111 | -0.649  | 137 | -0.546  | 129 |
| -7:-1   | -0.591  | 48 | -0.789  | 29  | -0.801  | 38  | -0.683  | 62  |
| -14:-8  | -0.747  | 11 | -0.427  | 5   | -0.747  | 11  | -0.686  | 28  |
| -21:-15 | -0.710  | 9  |         | 0   |         | 0   | -0.780  | 9   |
| -28:-16 |         | 0  |         | 0   |         | 0   | -1.372  | 2   |

in particular, and regional climate around the globe, have been the subject of a number of studies. The western United States was the focus of a recent study by Redmond and Koch (1991), who showed that El Niño is associated with dry and warm winters in the Pacific Northwest and wet and somewhat cool winters in the southwestern United States. They showed that the highest correlations were found when the six-month average Southern Oscillation Index (SOI) leads the six-month average climate variable by about four months. The SOI is a standardized index that consists of the monthly sea-level pressure at Tahiti minus the monthly sea-level pressure at Darwin, Australia, expressed as a departure in standard deviations from the average difference. A negative SOI is

associated with El Niño, and positive SOI is associated with the cool ocean water in the equatorial Pacific.

Crater Lake shows the same relationship to the Southern Oscillation as the rest of the Pacific Northwest. Scatter plots of June-November SOI versus the subsequent October-March precipitation and snowfall at Crater Lake are shown in Figs. 5 and 6. Although the overall correlation coefficient is modest, ( $r = 0.304$  for precipitation,  $n = 59$  years;  $r = 0.216$  for snowfall,  $n = 55$  years) the extreme cases (with absolute value of the SOI of 0.50 or greater) separate clearly into two groups. The total October-March snowfall in years with SOI of +0.50 or greater (12 cases, with an average six-month total of 13.22 m) is 2.78 m heavier than in years with SOI of -0.50 or less (16 cases, with an average six-month total of 10.44 m) over the past 60 years. The difference is significant at the 5 percent level. For years with SOI below -0.50, 11 of 16 such years are less snowy than average, and for years with SOI above +0.50, 11 of 12 such years are snowier than average.

As fall of 1991 approached, with low SOI values all summer, it became very apparent that the winter of 1991-1992 at Crater Lake would likely be a dry and warm winter. October through March precipitation totaled 84 cm and was second only to 1976-1977 levels when only 47 cm fell. Similarly, 1991-1992 temperature averaged 2.2°C above normal for the same six months, second only to temperatures in the period 1933-1934. Because of the dry and warm conditions, only 5.67 m of snow fell during the 6 months from October 1991 through March 1992, second only to October-March 1976-1977 when 4.83 m fell.

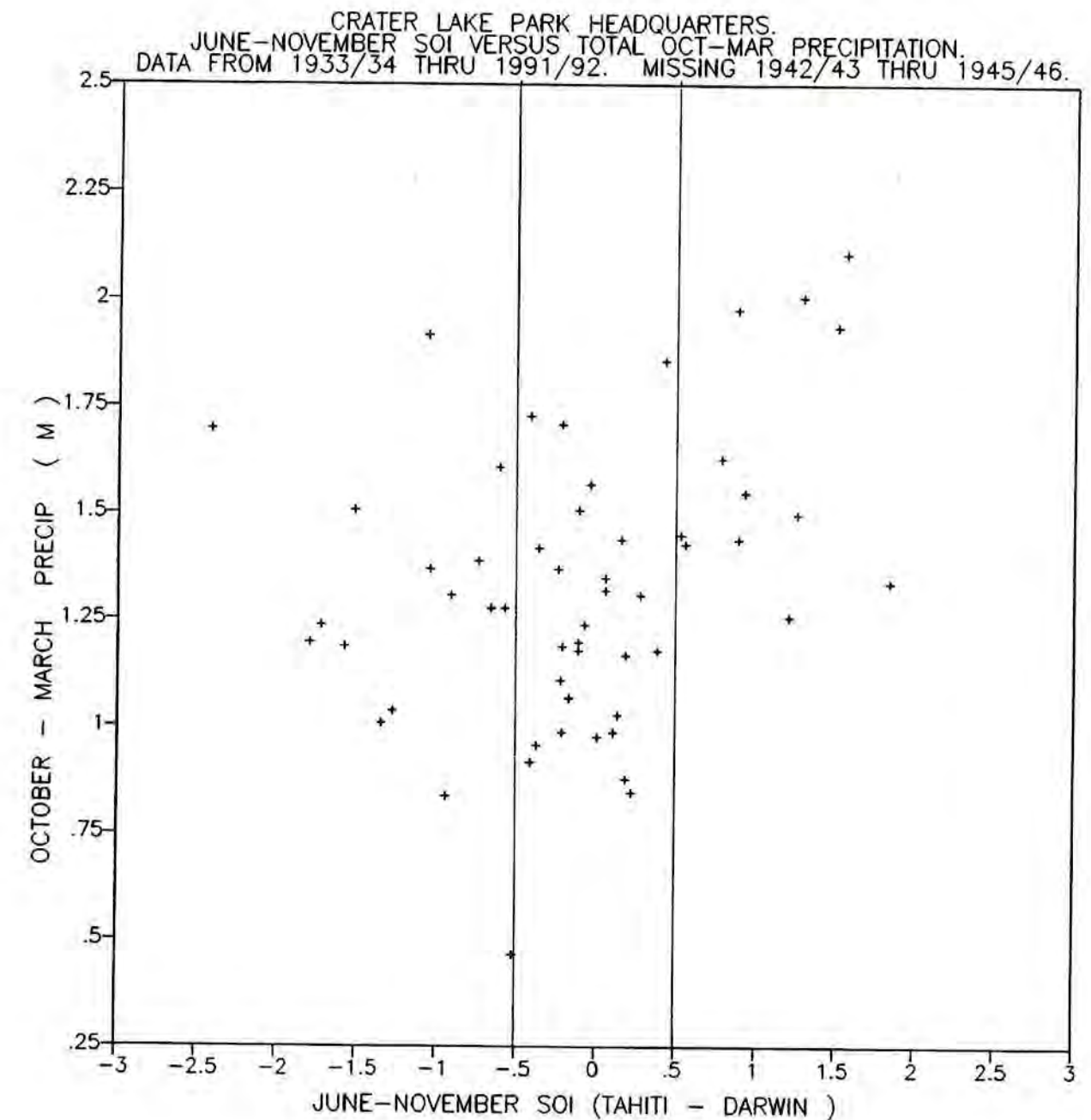


Figure 5. Scatter plot of June through November Southern Oscillation Index (SOI) and the total precipitation for the following October through March. Based on winters from 1933/34 through 1991/92. Vertical lines denote SOI values of -0.50 and +0.50. Years with absolute values greater than 0.5 appear to belong to different populations ( $p < 0.05$ ).

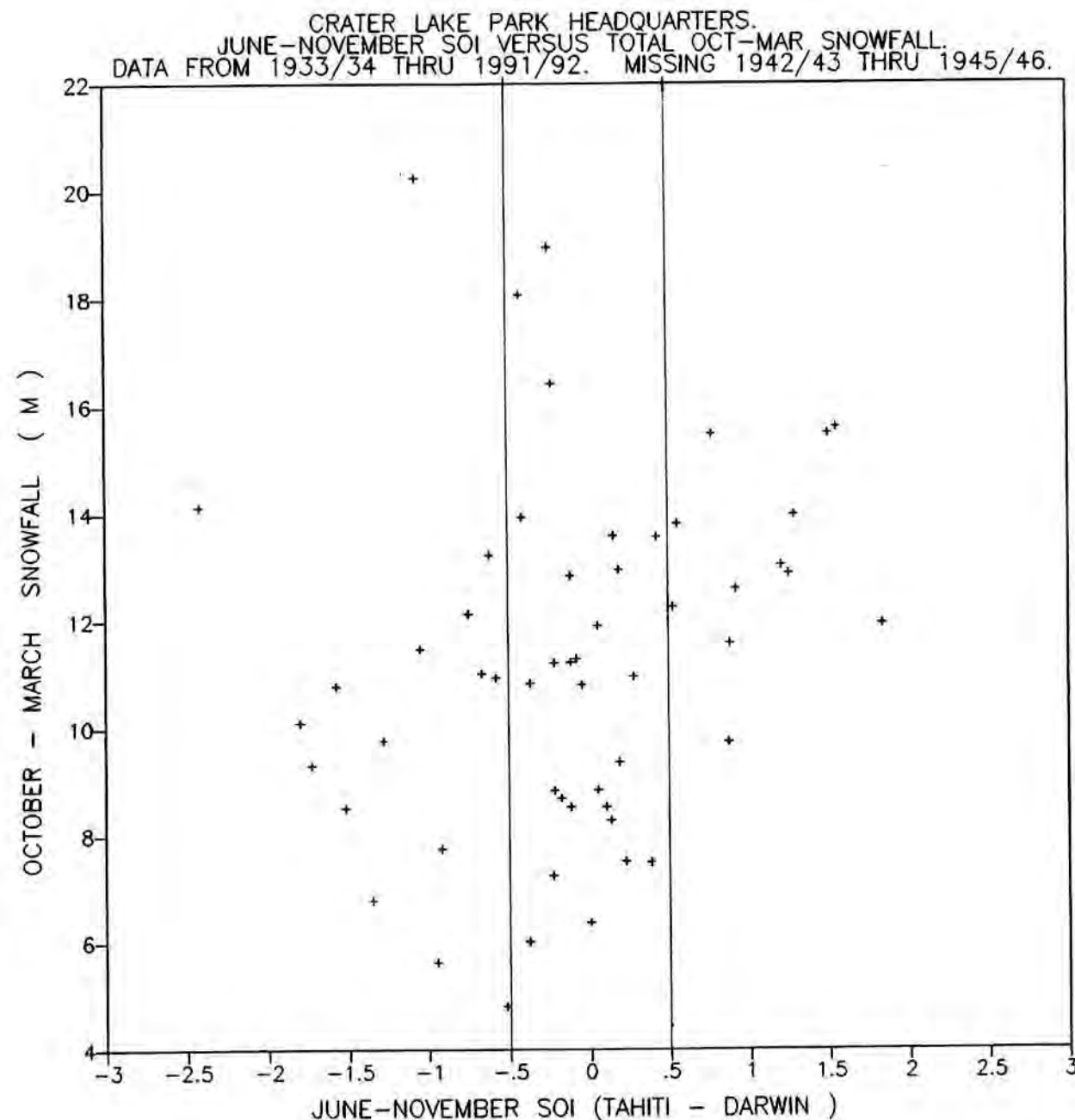


Figure 6. Scatter plot of June through November Southern Oscillation Index (SOI) and the total snowfall for the following October through March. Based on winters from 1933/34 through 1991/92. Vertical lines denote SOI values of -0.50 and +0.50. Years with absolute values greater than 0.5 appear to belong to different populations ( $p < 0.05$ , see text).

## Conclusions

The data records from the Crater Lake area are of modest length by climatological standards (30-60% of a century) but are relatively long in comparison with many geophysical, chemical, and biological records. The combination of these records and the unusual physical circumstances at the lake provide many interesting and unique possibilities for additional studies.

During the course of this project it was shown that the observed lake-level variations this century can be explained primarily by precipitation, with the effects of fluctuations in evaporation of secondary importance. The ability to directly determine a value for seepage as the result of a fortuitous congruence of unusual combinations of climatic conditions, the physical setting, and a long-term monitoring program is certainly unique.

The daily climate and lake-level records at Crater Lake constitute a potentially rich source of information about evaporation and the water budget. The ability to use direct measurements and employ the lake itself either as a precipitation gage or as an evaporation "pan" provides the prospect for novel ways of studying components of the water balance. For example, on winter days with no precipitation, the lake often falls more than on dry summer days. On dry winter days, more evaporation occurs on cold days than on warm days. The lake also falls more on days with just a little rain than on days with no rain (not presented), a physically plausible situation. Because of the altitude, humidity is usually low (even with frequent precipitation), wind speeds are often high, and the exchange coefficient is kept high because the water is warmer than the air.

The recent installation of automated weather instruments on the lake and rim will offer alternative ways of independently verifying conclusions derived using other types of

data. Evaporation can be calculated from the hourly weather data. The influence of wind on the underwater temperature stratification can be more easily assessed than before. The representativeness of shore-based measurements as a way of inferring lake surface conditions can be better established.

The value of time series of geophysical data increases at a rate faster than the linear rate at which the information is recorded. That is, a time series of 20 years can provide more than just twice the information of a 10-year time series. In addition many interesting phenomena will be recorded "by accident" and not recognized as such except retrospectively. Therefore, once measurement programs have been running for a few years, a concerted effort should be made to sustain them.

The lake level fell substantially over the dry winter of 1992. When the gaging station was visited on August 28, 1992, the elevation stood at 1,880.061 m above sea level, a decrease of 68 cm from the elevation on August 28, 1991. The water year total of 120.8 cm of precipitation at park headquarters through September 1992 would be expected to produce a drop of 71 cm from September 30, 1991 to September 30, 1992. This was the sixth successive year of decline, for a total drop of 292 cm from the value of September 30, 1986. The lake has now returned a substantial fraction of the way toward the historically low values observed in the 1930's.

#### **Acknowledgements**

At various times over the course of this project, several individuals have provided data, commentary, lodging, field trips, good Italian food, and other helpful services. Among these are Gary Larson, Mark Buktenica, Tom McDonough, Jim Moffet, Larry Hubbard, and Bob Collier. The assistance of these and others is gratefully acknowledged.

#### **References**

- Aceituno, P. 1992. El Niño, the Southern Oscillation, and ENSO: Confusing names for a complex ocean-atmosphere interaction. *Bulletin of American Meteorological Society* 73(4):483-485.
- Diller, J.S. 1902. The geology and petrography of Crater Lake National Park. U.S. Geological Survey Professional Paper 3 (part 1). 62 pp.
- Harding, S.T. 1953. Water supply of Crater Lake, Oregon. (unpublished manuscript available from K. Redmond, western Regional Climate Center, Desert Research Institute, Reno, NV).
- Meyers, J. 1962. Evaporation from the 17 western states. U.S. Geological Survey Professional Paper 272-D. 100 pp.
- Nathenson, M. 1992. Water balance for Crater Lake, Oregon. U.S. Geological Survey Open File Report 92-505. 33 pp.
- Phillips, K.N. 1968. Hydrology of Crater, East and Davis Lakes, Oregon, U.S. Geologic Survey Water Supply Paper 1859-E. 60 pp.
- Redmond, K.T. 1990. Crater Lake climate and lake level variability. Pages 127-144 in E.T. Drake, G.L. Larson, J. Dymond, and R. Collier, eds., *Crater Lake: An Ecosystem Study*. Pacific Division, American Association for the Advancement of Science, San Francisco, Calif. 221 pp.
- Redmond, K.T., and R.W. Koch. 1991. Surface climate and streamflow variability in the western United States and their relationship to large scale circulation indices. *Water Resources Research* 27(9):2381-2399.
- Simpson, H.J. 1970. Tritium in Crater Lake, Oregon. *Journal of Geophysical Research* 75 75:5195-5207.

Appendix I. Monthly statistics at Park Headquarters during the period since 1980.

Part A. Mean monthly and annual temperature at Park Headquarters, expressed as departure from 1961-1990 average ("Ave"), in degrees C.

| Year | Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov  | Dec  | Ann  |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 1980 | -0.7 | +1.3 | -1.2 | +0.6 | -0.6 | -3.3 | +0.4 | -1.2 | -0.1 | +1.5 | +1.5 | +3.3 | +0.1 |
| 1981 | +3.8 | +1.1 | +1.0 | +0.8 | -0.1 | +0.2 | +0.4 | +2.2 | +1.1 | -1.7 | +0.4 | +0.2 | +0.8 |
| 1982 | -1.9 | -1.2 | -1.4 | -2.9 | +0.1 | -0.9 | -1.2 | -0.4 | -2.1 | -1.8 | -1.6 | -0.1 | -1.3 |
| 1983 | +1.3 | -0.4 | +0.6 | +0.1 | -0.6 | -2.2 | -4.8 | -0.5 | -0.8 | +0.6 | -1.6 | -1.4 | -0.8 |
| 1984 | +1.8 | +0.8 | +1.2 | -1.9 | -0.8 | -2.0 | +0.5 | -0.3 | -1.4 | -3.8 | -2.8 | -2.3 | -0.9 |
| 1985 | +2.3 | -1.0 | -1.0 | +3.2 | -0.4 | +0.9 | +3.0 | -1.5 | -3.6 | -1.7 | -3.8 | +3.3 | -0.0 |
| 1986 | +2.1 | +1.2 | +2.7 | +0.1 | -0.3 | +1.9 | -1.6 | +2.6 | -3.8 | +0.6 | +0.8 | +1.2 | +0.6 |
| 1987 | -0.5 | +0.3 | -0.3 | +3.1 | +2.2 | +2.2 | -1.7 | +0.4 | +2.7 | +5.0 | +0.9 | -1.9 | +1.0 |
| 1988 | -1.1 | +2.7 | +0.7 | +1.8 | -1.3 | -0.4 | +1.7 | +1.0 | +1.1 | +5.2 | -1.4 | +0.7 | +0.9 |
| 1989 | +0.2 | -4.3 | -0.4 | +2.8 | -0.8 | +0.5 | -0.8 | -2.1 | +0.2 | -1.2 | +2.1 | +4.1 | -0.0 |
| 1990 | +0.2 | -1.8 | +2.1 | +3.9 | -0.3 | -0.1 | +1.7 | +0.3 | +2.1 | -0.6 | +0.2 | -2.9 | +0.4 |
| 1991 | +1.3 | +3.8 | -1.9 | -1.2 | -1.7 | -2.8 | +1.3 | +0.8 | +3.8 | +2.4 | +1.4 | +1.5 | +0.7 |
| 1992 | +1.3 | +2.3 | +4.3 | +2.8 | +5.7 | +3.0 | +0.1 | +2.6 | +0.8 | +1.8 | -0.6 | -1.6 | +1.9 |
| Ave  | -3.3 | -3.0 | -2.6 | -0.3 | 3.4  | 7.8  | 11.9 | 12.4 | 9.2  | 4.9  | -0.8 | -3.2 | 3.0  |

Part B. Monthly and annual precipitation at Park Headquarters, expressed as departure from 1961-1990 average ("Ave"), in mm. July-June total is for the 12 months ending in June of the year shown.

| Year | Jan  | Feb  | Mar  | Apr | May | Jun | Jul | Aug | Sep  | Oct  | Nov  | Dec  | Ann  | Jul-Jun |
|------|------|------|------|-----|-----|-----|-----|-----|------|------|------|------|------|---------|
| 1980 | +36  | +4   | -16  | +28 | -21 | +20 | -17 | -33 | -20  | -53  | -45  | -38  | -155 | +40     |
| 1981 | -148 | -8   | -61  | -37 | +42 | +17 | -1  | -33 | +18  | +69  | +69  | +326 | +253 | -401    |
| 1982 | +21  | +77  | -16  | +93 | -73 | +44 | +6  | -14 | +59  | +46  | -47  | +119 | +315 | +594    |
| 1983 | -20  | +146 | +151 | -19 | -17 | +8  | +36 | +44 | -51  | -59  | +157 | +198 | +574 | +452    |
| 1984 | -160 | +15  | +51  | +48 | +55 | +20 | -17 | -18 | -33  | +83  | +192 | -115 | +130 | +354    |
| 1985 | -229 | -45  | -3   | -29 | -26 | -26 | +24 | -4  | +59  | +39  | -52  | -155 | -447 | -266    |
| 1986 | +32  | +246 | -3   | +2  | +17 | -33 | +5  | -29 | +162 | -30  | -77  | -167 | +125 | +172    |
| 1987 | -18  | +4   | -29  | -78 | +3  | -12 | +87 | -20 | -60  | -120 | -96  | +76  | -263 | -266    |
| 1988 | +16  | -147 | -28  | +6  | +74 | +44 | -17 | -33 | -20  | -105 | +305 | -88  | +147 | -168    |
| 1989 | -25  | -77  | +181 | +29 | +31 | -24 | -16 | -6  | -15  | -10  | -149 | -237 | -318 | +157    |
| 1990 | +27  | +9   | -100 | -2  | +93 | -12 | -7  | +30 | -38  | +13  | -79  | -158 | -224 | -418    |
| 1991 | -36  | -31  | +91  | +41 | +32 | -25 | +25 | -5  | -57  | -16  | +50  | -124 | -55  | -167    |
| 1992 | -127 | -71  | -180 | +93 | -58 | +57 | +12 | -32 | -24  | -8   | +22  | +82  | -234 | -413    |
| Ave  | 245  | 198  | 202  | 117 | 77  | 50  | 17  | 33  | 60   | 121  | 268  | 275  |      | 1664    |

Part C. Monthly and seasonal snowfall at Park Headquarters, expressed as departure from 1961-1990 average ("Ave"), in cm. Seasonal total for July-June is the 12-month total ending in June of the year shown.

| Year | Jan  | Feb  | Mar  | Apr  | May | Jun | Jul | Aug | Sep  | Oct | Nov  | Dec  | Jul-Jun |
|------|------|------|------|------|-----|-----|-----|-----|------|-----|------|------|---------|
| 1980 | -73  | -46  | -24  | +15  | +9  | +1  | -1  | -1  | -10  | -7  | -81  | -95  | -163    |
| 1981 | -119 | -82  | -76  | -51  | -8  | 0   | +1  | -1  | -10  | +22 | +14  | +159 | -531    |
| 1982 | +174 | -69  | -6   | +103 | -49 | +3  | +4  | -1  | +11  | +9  | +5   | +89  | +341    |
| 1983 | -50  | +142 | +157 | -8   | +20 | -1  | -1  | -1  | -10  | -53 | +96  | +150 | +377    |
| 1984 | -166 | +50  | -16  | +43  | -3  | +28 | -1  | -1  | -9   | +68 | +223 | -39  | +117    |
| 1985 | -194 | -48  | +50  | -88  | +40 | -10 | -1  | -1  | +7   | -6  | +76  | -104 | -9      |
| 1986 | -20  | +175 | -100 | -28  | +20 | -8  | +3  | -1  | +132 | -11 | -23  | -99  | +10     |
| 1987 | -11  | +10  | -44  | -89  | -19 | -8  | +1  | -1  | -10  | -54 | -102 | +18  | -160    |
| 1988 | +25  | -168 | -100 | -5   | +56 | +30 | -1  | -1  | -10  | -54 | +203 | +15  | -310    |
| 1989 | +75  | -39  | +25  | +48  | +9  | -8  | -1  | 0   | -10  | +14 | -74  | -194 | +262    |
| 1990 | -16  | +58  | -98  | -97  | +2  | -10 | +8  | -1  | -10  | -44 | -38  | -114 | -413    |
| 1991 | -140 | -87  | +88  | +41  | +35 | -10 | -1  | -1  | -10  | +30 | -56  | -116 | -272    |
| 1992 | -106 | -56  | -194 | -64  | -49 | -5  | -1  | -1  | -9   | +16 | -42  | +164 | -628    |
| Ave  | 217  | 186  | 219  | 109  | 49  | 10  | 1   | 1   | 10   | 54  | 176  | 213  | 1245    |

## Lake Circulation

James McManus, Robert Collier, and Jack Dymond

An understanding of the physical processes that redistribute heat and salt in Crater Lake is essential to modeling the biogeochemical cycling of elements in the lake. There are only a few studies of Crater Lake's physical limnology. Kibby et al. (1968) reported surface current observations as well as the vertical and horizontal distribution of temperature in the upper water column. Radioisotope data from Simpson (1970 a, b) and Volchok et al. (1970) indicate that the characteristic time-scale of deep-lake ventilation is approximately one year. Neal et al. (1971, 1972) provided temperature microstructure measurements that demonstrate the hyperadiabatic nature of the thermal gradient in the deep lake. The term "hyperadiabatic" derives from the fact that the thermal gradient below 350 m in the deep lake is at least two orders of magnitude greater than the adiabatic gradient (Fig. 1). Williams and Von Herzen (1983) identified two areas of high heat flow along the lake floor; one in the north basin near Merriam Cone, and a second in the south basin where their highest heat flow measurements were recorded. Assuming a homogeneous salinity distribution, they discussed the apparent vertical instabilities and convection that would accompany the observed temperature distribution. Although the work of Williams and Von Herzen (1983) served as a catalyst for our work, a lack of high precision salt determinations limited their ability to interpret the temperature microstructure of the hypolimnion in Crater Lake. Our research has provided both the high precision temperature and salinity data that are necessary for the accurate determination of the physical properties and the mixing dynamics of the lake (McManus et al. 1992).

Although, to a first approximation, Crater Lake is well mixed with respect to major ions (Collier et al. 1990a, Nathenson 1990, Thompson et al. 1990, Nathenson and Thompson 1990, McManus et al. 1992), our measurements document a salinity gradient below 200 m at all times (Fig. 1) (McManus et al. 1992). Because of the active input of hydrothermal fluid and the transport of this fluid throughout the deep lake, both the salinity and temperature gradients of the deep-water column exhibit spatial and temporal variability. The primary source of the

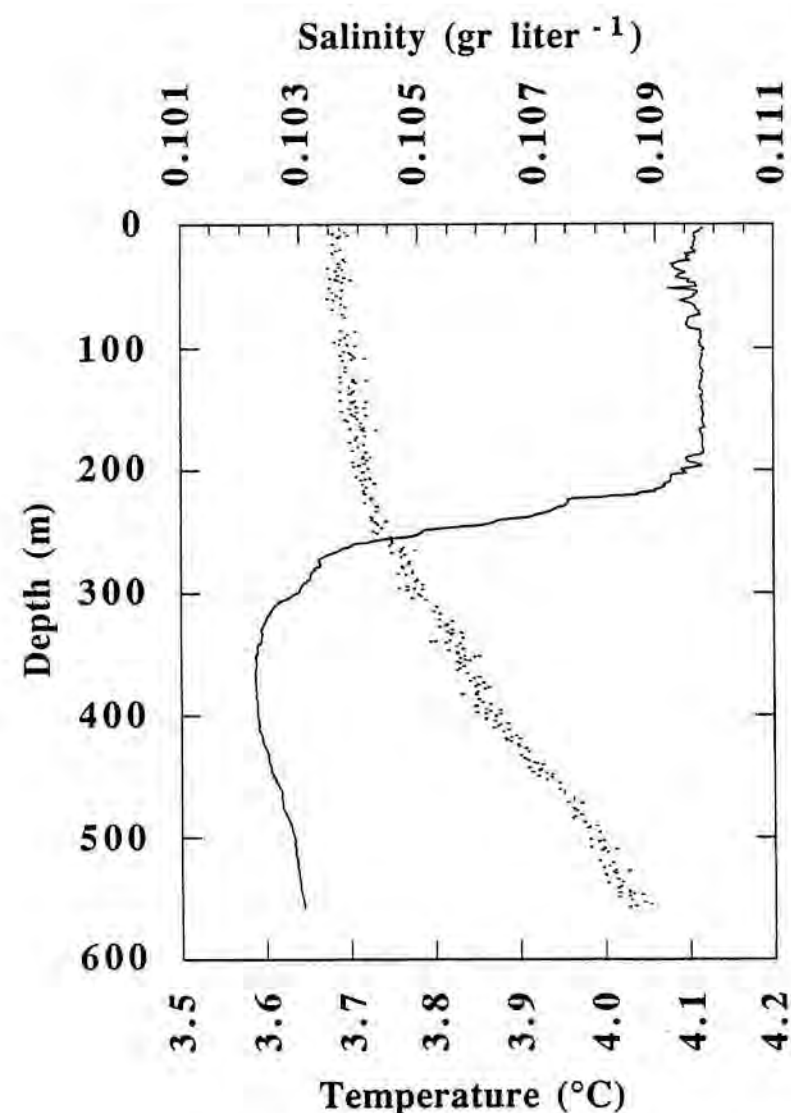


Figure 1. Salinity ( $\text{g liter}^{-1}$ ) and temperature ( $^{\circ}\text{C}$ ) as a function of depth. Data was taken from the north basin on 19 January 1990. Note the near-uniform salinity of the upper 200 m interval and the increase in temperature and salinity with depths below  $\sim 350$  m.

hydrothermally enriched fluids appears to be deep within the south basin (Williams and Von Herzen 1983, Dymond et al. 1989, Collier et al. 1990b, McManus et al. 1992). Variability in the vertical and horizontal temperature and salinity distribution occurs over time scales of weeks, suggesting that the hydrothermal fluid mixes rapidly throughout the deep lake.

The objective of this section is to define the magnitude of the hydrothermally derived heat and salt fluxes to the deep lake through a time-series of temperature and salinity measurements. In addition, we will discuss how this heat and salt mix throughout the deep lake. We will first examine mixing processes in the upper lake during seasonal changes in stratification. We will then estimate the degree to which water mixes from the surface layer to the deep lake during periods of minimum surface stratification, and we will present data that demonstrates the mechanism for deep lake ventilation. Finally, we will discuss how the hydrothermally enriched waters mix through the deep lake during periods of maximum surface stratification.

### Methods

Temperature, pressure, conductivity, and light transmission were measured using a CTD ("conductivity, temperature, depth" recording instrument, SEACAT<sup>®</sup> model SBE19, Sea-Bird Electronics Inc.) modified for low-conductivity waters and equipped with a 25-cm-path-length light-beam transmissometer (Sea Tech. Inc.). The CTD records all data internally at 2 scans per second. Temperature resolution is  $\pm 0.0005^{\circ}\text{C}$  and, based on laboratory triple point calibrations of the temperature sensor, the absolute accuracy of the temperature sensor is  $\sim 0.001^{\circ}\text{C}$  from 1987 to 1989. Laboratory calibration of the conductivity sensor using Crater Lake water and subsequent chemical analysis of this water provided us with sufficient salinity, conductivity, and temperature data to obtain an expression for salinity as a function of *in situ* conductivity and temperature (McManus et al. 1992). Salinities calculated from our expression are  $\sim 25\%$  greater than would be predicted from strong electrolytes alone. This is because silicic acid accounts for approximately 25% of the total dissolved solids in the lake. The details of the experiments and further explanation of the affects of silicic acid on the density of Crater Lake water are presented in McManus et al. (1992).

The CTD was deployed on a hydrographic wire lowered from the NPS research boat. The time series hydrographic data presented in this section was collected in the northeastern portion of the north basin at Station 13, the south basin at Station 23, and in the northwestern portion of the lake at Station 11 (Fig. 2). Time-series temperature data were also collected using two moored thermistor chains deployed in the south basin from 3 September 1989 until July 1990. One chain (TC1084) was located at 50-150 m depth, and the other (TC8) extended from 350 m to the bottom (450 m). The chains were equipped with 11 thermistors spaced at 10-m intervals. The thermistors recorded a temperature every three hours throughout deployment. We calibrated the thermistors at the OSU calibration facility both before and after deployment. The absolute accuracy of the thermistors is  $\pm 0.010$  °C, and the in-field precision, based on daily temperature measurements from the deep lake, is  $\pm 0.005$  °C.

Dissolved oxygen contents of water samples were determined using a whole-flask Winkler titration method with the modifications of Carpenter (1965 a, b). The overall precision of the oxygen measurement is based on the percent difference between duplicate sample analysis and is better than 0.5%. We employed the equations presented in Benson and Krause (1984) to determine the solubility of dissolved oxygen in Crater Lake. The mean atmospheric pressure at the lake surface was calculated from the altitude-dependent equation given by Mortimer (1981).

## Results and Discussion

### Heat and Salt Flux into the Deep Lake

A time-series of CTD data and data from a thermistor chain mooring indicate that there is a consistent input of heat and salt into the deep hypolimnion of Crater Lake. The input of heat is demonstrated in the deep lake by the gradual increase in temperature over time observed during periods of surface stratification (Fig. 3).

Integrated values for the flux of heat and salt are calculated from the time-series of CTD data. This is accomplished by integrating the area under a vertical profile (either salinity or temperature) and subtracting the area under a profile taken at the same location at an earlier time. For instance, the integrated temperature change between 17 July and 17 August below 350 m

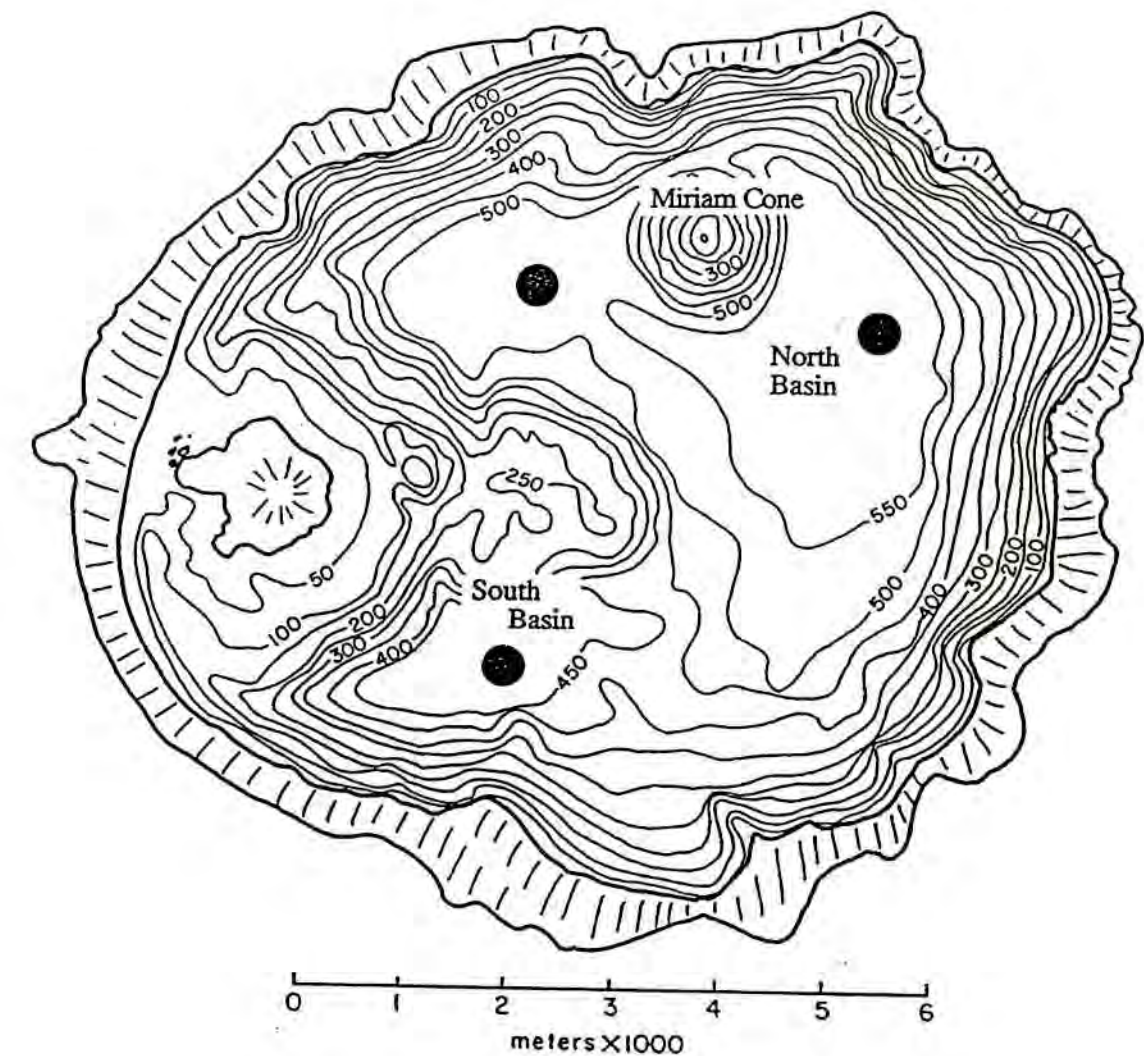


Figure 2. Bathymetric map of Crater Lake with geologic features. Large dots represent approximate locations of time series monitoring stations: Station 23 located in the south basin, Station 13 located in the north basin, and Station 11 located in the northwest portion of the lake. The bathymetry is taken from Byrne (1965).

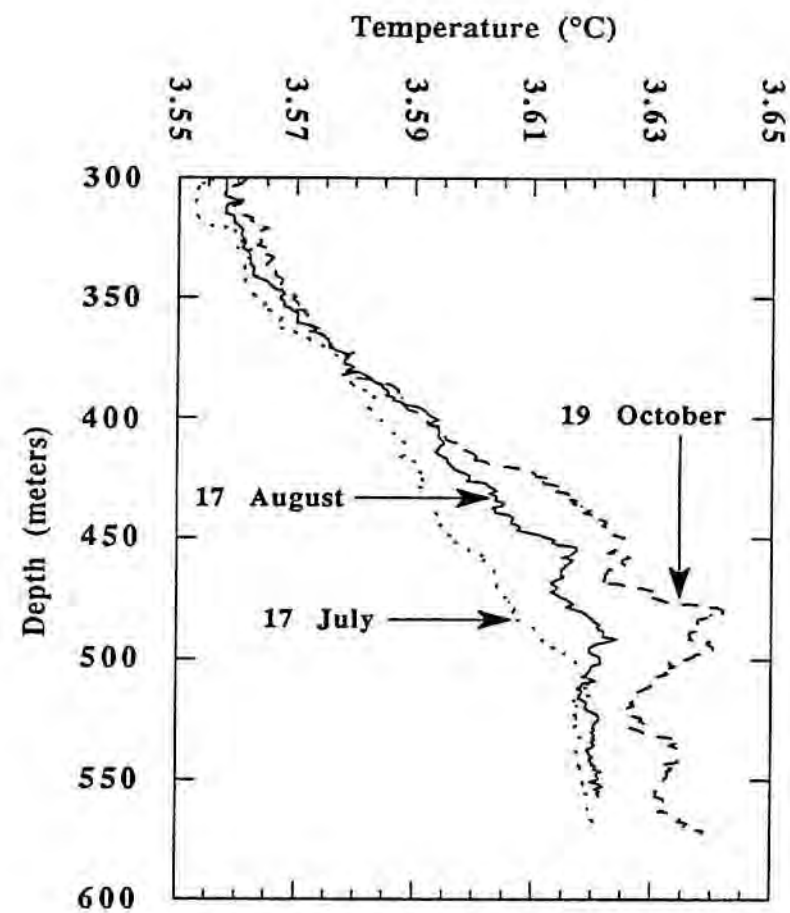


Figure 3. Temperature as a function of depth in time series. This CTD data was taken from the north basin. The data demonstrates the accumulation of heat in the hypolimnion throughout the summer months.

(Fig. 3) is converted to a net heat flux. Each flux calculation represents a volume-weighted average of CTD data from the three monitoring stations (Fig. 2). Basin volumes were determined from the hypsographic curve presented in Byrne (1965).

The rate of deep-lake warming can also be estimated using deep-lake temperature data from the thermistor chain moored within the south basin. This is accomplished in a manner similar to the treatment of the CTD data by calculating the change in temperature between 440 and 350 m during periods of surface stratification. To demonstrate the warming of the deep lake, we show an expanded-scale plot of temperature versus time for the thermistor deployed at 410 m (Fig. 4). The arrows indicate deep-lake warming during periods of upper-water-column stability (fall and late spring/early summer). During winter there is some cooling of the deep waters, which is associated with deep-lake ventilation.

Table 1 presents the results of the calculations for heat and salt flux. The heat and salt flux values are for discrete time intervals during a given year, and the flux values represent differences between two profiles separated in time by at least several weeks. Our method of calculating the net heat flux yields results that agree with those of Williams and Von Herzen (1983) who reported values between 0.7 and 1.4 W m<sup>-2</sup>.

Fluid flow (Table 1) is estimated directly from the salt flux values. In calculating the fluid flow, we have assumed that the salinity of the hydrothermal fluid is 0.6 gr kg<sup>-1</sup> as it enters the south basin. This salinity value is based on pore-water chemistry data (Wheat, unpublished) and the chemical composition of brines, which are found at the source of the thermal inputs in the south basin (Collier et al. 1990b). The estimates of fluid flow are consistent with other values suggested by Nathenson (1990), 80-1900 liters sec<sup>-1</sup>. Because there may be variations in the end-member composition, the estimated flow rates are only rough estimates of the net fluid flow associated with these inputs.

Although the annual fluid input due to hydrothermal activity is small compared to the lake volume (17.3 km<sup>3</sup>), the fluid flow rate given in Table 1 (~0.2 m<sup>3</sup> sec<sup>-1</sup>) is large (~5%) compared

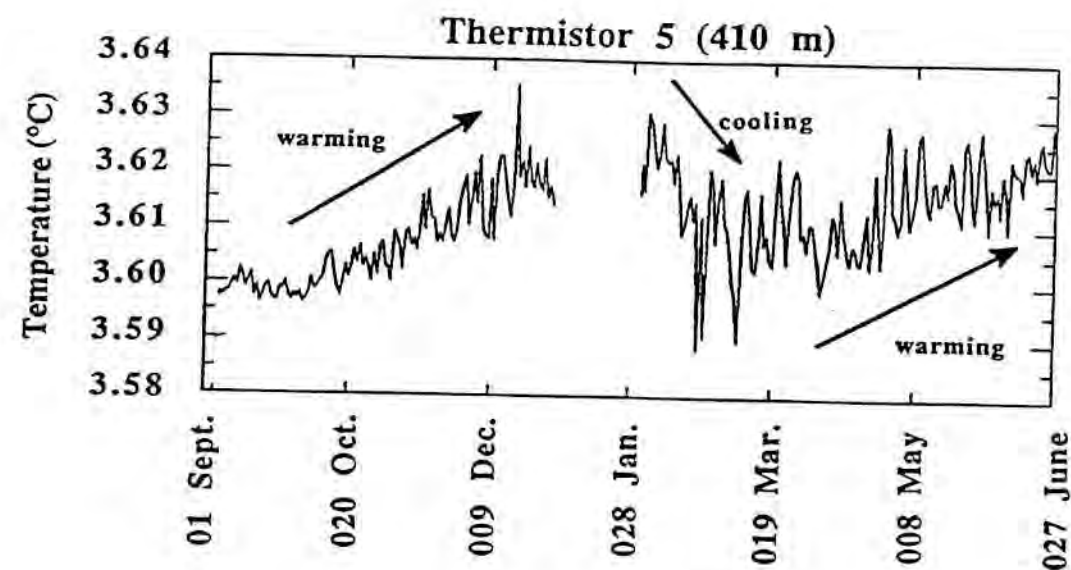


Figure 4. Temperature as a function of time from the thermistor at a depth of 410 m in the south basin from September 1989 to July 1990. The figure demonstrates the warming due to the constant input of heat from hydrothermal activity and the cooling due to winter mixing. The absence of data apparent in the figure marks a period of time of recorder malfunction.

Table 1. Heat flux, salt flux, and fluid flow.<sup>1</sup>

| Year/<br>season | Method     | Heat Flux<br>(W m <sup>-2</sup> ) | Salt Flux<br>(mg m <sup>-2</sup> sec) | Estimated<br>Fluid flow<br>(liters sec <sup>-1</sup> ) |
|-----------------|------------|-----------------------------------|---------------------------------------|--------------------------------------------------------|
| 1989/S          | CTD        | 0.9 ± 0.5                         | 4.2 ± 2.5                             | 141±84                                                 |
| 1989/F          | Thermistor | 1.0 ± 0.3                         | N/A                                   | N/A                                                    |
| 1990/Sp         | Thermistor | 1.2 ± 0.6                         | N/A                                   | N/A                                                    |
| 1990/ES         | CTD        | 0.9 ± 0.2                         | 5.2 ± 3.0                             | 254±146                                                |
| 1990/LS         | CTD        | 1.0 ± 0.4                         | 5.7 ± 3.0                             | 278±146                                                |

<sup>1</sup>S, F, and Sp represent summer, fall, and spring, respectively where E and L are early and late, respectively. The surface area of the lake over which the integration was calculated was 22.9 km<sup>2</sup> for 1989 and 20.2 km<sup>2</sup> for 1990.

to the annual input of water due to precipitation (~4.2 m<sup>3</sup> sec<sup>-1</sup>, Redmond 1990). Because the hydrothermal fluid is rich in salt relative to precipitation, the input of this high-salinity fluid will have a dominant effect on the salt budget. A more detailed treatment of the geochemical budgets are presented in Collier et al. (1991). It is sufficient for the purposes of this section to point out that hydrothermal activity is the dominant source of salt to Crater Lake.

The data presented here represent the first direct observations of the accumulation of heat and salt over time in the deep water column of Crater Lake. Despite the uncertainties in the calculations, the method for estimating heat flux, salt flux, and fluid flow confirm and refine the previously reported values.

#### Vertical mixing of heat and salt

During periods of reduced vertical stability of the water column, some deep lake water is mixed with surface water. This mixing results in the exchange of thermally and chemically enriched water from the deep lake with cooler, lower-salinity surface water. Since deep-lake water is rich in biochemically important nutrients, particularly dissolved nitrate, this exchange is critical to new biological productivity in the upper 200 m. Such exchange also carries cooler, oxygen-rich

waters from the surface to the hypolimnion. Therefore, the dissolved oxygen content of the deep lake allows us to estimate the degree to which surface-to-bottom exchange has occurred. For example, if at any period the entire lake was to reach atmospheric saturation with respect to dissolved oxygen, we could then conclude that all of the waters have come into contact with the surface during a single mixing period. In the following sections, we examine three stages of vertical mixing in Crater Lake - the breakdown of the seasonal thermocline, inverse stratification, and the mixing of surface water with deep water that takes place during a minimum in water column vertical stability.

Breakdown of the seasonal thermocline. Most temperate lakes undergo three stages of cooling -the breakdown of the seasonal thermocline, isothermal overturn, and inverse stratification (Carmack and Farmer 1982). The breakdown of the thermocline is characterized by a decrease in the surface density gradient and an increase in the depth of the surface mixed layer. In many lakes, continued wind mixing and cold-water convection result in an isothermal water column near the temperature of maximum density. The formation of an isothermal water column is then followed by surface restratification due to continued cooling of the surface water. However, for very deep lakes like Crater Lake, the full water column is rarely isothermal because the temperature of maximum density decreases at a rate of approximately  $0.02\text{ }^{\circ}\text{C bar}^{-1}$  ( $\sim 0.002\text{ }^{\circ}\text{C m}^{-1}$ ). Thus, waters near their density maximum at the surface will not be able to undergo free convection to the lake bottom. The maximum depth of complete mixing in deep lakes is, therefore, influenced by the *in situ* physical properties of lake water, which influence the depth of free convection, as well as wind forcing.

The upper water column of Crater Lake begins to undergo destratification in early fall as the density of the surface water increases due to cooling. As the thermocline breaks down, mixing of the surface water with water below causes an initial increase in temperature at depth (i.e. arrows in Fig. 5). This mixing is driven by wind mixing at the surface and convection of the surface water as it cools. The increase in temperature is seen at 90 m by late December (Fig. 6a). By mid-

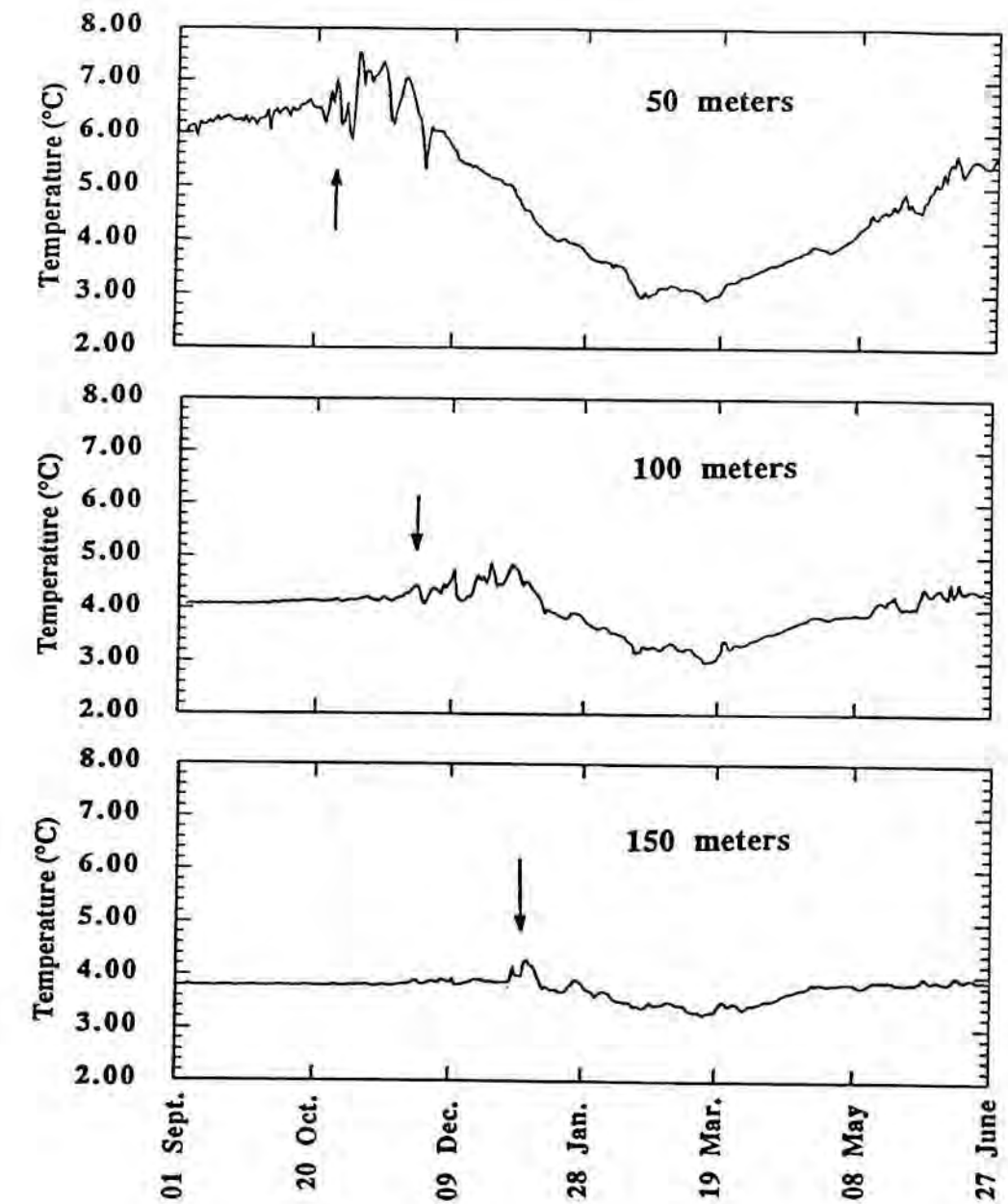


Figure 5. Thermistor data from the upper water column demonstrating the change in temperature over time. Thermistors were spaced at 10-m intervals between 50 m and 150 m. Data from the 50-m, 100-m, and 150-m thermistors are shown as examples. During the breakdown of stratification, warm water from above is mixed with ambient (cooler) water (arrows).

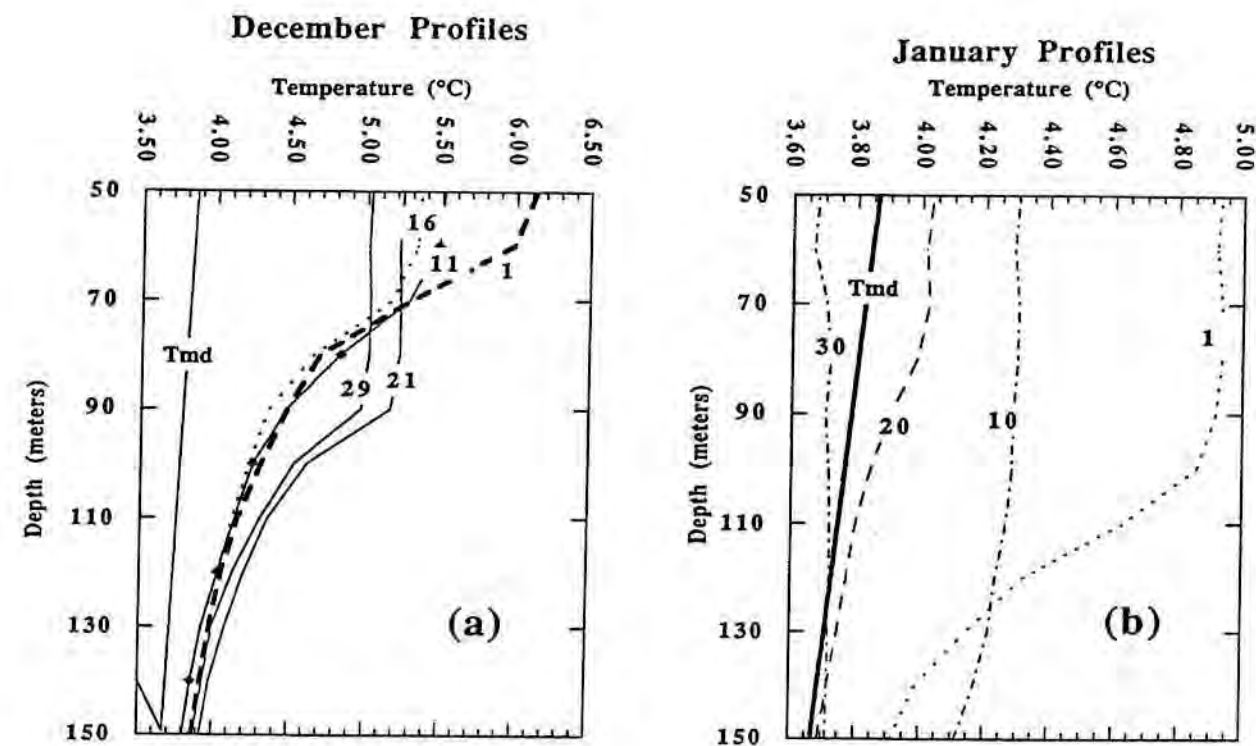


Figure 6. Temperature as a function of depth in the upper part of the water column for (a) December and (b) January. Data are taken from the thermistor chain between 50 m and 150 m and demonstrates the results of the breakdown of thermal stratification in the upper 200 m.

January this warming signal has penetrated to >150 m (Fig. 6b). At this time, at least the entire upper 150 m are isothermal and the mixed layer reaches depths of at least 200 m (Fig. 1).

The rate of penetration of the mixed layer also reflects the stronger stratification initially present in the upper 100 m as compared to the depth range of 100-150 m. Between 50 and 90 m, the base of the mixed layer descends through the water column at a rate of approximately 1 m day<sup>-1</sup> until it reaches ~90 m (Fig. 5 and 6). The rate of mixed layer deepening from 100 m to 130 m increases to ~8 m day<sup>-1</sup>. Although the data are inadequate to accurately determine the descent rate below this depth, the rate appears to be between 10 and 20 m day<sup>-1</sup>. In Babine Lake, Carmack and Farmer (1982) found the mixed layer penetration rate to be ~0.4 m day<sup>-1</sup> at the surface and found it to increase to rates as high as 20 m day<sup>-1</sup> during the later stages of mixed layer deepening. It is surprising that the rate of mixed layer formation in Crater Lake, a sheltered near-circular lake with a maximum fetch of 10 km, is similar to that in Babine Lake, which is 150 km in length, 4 km in width, and has a maximum depth of 230 m. The similarities between the two lakes emphasize the importance of convection in the breakdown of the seasonal thermocline and formation of the winter mixed layer in freshwater systems.

**Inverse stratification.** After the initial mixing, which results in an increase in temperature at the deeper levels of the thermocline, continued winter cooling causes a gradual decrease in the temperature of the upper water column. During the winter of 1990, this cooling continued until mid-March (Fig. 5) and by early April, water column warming was occurring at depths greater than 50 m. Once the temperature profile crossed the  $T_{md}$  in mid-April, thermocline development began.

Since the surface waters are still colder than the  $T_{md}$  in early April, initial warming produces parcels of water of greater density that drive convection. Temperature profiles obtained with the CTD from early May 1989 (Fig. 7) illustrate the results of this process. Heating of the surface waters during the day form convective cells that sink throughout the course of the day (solid line Fig. 7). This continued process warms the entire water column through which convection may occur, leaving a warmer column of near-uniform temperature water at the end of

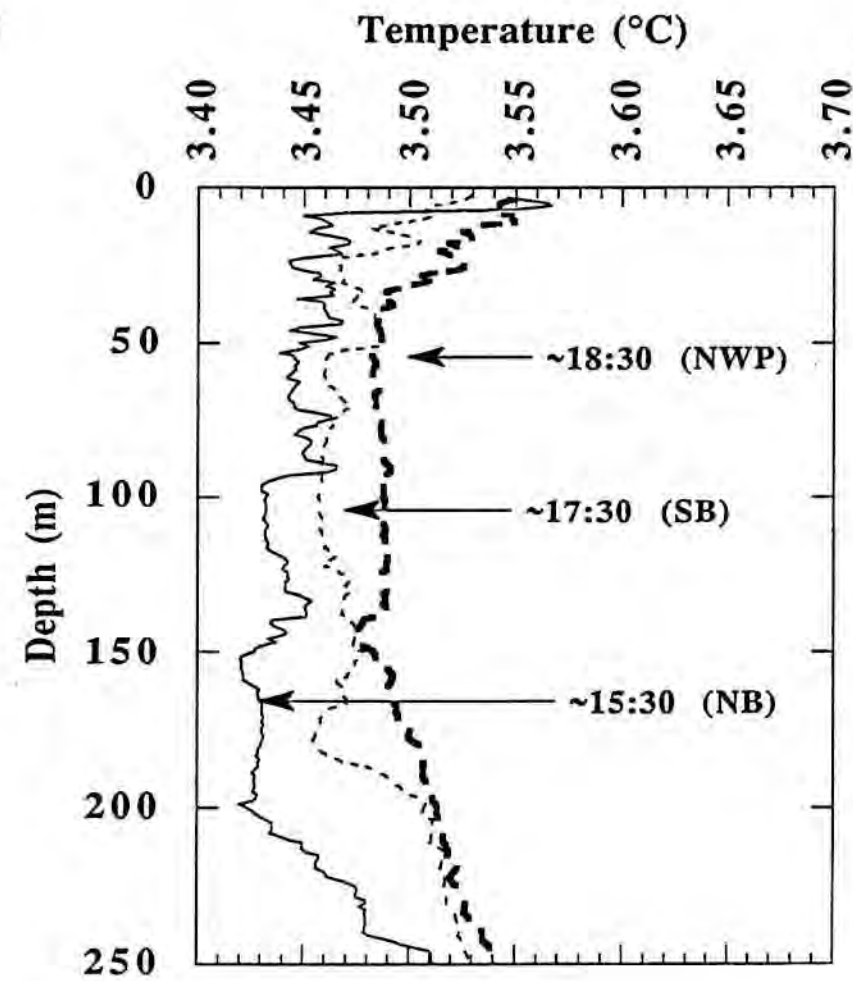


Figure 7. One-day time series of temperature vs. depth for Crater Lake taken in May 1989. The figure demonstrates convective warming in the late afternoon (solid line), the gradual slowing of the convection by early evening (dotted line), and the near-uniform temperature profile by sunset (heavy dashed line). NB represents north basin; SB south basin; and NWP represents the northwest portion of the lake.

the day (dashed line Fig. 7). The three profiles in Fig. 7 are from the three different monitoring stations (Fig. 2) on 11 May and some of the differences are due to horizontal variations in mixing and heating. Therefore, the net warming, which is apparent between the three profiles, can not be used to estimate a one-dimensional heat input into the upper lake.

Spring heating of the water column results in a cycle of warmer temperatures during the day and cooler temperatures at night in the thermistor record of the upper water column (Fig. 8). The maximum daily water temperature, recorded at 50 m during the month of April, occurs at 1,300 and the minimum between 100 m and 500 m. As the temperature of the upper lake approaches the temperature of maximum density at 50 m (~April 20), the upper water column becomes nearly isothermal at about 3.9°C (Fig. 8). After this point (~1 May), rapid warming of the surface water leads to a stratified water column, thereby isolating the deeper water as suggested by the near-constant water temperature at 100 m until approximately 10 May. After approximately 10 May, we observe large variations in the daily water column temperatures. These fluctuations are probably driven by a combination of storms, surface driven convection due to cooling, strong horizontal thermal gradients, and other upper water column mixing processes.

Of particular importance with respect to this work is the relative speed with which the water column undergoes restratification in the spring. Once the upper waters are restratified, mixing between the upper and deep lake can no longer occur. Storms occurring during periods of minimum stability, i.e., while the water column temperature is closest to the  $T_{md}$ , as seen on 10 May, may provide the impetus for deep mixing. Climate variability will therefore influence deep mixing in the spring, as well as during the winter.

A more detailed study of the upper water column-atmosphere interactions should include thermistors that extend to the surface as well as detailed meteorological data. In addition, future modeling efforts should accurately represent convection as well as shear-induced wind mixing. For our purposes it is important to point out that the upper 200 m of the water column in Crater Lake are well-mixed twice annually (winter and late spring). During these periods of mixing, both

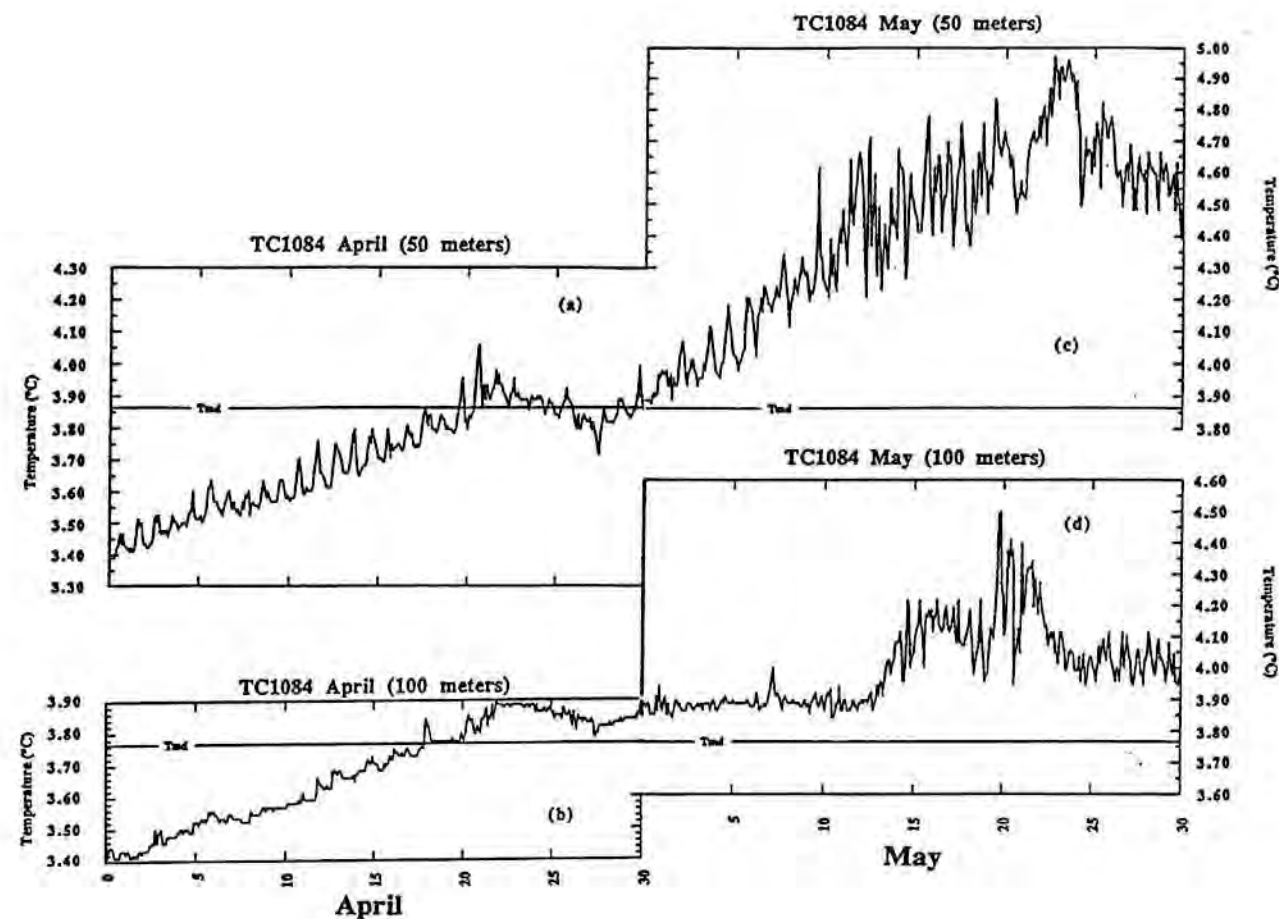


Figure 8. April - May 1990 expanded-scale thermistor chain data (TC1084). Data are from 50 m (top) and 100 m (bottom). The temperature of maximum density (Tmd) was calculated from the equation of state (Chen and Millero 1986).

CTD measurements and our thermistor data indicate that the upper 200 meters of the water column is isothermal.

It is remarkable that the mixed layer in Crater Lake achieves such great depths. The similarities in the rate of mixed-layer deepening for Crater Lake and Babine Lake appear to be a function of convective mixing. In addition, the fact that fresh water has a density maximum that is between 3 and 4 °C in the upper 200 m has an influence on mixing in deep lakes (Weiss et al. 1991).

Mixing of surface water with deep lake water. Time-series dissolved-oxygen data, CTD data, and thermistor chain data all indicate that some exchange of surface water (defined here as water from the upper 200 m) with deep water occurs in Crater Lake at least once a year. The data suggest that this annual mixing process is likely to be incomplete.

Dissolved oxygen is a useful tool for the study of mixing processes in lakes. We discuss the details of the oxygen budget of the deep lake elsewhere; however, it is sufficient for the purposes of this section to point out that deep-oxygen consumption can occur by two processes. Dissolved oxygen is consumed by the decomposition of particulate organic material raining out of the euphotic zone. Also, in Crater Lake, reduced chemical inputs from hydrothermal activity contribute to the depletion of dissolved oxygen in the deep lake.

Convective mixing during the winter and spring tends to saturate the upper water column with dissolved oxygen (e.g., April oxygen profile in Fig. 9). Because annual mixing of deep lake water with well-oxygenated surface water is the only mechanism that will increase the dissolved oxygen contents of the deep lake, changes in deep-lake dissolved oxygen serve as a semi-quantitative measure of the extent of vertical mixing in Crater Lake.

Data collected from September 1988 and April 1989 demonstrate an increase in dissolved oxygen, measured at 550 m, of nearly  $10 \mu\text{mol liter}^{-1}$  (Fig. 9). Likewise, from January 1990 to July 1990 we observe another increase in deep lake dissolved oxygen, indicating that the ventilation process reoccurred during the winter and possibly spring of 1990. This mixing is, however, incomplete, leaving the deep lake undersaturated with respect to atmospheric saturation

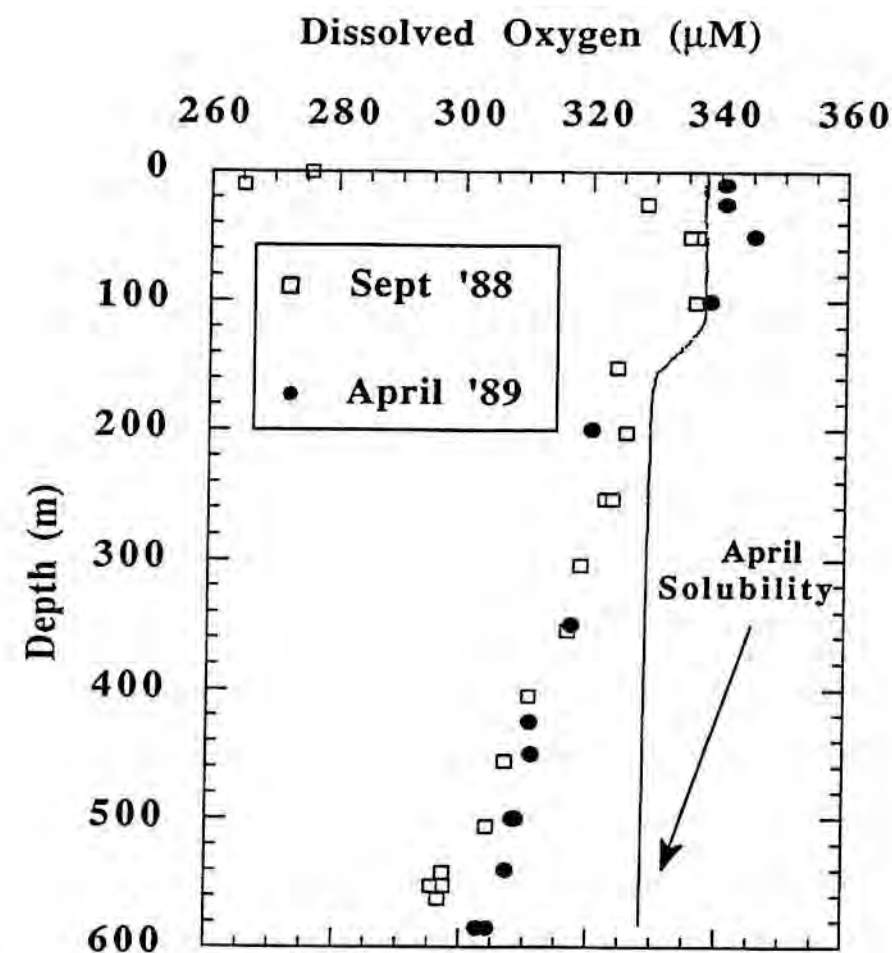


Figure 9. Expanded-scale dissolved oxygen as a function of depth for September 1988 and April 1989. Note that the measured dissolved oxygen is always within ~15% of the saturated value. The figure demonstrates the increase in deep-lake oxygen from fall/winter to spring/summer. The line of oxygen solubility is for April and is calculated from equations presented in Benson and Krause (1984). Solubility is calculated with respect to atmospheric saturation of dissolved oxygen at the *in situ* temperature.

of dissolved oxygen at all times sampled. Mass balance calculations indicate that for the 1988-89 field season 30-45% of deep lake water was exchanged with aerated surface water. This implies a characteristic time scale of deep lake ventilation between 2 and 4 years. This age is consistent with that estimated by Simpson (1970a) who obtained a value of 1 to 2 years based on tritium in the deep lake, and with the estimate by Weiss (1992) who calculated an apparent age of the deepest water (~550 m) of 3.2 years based on the deep water concentration of chlorofluorocarbons.

CTD data collected at the same time as the dissolved oxygen data and thermistor chain data also provide evidence for the exchange of surface water with water from the deep hypolimnion. A one dimensional approximation of the heat budget in the deep north basin from January 1990 to July 1990 (Fig. 10) indicates that a net loss of heat ( $225 \text{ kcal m}^{-2}$ ) occurred between January 1990 and July 1990 in north basin deep water (> 475 m). This calculation simply represents the difference in the heat contents of the deep north basin between January and July 1990. This loss of heat is due to the transfer of the warmer deep-water upward, providing further evidence for exchange between surface and deep water. Both the dissolved-oxygen data and the CTD data are consistent with the deep-water cooling evident in the thermistor chain data collected from the south basin (Fig. 4).

The deep lake thermistor chain data imply that deep-lake vertical mixing lasted approximately one month during the winter of 1990 (Fig. 4). Most of the thermistors in this chain recorded the maximum in deep-lake temperature in early February. After this time the deep lake underwent cooling until it again began to warm. Water-column cooling occurs during a period of reduced upper water-column stability, which is due to a reduction in stratification as described in the previous sections. During a minimum in water-column stability, cold waters from the upper 200-300 m exchange with the deeper warmer waters.

There are two phases of deep lake mixing which are illustrated in Fig. 11 - a turbulent diffusion phase and a sudden or episodic convective mixing phase. The gradual decrease in temperature between 1 February and 20 February, over the depth interval 350 m to 420 m is a

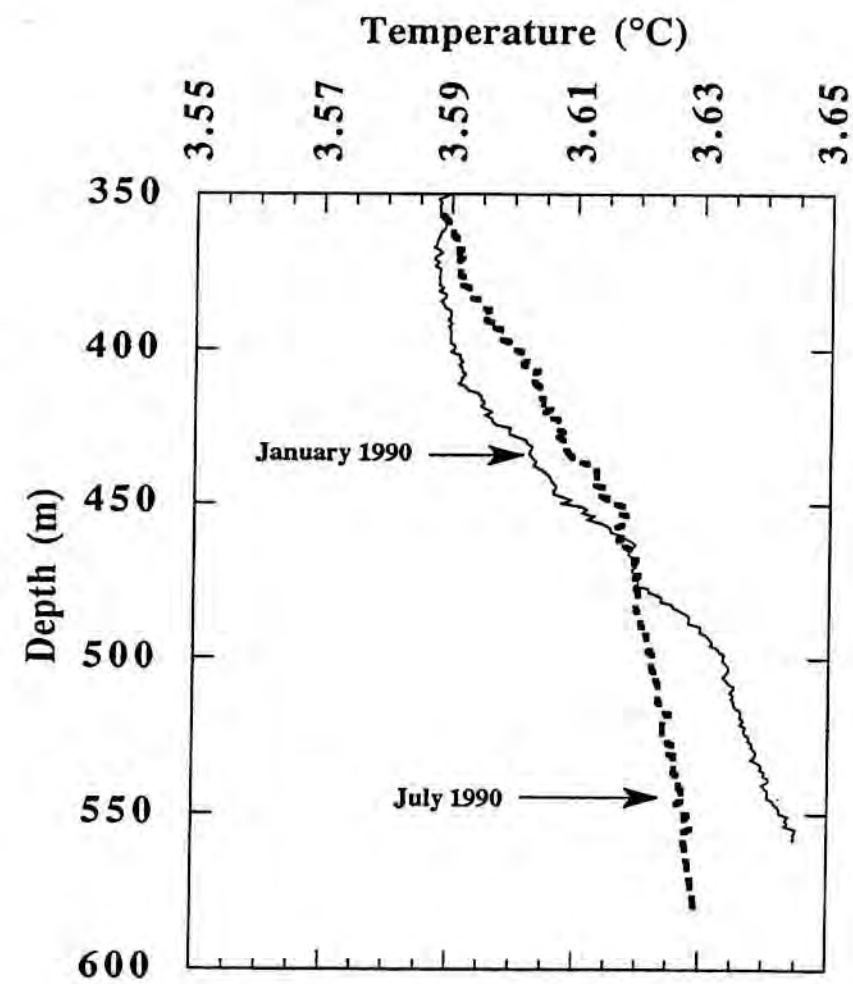


Figure 10. Temperature as a function of depth for January 1990 and July 1990. The cooling of the deep water column due to the exchange of surface water with deep lake water during the winter results in a lower total heat content of the deep water measured in July 1990.

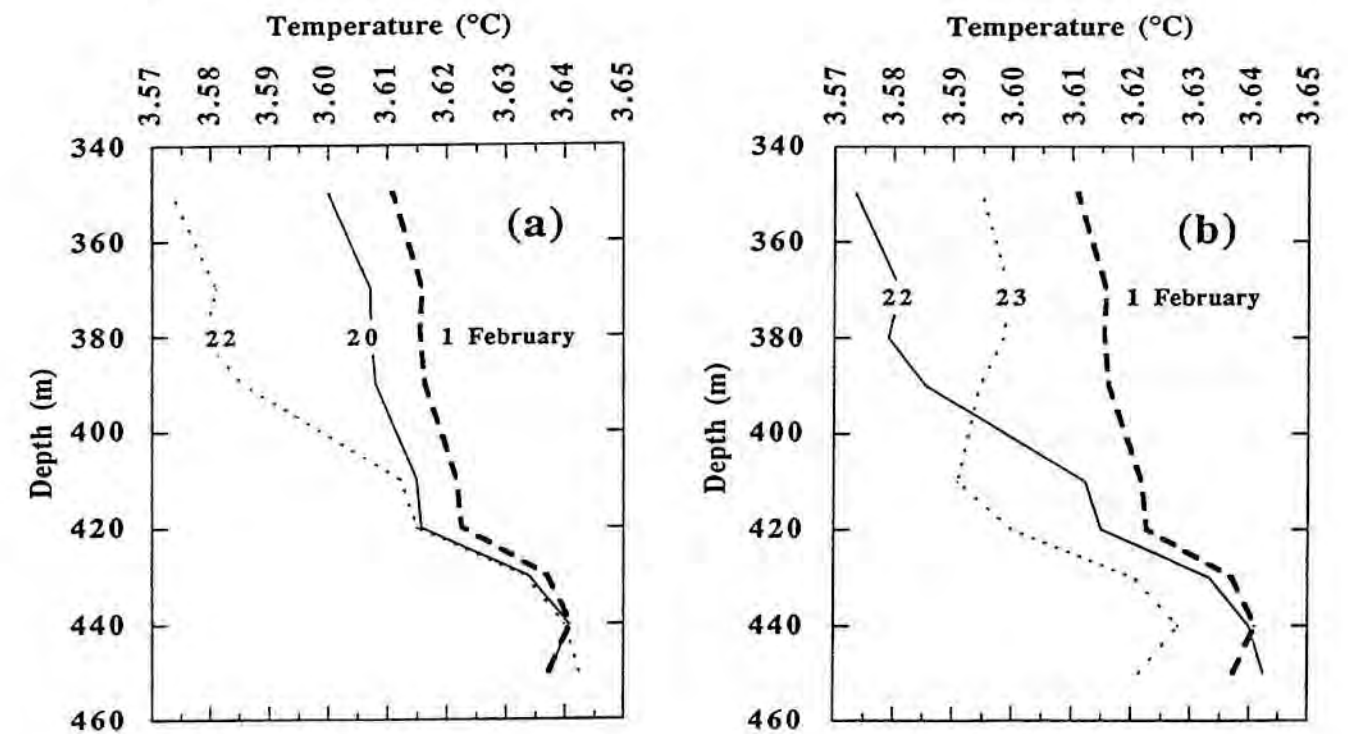


Figure 11. (a) Temperature as a function of depth for 1, 20, and 22 February. (b) Temperature vs depth for 1, 22, and 23 February. In (a) the diffusion of cold water from above dominates the mixing process from 1 February to 20 February. This is followed by the development of an unstable deep water column due to the accelerated (sudden) mixing of cold water from above.

result of mixing the colder water from above with the deeper warm water and can be modeled with a turbulent diffusion model:

$$F_H(z,t) = \int_0^z rC (\partial T[z,t]/\partial t)_z dz \quad (1)$$

and

$$F_H(z,t) = -rC K[z,t] (\partial T[z,t]/\partial z)_t \quad (2)$$

In eqn. 1 and 2,  $F_H$  is the heat flux,  $\partial T/\partial z$  and  $\partial T/\partial t$  are the slopes of the temperature versus depth and temperature versus time relationships respectively (Li 1973), and  $r$  and  $C$  are the density and the specific heat capacity, respectively. The vertical diffusion coefficient ( $K[z,t]$ ) evaluated from this data is  $1.5 - 2 \times 10^{-3} \text{ m}^2 \text{ sec}^{-1}$ . This diffusion coefficient is compared to the effective diffusion coefficient calculated for the hypolimnion during periods of upper water surface stratification, later in the text.

We hypothesize that the majority of the exchange between surface and deep water occurs by way of a mechanism that is similar to that proposed by Farmer and Carmack (1981), Carmack and Farmer (1982), Carmack et al. (1989), Carmack and Weiss (1991), and Weiss et al. (1991). This mechanism relies on the effects of pressure on the temperature of maximum density and has, therefore, been termed "thermobaric instability" (Carmack et al. 1989, Carmack and Weiss 1991). Because the temperature of maximum density decreases with increasing pressure, colder water overlying warmer water becomes "conditionally unstable" with respect to water immediately below. Wind forcing and/or internal waves displace a water parcel vertically to a depth where its temperature is closer to the temperature of maximum density than the ambient water at that depth. Once the parcel is displaced, it will continue to descend through the water column, because of its greater density relative to the surrounding water, until it reaches a point of neutral stability.

A requirement for the deep penetration of a water parcel is that  $\Delta S \Delta z^{-1}$  (the vertical salinity gradient) is approximately equal to zero or is negligible compared to the temperature and pressure effects on the density of adjacent water parcels. In Lake Baikal, U.S.S.R., where the results of

this process have been clearly shown, this requirement is satisfied (Carmack et al. 1989, Carmack and Weiss 1991, Weiss et al. 1991, Falkner et al. 1991). Surface water descends in Lake Baikal through the water column to near-bottom depths with a well-preserved surface signature in temperature, dissolved oxygen, and other geochemical tracers (Carmack and Weiss, 1991, Weiss et al. 1991). In Crater Lake between the depths of 200 and 400 m, the approximation of  $\Delta S \Delta z^{-1} = 0$  may hold; however, the gradual increases in salinity below this depth range will increase the density of the ambient fluid making exchange of the colder, less salty fluids (upper waters) with the warmer, saltier fluids more difficult.

Using estimates of the salinity gradient obtained from January 1990 CTD data and the thermistor data presented in Fig. 11a, we calculate that the density, relative to 400 dbars, of the water above 390 m on 22 February is more dense than the water below 400 m. The temperature profile for the following day shows that there has been some apparent exchange between the colder water from above and the warmer water below, resulting in colder waters now underlying warmer water (Fig. 11b). In the subsequent days there are rapid changes in the vertical temperature distribution in this part of the water column, eventually resulting in a stable density gradient. It is also apparent from the figure that the near-bottom waters have not been mixed to the same degree as the waters above 420 m. The net effect of mixing dense cold waters from above with warm, salty waters from below is that any instability-driven mixing decreases in effectiveness with increasing depth in Crater Lake due to the resisting force of the salinity gradient. In addition, the surface temperature and oxygen signal will simply decrease as it mixes with ambient waters during its decent to the deep lake.

It is reasonable to expect that the magnitude or effectiveness of this type of mixing will vary from year to year. As surface waters cool below the temperature of maximum density, the upper waters become restratified. The rate of cooling and restratification of the upper waters will influence the "completeness" of deep water ventilation. This ventilation is more likely to occur during the winter mixing phase rather than in the spring. Although thermally driven convection will also occur during spring warming, calmer weather at Crater Lake typically dominates during

spring. Thus, heating of surface water occurs fairly rapidly, thereby making vertical exchange less likely or less efficient during this period. Year-to-year climate variations will, therefore, affect the extent of annual vertical exchange. This has recently been demonstrated by McCormick (1990) who finds that circulation models coupled with global climate models predict that during warmer years, Lake Michigan may not completely turn over and a permanent thermocline may form in the deep regions of the lake.

The oxygen and temperature data presented here suggest that the annual exchange of surface water with deep water is a critical process for the vertical redistribution of heat and salt in the lake. It is difficult to predict the annual magnitude or extent of this mixing process in the water column without a yearly time series of data. It is likely that a comprehensive model of surface-to-bottom exchange is impossible without detailed meteorological data as well as water column chemistry and temperature data. Pearle et al. (1975) used the appearance of nitrate enrichments in the surface waters to estimate the timing of turnover; unfortunately, we can not apply this approach to the Crater Lake system without frequent collection of nitrate data throughout the year. Crater Lake's inaccessibility makes this method difficult. Some enrichments in surface nitrate have been observed during early April in the upper isothermal layer (Larson 1988); however, it is not clear if these observed surface enrichments are due to upwelling of bottom water, atmospheric inputs, or some combination of the two.

### **Transport of heat and salt through the deep lake**

Deep-lake mixing of hydrothermal fluids during periods of upper water column stratification takes place through a variety of horizontal and vertical mixing processes. Without an understanding of the time scales of this mixing, we can not place confidence in our method for determining the hydrothermal component of the deep lake heat and salt budgets as discussed earlier. This section is, therefore, primarily concerned with understanding the transport of hydrothermal fluids through the deep lake, i.e. deeper than 350 m, during periods of thermal stratification.

**Horizontal mixing in the deep lake.** During thermal stratification of the upper water column, horizontal basin-to-basin exchange processes dominate deep-lake mixing. This mixing is indicated by changes in the vertical distribution of temperature, salinity, and other geochemical tracers (e.g. dissolved gases and trace elements).

CTD data taken from the north basin in September 1988 show that the vertical temperature and salinity distribution may deviate from the normal near-linear increase with depth (cf. Fig. 1 with Fig. 12). We refer to such variations in the vertical gradients as "microstructure" features. We propose that these features are due to the lateral flow of hydrothermally enriched water from the south basin. As the south basin fills with warm, salty water, it will "spill over" into the deeper portions of the lake because of its greater density relative to non-enriched fluids. The sill depth between these two basins is between a depth of 425 and 450 m. The sill depth corresponds to the depth of the microstructure features observed in the south basin (near the sediment-water interface) and the north basin (mid-water column) (Fig. 12a). The presence of warmer waters in both basins at the same depth (~425 m) supports our hypothesis that the fluids originated in the south basin.

In order to accurately assess the stability of the deep-water column in September 1988, we computed  $\sigma_{0.5}$ . Where  $\sigma_{0.5} = (\rho_{0.5} - 1) \times 1000$  and  $\rho_{0.5}$  is the potential density of a fluid at 500 dbars. In deep aquatic systems,  $\sigma_{\theta}$  does not accurately represent the local "stability" of the water column (Fig. 12d). This is due to the effect of pressure on the density of a fluid, where  $\sigma_{\theta}$  is calculated for 1 atm pressure as opposed to a pressure more representative of two deep parcels of water under consideration (i.e. 500 dbars pressure). Most of the water throughout the water column appears to be statically stable with respect to 500 dbars (Fig. 12c); however, stability calculations for some individual points within the water column suggest that there are some unstable parcels of water. These parcels are unstable over vertical distances of 5-10 m. Because changes in the vertical density structure on this scale approach the resolution of our instrument, there is significant uncertainty associated with classifying the "stability" of parcels of water over this depth range. The thermal structure of the deep lake, shown in Fig. 12a, tends to vary over periods of hours. In addition, when we've been able to revisit the lake within weeks of observing

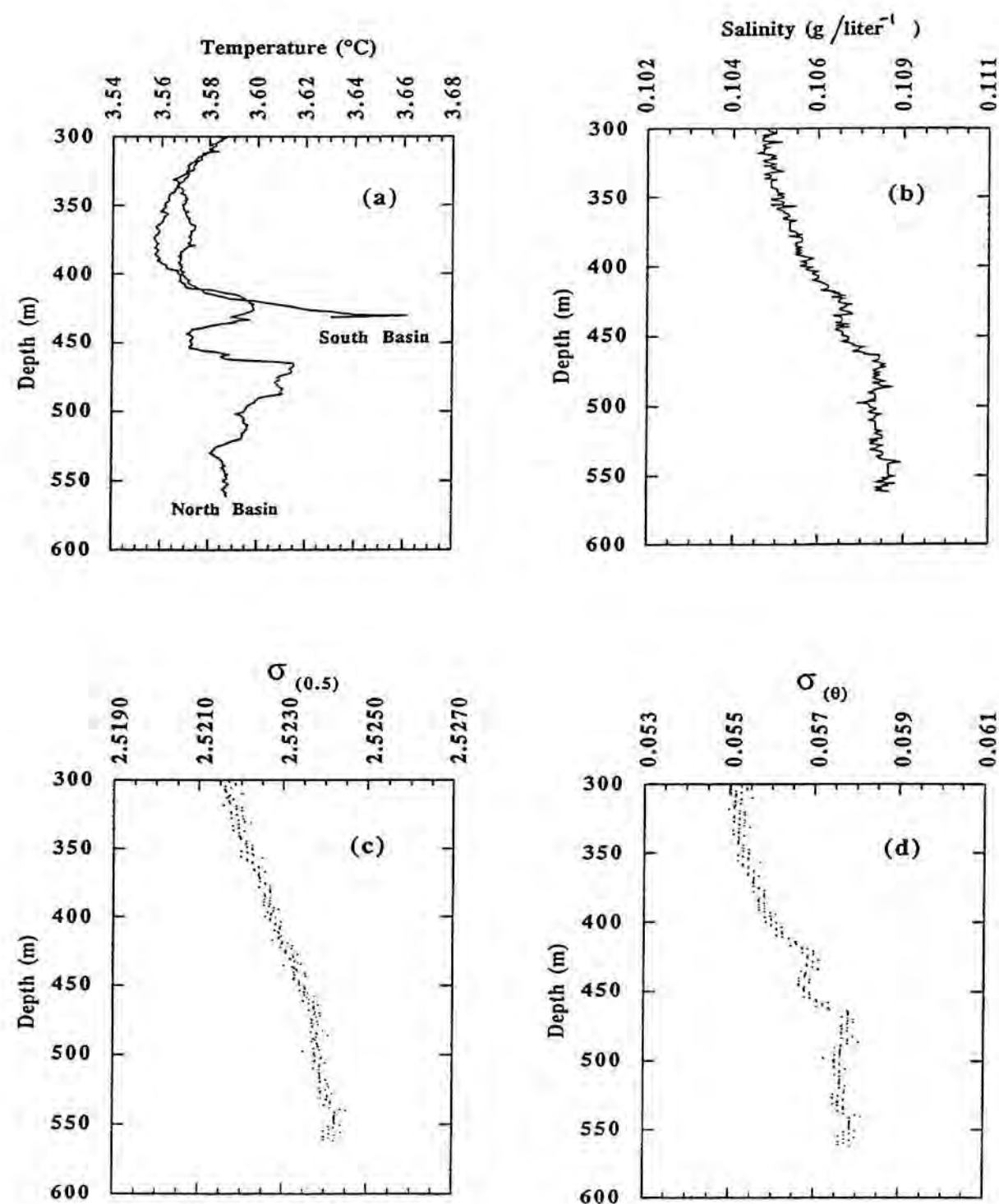


Figure 12. Hydrographic data taken 19 September 1988. (a) Temperature as a function of depth for both the south and the north basins, (b) Salinity as a function of depth for the north basin, (c)  $\sigma_{0.5}$  as a function of depth for the north basin, (d)  $\sigma_{\theta}$  as a function of depth for the north basin. Densities are calculated from equations presented in Chen and Millero (1986).

these microstructure features, they are no longer present in the water column. These additional observations suggest that these features are indeed unstable and transient.

$^{222}\text{Rn}$  and Fe (dissolved and particulate) measurements further illustrate the basin-to-basin exchange process. Water with high  $^{222}\text{Rn}$  and Fe contents overlay water of lower  $^{222}\text{Rn}$  and Fe content in the north basin (Fig. 13). These single profiles exhibit the net effect of horizontal exchange. Both  $^{222}\text{Rn}$  and Fe are time-dependent tracers of the south basin's hydrothermally enriched water. Iron is highly reactive in well-oxygenated environments and is only found at high concentrations near reduced sediments or hydrothermal vents. Radon is a radioisotope with a half-life of  $\sim 3.8$  days. It too should only be found near a hydrothermal vent or in the sediments in Crater Lake. The horizontal transport of iron from the south basin leads to a maximum in dissolved and particulate Fe between 450 and 500 m in the north basin (Fig. 13a).  $^{222}\text{Rn}$  also exhibits a deep-water maximum at  $\sim 475$  m in the north basin (Fig. 13b). The net effect of the proposed horizontal movement of waters from the south basin to the north basin is that "younger" ( $^{222}\text{Rn}$ -enriched) waters overlay the "older" ( $^{222}\text{Rn}$ -depleted) waters in the north basin.

Although the water column features, indicative of horizontal mixing, have been observed at various times throughout the summer, the most dramatic features are consistently observed in late summer or early fall (September-October). These periods of more-intense horizontal exchange have larger thermal anomalies in the north basin than those typically observed during the summer. Since September and October are periods of thermal stratification, surface disturbances can not supply the necessary forcing for the initiation of this deep lake mixing process.

From our hydrothermal fluid inflow and composition estimates, and the observed near-bottom salinities of south basin waters, we estimate that the south basin could "fill-up" with a mixture of hydrothermal and ambient fluid on the time scale of several weeks to months. The horizontal exchange process proposed here is not necessarily a continuous process. Consequently, the non-steady-state nature of this mixing process in the deep lake results in the relatively large uncertainty ( $1\sigma$ ) in the net heat and salt flux estimates, which are based on a few individual vertical profiles (Table 1).

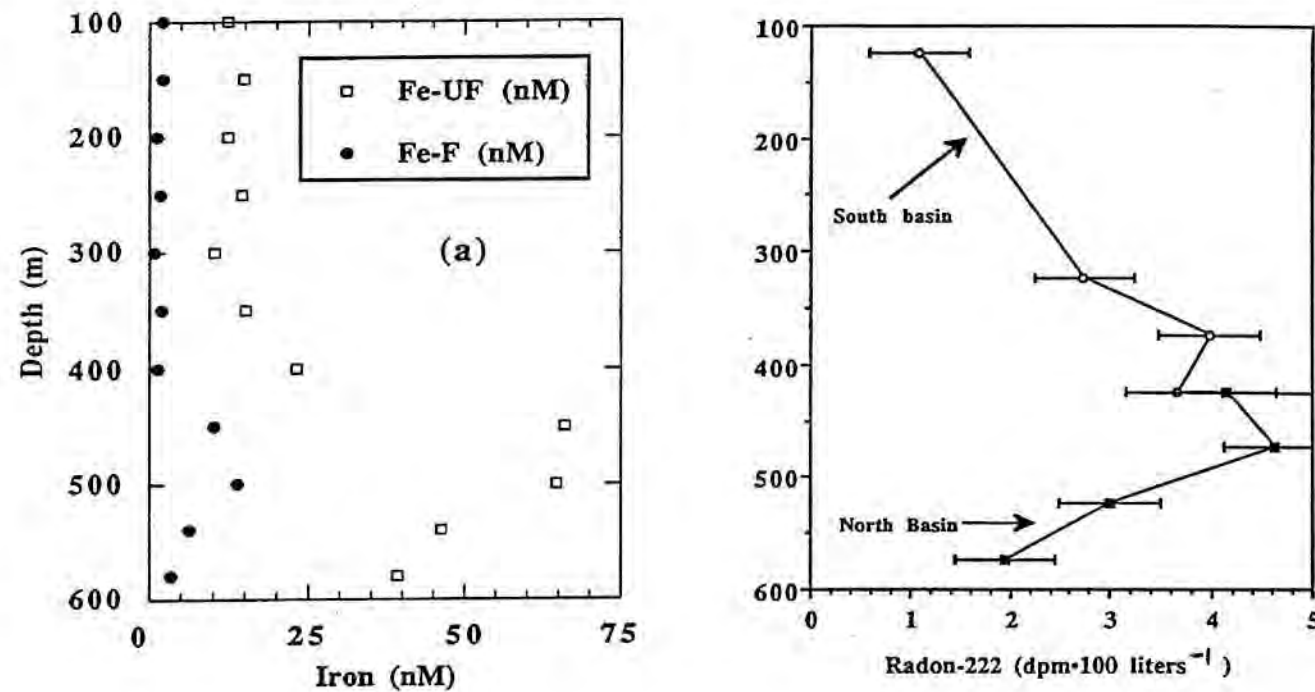


Figure 13. (a) Dissolved and particulate iron as a function of depth from the north basin (data from Collier et al. 1990a). (b) <sup>222</sup>Rn as a function of depth for the north and south basin. Although not on the graph, the deepest <sup>222</sup>Rn value from the particular south basin hydrocast shown on the figure was 35 dpm 100 l<sup>-1</sup>.

Vertical mixing processes in the deep lake. In addition to horizontal advection playing a large role in the transport of heat and salt through the deep lake, we propose that turbulent diffusion coupled with vertical convection transport heat and salt transport through the hypolimnion. We base this hypothesis on two observations: (1) because the calculated effective vertical diffusivities for both heat and salt in Crater Lake are the same order of magnitude ( $10^{-4} \text{ m}^2 \text{ sec}^{-1}$ ) and are many orders of magnitude larger than the molecular values ( $10^{-7}$ - $10^{-9} \text{ m}^2 \text{ sec}^{-1}$  for heat and salt respectively), the mixing process can not be accounted for by molecular diffusion (or double diffusion); (2) there are small-scale vertical thermal instabilities in the water column which do not appear to be due to the horizontal transport of heat and salt described in the previous section.

The effective diffusivities for heat ( $K_{eT}$ ) and salt ( $K_{eS}$ ) can be modeled according to a simple diffusion model (see equations 1 and 2 for the development);

$$F_T = K_{eT} \left( \frac{dT}{dz} \right) \quad (3)$$

and

$$F_S = K_{eS} \left( \frac{dS}{dz} \right) \quad (4)$$

where  $F_T$  and  $F_S$  are the measured flux of temperature ( $^{\circ}\text{C m s}^{-1}$ ) and salt ( $\text{g m kg}^{-1} \text{ s}^{-1}$ ), respectively. For dimensional simplicity we use  $F_T$  as opposed to  $F_H$  -- the heat flux. These measurements are again based on time-series CTD measurements (Table 1). Our calculations reveal that the effective diffusivities for heat and salt are approximately  $6$  to  $8 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ . If molecular diffusion was an important mechanism for the transport of heat and salt through the water column, the calculated effective diffusivity for heat should be two orders of magnitude larger than the effective diffusivity for salt. The effective diffusion coefficient calculated here for the summer-fall period is approximately a factor of two smaller than the diffusion coefficient calculated (earlier in the text) for diffusion during the month of February  $\sim 2 \times 10^{-3} \text{ m}^2 \text{ sec}^{-1}$ . This observation suggests that the intensity of deep-lake mixing during the winter is slightly greater than during the summer. This is reasonable because the overall stability of the upper water column is

greater during the summer than during the winter. However, at all times, turbulent diffusion processes will obviously be smaller in magnitude than the instability-driven convection from the upper lake described earlier in the text.

Observations of small temperature inversions through the mid-water column suggest the presence of small, buoyant "plumes" (Fig. 14). Salinity profiles lack the sensitivity of the temperature profiles and do not show this effect. Therefore we can not accurately calculate the stability of these thermal features. Our data suggest however that they are transient features that occasionally occur in the mid-to-deep lake. These "plumes" could be caused by either of two processes (or some combination of the two). The plumes may be caused by direct inputs of buoyant water into the south basin. Alternatively, they may be generated by conductive heating or double-diffusive development of thermally and chemically enriched waters resting at the sediment-water interface. These processes could eventually lead to instability and formation of thermal convection cells that vertically mix the excess heat and salt.

An alternate convective mechanism for mixing heat and salt through the water column, is suggested as a large temperature anomaly in the middle of the water column (Fig. 15a). We observed this temperature anomaly in the south basin of Crater Lake on 11 September 1987. This anomaly is greater than  $0.1^{\circ}\text{C}$  between 225 and 275 m, relative to the north basin profile. This corresponds to a total heat anomaly of  $9600 \text{ kcal m}^{-2}$ , which is a factor of five to ten larger than typical near-bottom thermal anomalies measured in the south basin (McManus 1992). Shown with this data (Fig. 15a) are temperature profiles taken from the south basin approximately 6 hours earlier (solid line) and the north basin approximately 3 hours earlier (dotted line). Although the two south basin profiles are from the same general location, they may be separated in space by as much as 500-1,000 meters. T-S diagrams (Fig. 15b-d) of the three hydrocasts (below 100 m) illustrate the dramatic change in the characteristics of the large thermal anomaly. However, the T-S diagrams of all the CTD data show some influence of the warmer, more-saline water, suggesting that the heat and salt seen in SBE028 may be spreading horizontally along a constant density surface.

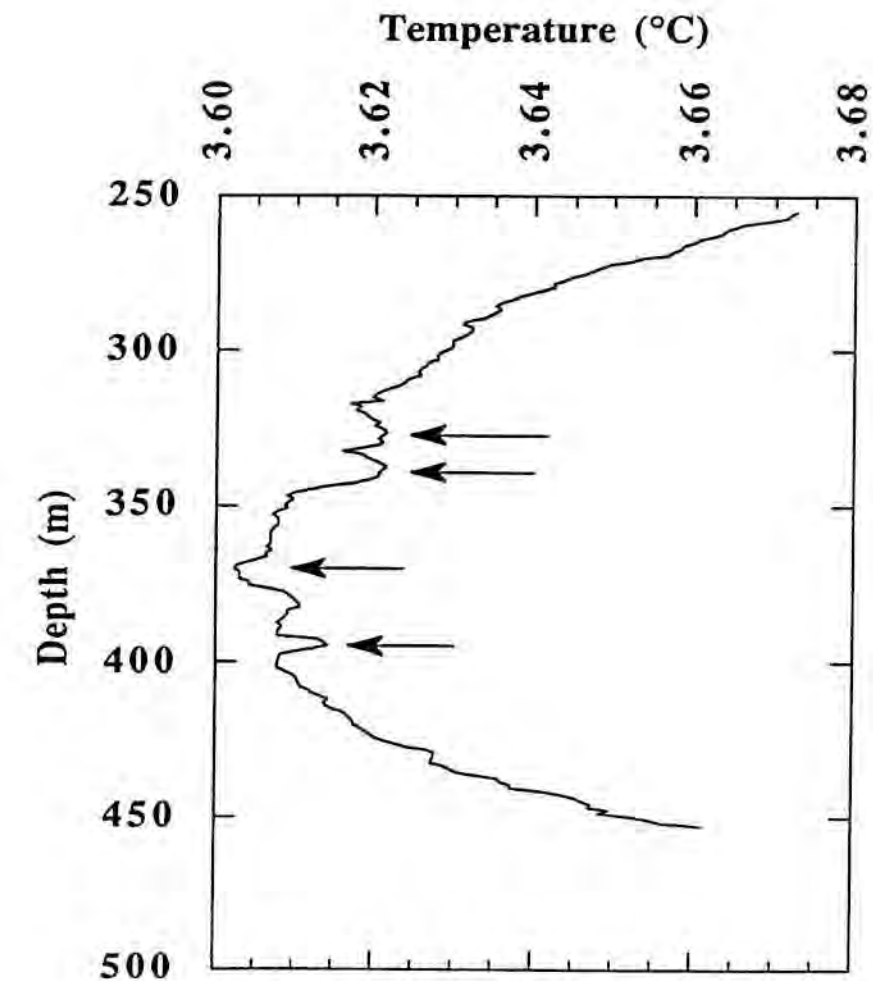


Figure 14. Examples of vertical instabilities (arrows). Data is from 18 September 1990 from the south basin.

This large thermal anomaly is hydrostatically stable with respect to 250 dbars and is buoyant relative to 450 dbars. This suggests that perhaps the water column anomaly represents a "plume" that originated at the sediment-water interface and has risen to neutral buoyancy. Alternatively, there could be a source of thermally enriched and chemically enriched water along the caldera wall at this depth, which we have not observed to date.

Our calculations suggest that turbulent diffusion rather than molecular or double diffusion dominates vertical mixing in the deep lake. However, the mechanism that initiates turbulence in Crater Lake is not known. Horizontal advection followed by vertical mixing and vertical convection also play a role in the vertical redistribution of heat and salt through the water column. As would be expected, our calculated diffusion coefficients for the deep lake are larger than values for the region just below the thermocline (50-150 m) in Crater Lake ( $10^{-5}$  -  $10^{-6}$   $\text{m}^2 \text{sec}^{-1}$ ). Also, the range in diffusion coefficients calculated for the deep lake ( $6$ - $20 \times 10^{-4}$   $\text{m}^2 \text{s}^{-1}$ ) compares well with the range for the deep ocean ( $0$  [ $1$ - $100 \times 10^{-4}$   $\text{m}^2 \text{s}^{-1}$ ]) as derived from  $^{222}\text{Rn}$ -depth profiles (Sarmiento et al. 1976). This comparison illustrates the importance of turbulence in the redistribution of heat and salt in the hypolimnion.

The physical processes described here appear to be directly tied to the active input of thermally and chemically enriched waters and because of these processes the deep lake remains relatively well mixed.

### Summary

Our estimates of the deep lake heat budget of Crater Lake are consistent with the previous estimates of Williams and Von Herzen (1983). Because our methods are independent from those of Williams and Von Herzen (1983), who used sediment heat flow measurements, the agreement between the two data sets supports our results. Our data provide the first direct observations of the accumulation of heat and salt in the deep lake and lead to direct estimates of these fluxes.

Dissolved oxygen data, thermistor chain data, and CTD data all indicate that annual vertical mixing is significant in the Crater Lake. Our data also indicate that such ventilation is incomplete, resulting in undersaturation of dissolved oxygen at all times in the hypolimnion. The lack of

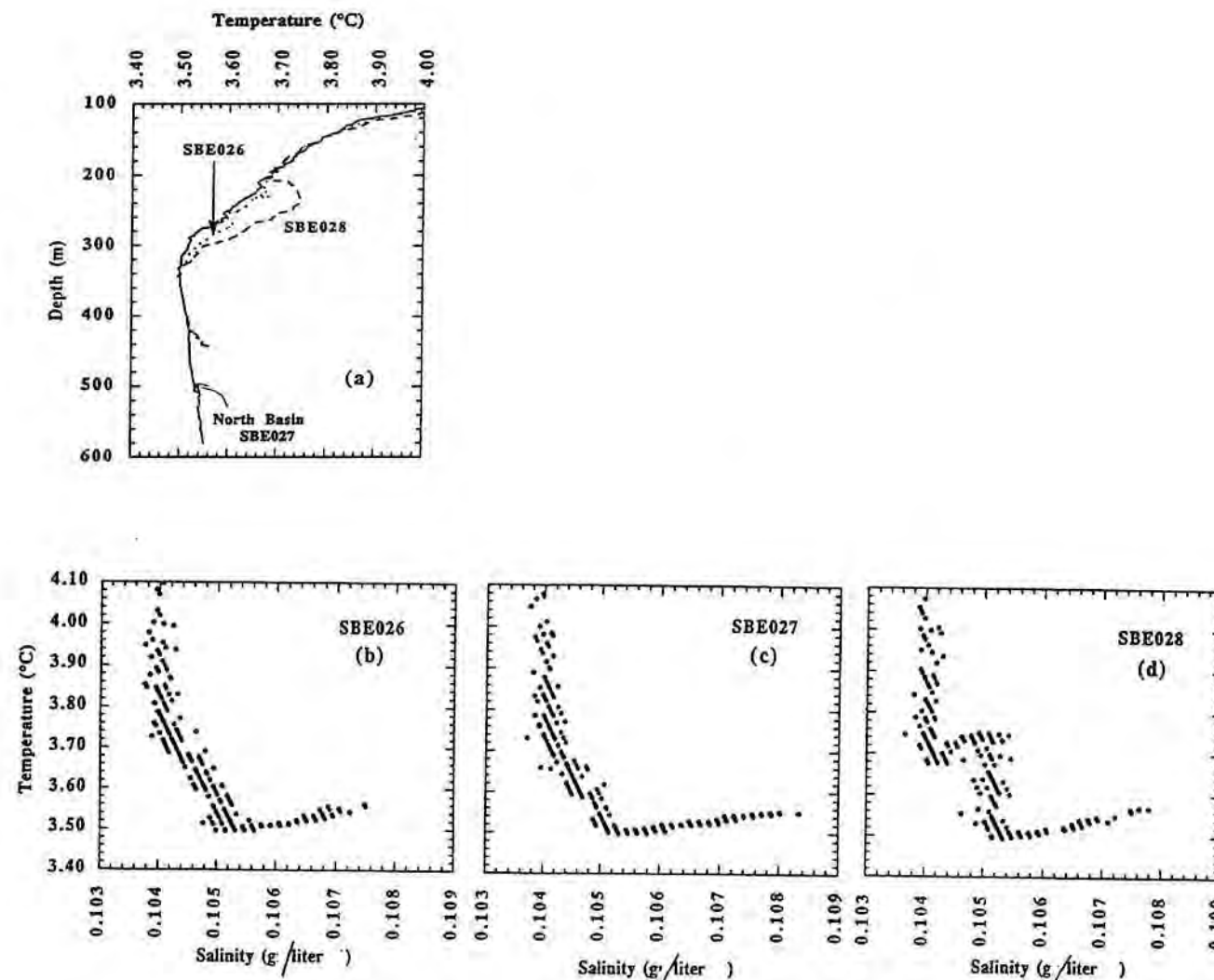


Figure 15. (a) Temperature as a function of depth for SBE026 (solid line, south basin), SBE027 (dotted line, north basin), and SBE028 (dashed line, south basin). (b-d) T-S diagrams for the three hydrocasts. Data shows the T-S anomaly in all three hydrocasts, but is particularly striking for SBE028.

complete water column mixing in Crater Lake is a consequence of the lake's depth and the vertical density gradient within the deep lake. Incomplete ventilation is a characteristic of deep lakes, and Crater Lake offers a unique environment for the study of deep lake ventilation processes. During periods of surface stratification, turbulent diffusion and horizontal advection rather than molecular diffusion dominate deep lake mixing, although the forcing mechanism of the turbulence is not known.

## References

- Benson, B.B., and D. Krause, Jr. 1984. The concentration and isotopic fractionation of oxygen in freshwater and seawater in equilibrium with the atmosphere. *Limnology and Oceanography* 29:620-632.
- Byrne, J.V. 1965. Morphometry of Crater Lake, Oregon. *Limnology and Oceanography* 10:462-465.
- Carmack, E.C., and D.M. Farmer. 1982. Cooling processes in deep, temperate lakes: A review with examples from two lakes in British Columbia. *Journal of Marine Research* 40:85-111.
- Carmack, E.C., R.F. Weiss, and V.M. Koropalov. 1989. Physical studies of mixing processes in Lake Baikal. *EOS* 70 (43):1136.
- Carmack, E.C., and R.F. Weiss. 1991. Convection in Lake Baikal: An example of thermobaric instability. In P.C. Chu and J.C. Gascard, eds., *Deep Convection and Deep Water Formation in the Oceans*. Elsevier, New York.
- Carpenter, J.H. 1965a. The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method. *Limnology and Oceanography* 10:141-143.
- Carpenter, J. H. 1965b. The accuracy of the Winkler method for dissolved oxygen analysis. *Limnology and Oceanography* 10:135-140.
- Chen, C.T. and F.J. Millero. 1986. Precise thermodynamic properties for natural waters covering only the limnological range. *Limnology and Oceanography* 31:657-662.
- Collier, R. W., J. Dymond, J. McManus, and J. Lupton. 1990a. Chemical and physical properties of the water column at Crater Lake, OR. Pages 69-80 in E. T. Drake, G. L. Larson, J. Dymond, and R. Collier, eds., *Crater Lake: An Ecosystem Study*. Pacific Division, American Association for the Advancement of Science, San Francisco, Calif.
- Collier, R., J. Dymond, J. McManus, R. Conard, C. Meredith, and C.G. Wheat. 1990b. Mass balances and geochemical fluxes derived from hydrothermal activity in Crater Lake, OR. *EOS* 71:1674.
- Collier, R., J. Dymond, and J. McManus. 1991. Studies of hydrothermal processes in Crater Lake, Oregon. Report No. 90-7, College of Oceanography, Oregon State University, Corvallis. 201 pp + appendices.

- Dymond, J., R. W. Collier, and M. E. Watwood. 1989. Bacterial mats from Crater Lake, Oregon and their relationship to possible deep-lake hydrothermal venting. *Nature* 342:673-675.
- Farmer, D.M. and E.C. Carmack. 1981. Wind mixing and restratification in a lake near the temperature of maximum density. *Journal of Physical Oceanography* 11:1516-1533.
- Falkner, K.K., C.I. Measures, S.E. Herbelin, J.M. Edmond, and R.F. Weiss. 1991. The major and minor element geochemistry of Lake Baikal. *Limnology and Oceanography* 36:413-423.
- Kibby, H.V., J.R. Donaldson, and C.E. Bond. 1968. Temperature and current observations in Crater Lake, Oregon. *Limnology and Oceanography* 363-366.
- Larson, G. L. 1988. Crater Lake Limnological Studies. 1987 annual report. National Park Service, Cooperative Park Studies Unit, Oregon State University, Corvallis.
- Li, Y.-H. 1973. Vertical eddy diffusion coefficient in Lake Zurich. *Hydrologie* 35(1):1-7.
- McCormick, M.J. 1990. Potential Changes in thermal structure and cycle of Lake Michigan due to global warming. *Transactions, American Fisheries Society* 119:183-194.
- McManus, J., R. Collier, and J. Dymond. 1990. Heat and salt flux in Crater Lake, OR as deduced from water column CTD measurements. *EOS* 71:1674.
- McManus, J., R. Collier, C.T. Chen, and J. Dymond. 1992. Physical properties of Crater Lake, Oregon: A method for the determination of a conductivity- and temperature-dependent expression for salinity. *Limnology and Oceanography* 37:41-53.
- McManus, J. 1992. On the Chemical and Physical Limnology of Crater Lake, Oregon. Ph. D. thesis, Oregon State University, Corvallis. 143 pp.
- Mortimer, C.H. 1981. The oxygen content of air-saturated fresh waters over ranges of temperature and atmospheric pressure of limnological interest. *Mitteilungen-Internationale Vereinigung fuer Theoretische und Angewandte Limnologie* 22:23.
- Nathenson, M.. 1990. Chemical balance for major elements in water in Crater Lake, Oregon. Pages 103-114 in E.T. Drake, G.L. Larson, J. Dymond, and R. Collier, eds., *Crater Lake: An Ecosystem Study*. Pacific Division, American Association for the Advancement of Science, San Francisco, Calif.
- Nathenson, M. and J.M. Thompson. 1990. Chemistry of Crater Lake, Oregon, and nearby springs in relation to weathering. Pages 115-126 in E.T. Drake, G.L. Larson, J. Dymond, and R. Collier, eds., *Crater Lake: An Ecosystem Study*. Pacific Division, American Association for the Advancement of Science, San Francisco, Calif.
- Neal, V.T., S.J. Neshyba, and W.W. Denner. 1971. Temperature microstructure in Crater Lake, Oregon. *Limnology and Oceanography* 16:695-700.
- Neal, V.T., S.J. Neshyba, and W.W. Denner. 1972. Vertical temperature structure in Crater Lake, Oregon. *Limnology and Oceanography* 17:451-454.

- Pearl, H.W., R.C. Richards, R.L. Leonard, and C.R. Goldman. 1975. Seasonal nitrate cycling as evidence for complete vertical mixing in Lake Tahoe, California-Nevada. *Limnology and Oceanography* 20:1-8.
- Phillips, K.N. 1968. Hydrology of Crater Lake, East Lake, and Davis Lakes, Oregon. U.S. Geological Survey Water Supply Paper 1859-E. 60 pp.
- Redmond, K.T. 1990. Crater Lake climate and lake level variability. Pages 127-141 in E.T. Drake, G.L. Larson, J. Dymond, and R. Collier, eds., *Crater Lake: An Ecosystem Study*. Pacific Division, American Association for the Advancement of Science, San Francisco, Calif.
- Sarmiento, J.L., H.W. Feely, W.S. Moore, A.E. Bainbridge, and W.S. Broecker. 1976. The relationship between vertical eddy diffusion and buoyancy gradient in the deep sea. *Earth and Planetary Science Letters* 32:357-370.
- Simpson, H.J. 1970a. Closed basin lakes as a tool in geochemistry. Ph.D. thesis, Columbia University, New York.
- Simpson, H.J. 1970b. Tritium in Crater Lake, Oregon. *Journal of Geophysical Research* 75:5195-5207.
- Thompson, J.M., M. Nathenson, and L.D. White. 1990. Chemical and isotopic compositions of waters from Crater Lake and nearby vicinity. Pages 91-102 in E.T. Drake, G.L. Larson, J. Dymond, and R. Collier, eds., *Crater Lake: An Ecosystem Study*. Pacific Division, American Association for the Advancement of Science, San Francisco, Calif.
- Volchok, H.L., M. Feiner, H.J. Simpson, W.S. Broecker, V.E. Noshkin, B.T. Bowen, and E. Willis. 1970. Ocean fallout-the Crater Lake experiment. *Journal of Geophysical Research* 75:1084-1091.
- Weiss, R.F. 1992. Rates and variability of deep water renewal and biological production in deep temperate lakes: Lake Baikal and Crater Lake. *EOS* 73:198.
- Weiss, R.F., E.C. Carmack, and V.M. Koropalov. 1991. Deep water renewal and biological production in Lake Baikal. *Nature* 349:665-669.
- Williams, D.L. and R. P. Von Herten. 1983. On the terrestrial heat flow and physical limnology of Crater Lake, Oregon. *Journal of Geophysical Research* 88(B2):1094-1104.

## Temperature and Water Quality

Gary L. Larson and C. David McIntire

Early studies of the chemical properties and temperature patterns in the water column of Crater Lake were confined to the summer months and were limited in scope (Larson 1987). However, sufficient data were obtained during these studies to demonstrate the following about the lake: (1) it is thermally stratified in late summer and early fall with a shallow epilimnion; (2) it is slightly basic with a low alkalinity and conductivity; (3) it has very low concentrations of plant nutrients, particularly nitrogen and phosphorus; (4) it has relatively high concentrations of silica and sulfate sulfur; and (5) it is oxygenated throughout the water column. The 10-year study of Crater Lake included an analysis of the chemical properties of the lake at Station 13, with an emphasis on seasonal patterns, and a concurrent evaluation of the most recent data in relation to long-term changes in water quality. In addition, the study was designed to determine if the water column circulated to the lake bottom at any time during the winter or spring months during any year.

### Sampling and Analytical Methods

All temperature measurements and water samples for chemical analyses were obtained at Station 13 (see Study Area and Facilities section). Also, some historical temperature data from other studies dating back to 1913 were analyzed along with the more recent data to illustrate long-term trends in the near-surface water of the lake. Samples for nutrient analyses were obtained with 4-l Van Dorn bottles, usually from the depths of 0 m, 5 m, 10 m, 20 m, 60 m, 100 m, 200 m, 300 m, 400 m, 500 m, and 550 m. In general, water quality data presented in this report were collected from 1982 through 1991 in the months of January, March, April, May, June, July, August, September, and October. Not all variables were measured on each sampling date (Tables 1 and 2).

Table 1. A summary of the years and months when measurements of temperature, total alkalinity, dissolved oxygen, pH, and conductivity were made in Crater Lake at Station 13 during the 10-year study. Only samples that were included in this analysis are listed.

| Time          | Temp | Talk | DO | pH | Cond |
|---------------|------|------|----|----|------|
| <b>Year:</b>  |      |      |    |    |      |
| 1982          | X    | X    | X  | X  |      |
| 1983          | X    | X    | X  | X  |      |
| 1984          | X    | X    | X  | X  |      |
| 1985          | X    | X    | X  | X  |      |
| 1986          | X    | X    | X  | X  | X    |
| 1987          | X    | X    | X  | X  | X    |
| 1988          | X    | X    | X  | X  | X    |
| 1989          | X    | X    | X  | X  | X    |
| 1990          | X    | X    | X  | X  | X    |
| 1991          |      |      | X  |    | X    |
| <b>Month:</b> |      |      |    |    |      |
| Jan           | X    | X    | X  | X  | X    |
| Mar           | X    | X    | X  | X  | X    |
| Apr           | X    | X    | X  | X  | X    |
| May           | X    | X    | X  | X  | X    |
| Jun           | X    | X    | X  | X  | X    |
| Jul           | X    | X    | X  | X  | X    |
| Aug           | X    | X    | X  | X  | X    |
| Sep           | X    | X    | X  | X  | X    |
| Oct           | X    | X    | X  | X  | X    |

Table 2. A summary of the years and months when measurements of sodium, potassium, magnesium, calcium, sulfate sulfur, silicon, nitrate and ammonium nitrogen, and orthophosphate phosphorus were made in Crater Lake at Station 13 during the 10-year study. Only samples that were included in this analysis are listed.

| Time          | Na | K | Mg | Ca | S | Si | Nit-N | Am-N | Orth-P |
|---------------|----|---|----|----|---|----|-------|------|--------|
| <b>Year:</b>  |    |   |    |    |   |    |       |      |        |
| 1983          |    |   |    |    |   | X  | X     | X    | X      |
| 1984          |    |   |    |    |   | X  | X     | X    | X      |
| 1985          |    |   |    |    |   | X  | X     | X    | X      |
| 1986          | X  | X | X  | X  | X | X  | X     | X    | X      |
| 1987          | X  | X | X  | X  | X | X  | X     | X    | X      |
| 1988          | X  | X | X  | X  | X | X  | X     | X    | X      |
| 1989          | X  | X | X  | X  | X | X  | X     | X    | X      |
| 1990          | X  | X | X  | X  | X | X  | X     | X    | X      |
| 1991          |    |   |    |    |   | X  | X     | X    | X      |
| <b>Month:</b> |    |   |    |    |   |    |       |      |        |
| Jan           | X  | X | X  | X  | X | X  | X     | X    | X      |
| Mar           |    |   |    |    |   | X  | X     | X    | X      |
| Apr           | X  | X | X  | X  | X | X  | X     | X    | X      |
| May           | X  | X | X  | X  | X | X  | X     | X    | X      |
| Jun           | X  | X | X  | X  | X | X  | X     | X    | X      |
| Jul           | X  | X | X  | X  | X | X  | X     | X    | X      |
| Aug           | X  | X | X  | X  | X | X  | X     | X    | X      |
| Sep           | X  | X | X  | X  | X | X  | X     | X    | X      |
| Oct           |    |   |    |    |   | X  | X     | X    | X      |

Temperature was recorded using a Montedoro-Whitney thermister with a 250 m cable between 1982 and 1987; thereafter, measurements were made with a Sea Bird conductivity-temperature depth probe, Model SBE19. The concentration of dissolved oxygen was determined using the modified azide Winkler technique, and percentage saturation, corrected for elevation, was estimated following the method outlined by Wetzel (1975). Total alkalinity was determined colorimetrically (0.018 N H<sub>2</sub>SO<sub>4</sub> and brom-cresol green-methyl red) at the park laboratory from 1982 through 1988. Thereafter, the potentiometric method was used. Nutrient and element analyses were performed by the Cooperative Chemical Analytical Laboratory at Oregon State University using the methods listed in Table 3 (also see Quality Assurance Program of the Cooperative Chemical Analytical Laboratory).

## Results

### Temperature

Crater Lake was covered by a thin layer of ice and snow for four weeks in January and February of 1985. In 1986, the lake was nearly covered by ice at various times between January and March (Larson 1986, 1987). An ice cover was not observed at any other time during the 10-year study. Historically, ice cover is relatively infrequent.

In the winter and spring, the water mass in Crater Lake circulated to a depth of between 200 m and 250 m (see Dissolved Oxygen in the Deep Lake section), which often resulted in colder water occurring between the surface and the depth of mixing than at depths below the depth of mixing (Fig. 1). In late spring or early summer, the temperature of the lake near the surface increased, and a thermocline formed, usually sometime between July and September. Thermal stratification was evident as early as June in some years, while the process was not complete until September in other years (Table 4). In all years of the study, the epilimnion was between 5 m and 20 m in depth and was deepest in September, presumably because of cooler air temperatures and an increase in mixing

Table 3. Methods used for the measurement of chemical and physical variables for samples obtained in Crater Lake during the period from 1982 through 1990.

| Variable         | Chemical/Physical Method                                                                                                                                                 |
|------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| pH               | Electrometric glass electrode (Radiometer, Model G202L, reference electrode mercury-mercury chloride half cell K401) with temperature compensation, Radiometer type TTIC |
| Conductivity     | Wheatstone Bridge, Yellow Springs model 33, temperature corrected to 25 C                                                                                                |
| Nitrate-N        | Technicon Autoanalyzer, automated cadmium reduction                                                                                                                      |
| Kjeldahl-N       | Nessler's Reagent finish                                                                                                                                                 |
| Ammonia-N        | Technicon Autoanalyzer, colormetric automated phenate                                                                                                                    |
| Total Phosphorus | Persulfate digestion, ascorbic acid finish                                                                                                                               |
| Orthophosphate-P | Reactive phosphate, ascorbic acid finish                                                                                                                                 |
| Sulfur           | Technicon Autoanalyzer, method 105-72W                                                                                                                                   |
| Silica           | Technicon Autoanalyzer, method 105-71W/B                                                                                                                                 |
| Sodium           | Flame atomic absorption                                                                                                                                                  |
| Calcium          | Flame atomic absorption                                                                                                                                                  |
| Magnesium        | Flame atomic absorption                                                                                                                                                  |
| Potassium        | Flame atomic absorption                                                                                                                                                  |

## Crater Lake Temperature Profile April 1987

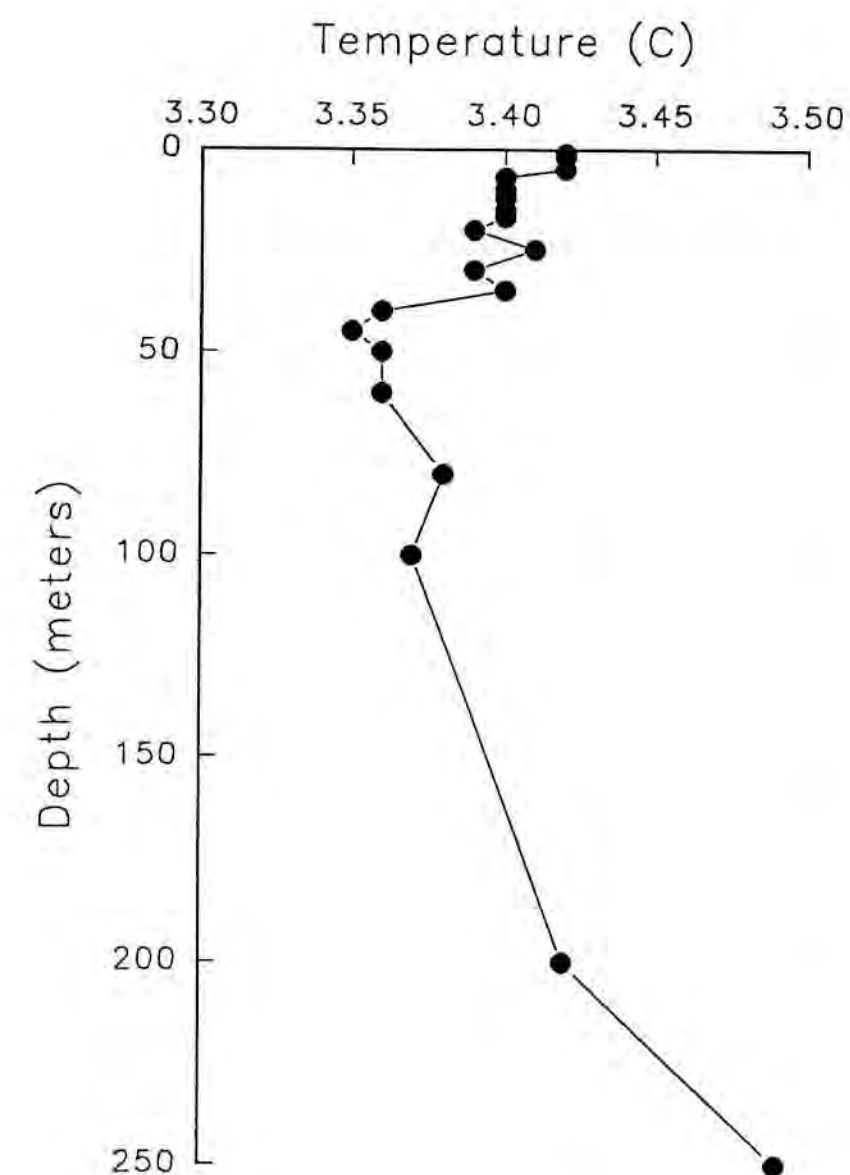


Figure 1. Temperature-depth profile from the water surface to a depth of 250 m at Station 13 in April 1987.

Table 4. Approximate depth of the epilimnion during observed periods of thermal stratification in Crater Lake, 1982-1990.

| Year | Sample Date | Maximum Depth of Epilimnion (meters) |
|------|-------------|--------------------------------------|
| 1982 | August      | 9                                    |
|      | September   | 10                                   |
|      | September   | 11                                   |
| 1983 | September   | 16                                   |
|      | September   | 9                                    |
| 1984 | August      | 8                                    |
|      | August      | 13                                   |
|      | September   | 15                                   |
| 1985 | August      | 14                                   |
|      | September   | 20                                   |
| 1986 | September   | 20                                   |
| 1987 | July        | 10                                   |
|      | September   | 12                                   |
| 1988 | July        | 10                                   |
|      | August      | 12                                   |
|      | September   | 16                                   |
| 1989 | June        | 15                                   |
|      | August      | 10                                   |
|      | September   | 10                                   |
|      | October     | 20                                   |
| 1990 | June        | 10                                   |
|      | July        | 10                                   |
|      | August      | 12                                   |
|      | September   | 15                                   |

generated by storm events in the fall (Table 4). The maximum near-surface water temperature observed in the summer ranged from 14.6° C in 1987 and 1989 to 19.2° C in 1982 (Table 5).

The metalimnion in Crater Lake usually extended to a depth of about 80 m (Figs. 2 and 3). Therefore, most of the water volume in the lake during thermal stratification (i.e., water between the depth of 80 m and the bottom) was part of the cold hypolimnion. The minimum temperature in the water column during thermal stratification was located at approximately 250 m below the surface, and owing to hyperadiabatic processes, water temperature increased slightly with depth below this level. The ambient temperature at the bottom of the lake was about 3.5° C (see Dissolved Oxygen in the Deep Lake section).

Historical data and data obtained during the 10-year study indicated that water temperatures were maximum near the lake surface in August and then decreased in September and October (Fig. 4). Temperatures were lowest in the upper 250 m of the water column in March and April (Figs. 4 - 6). At depths of 20 m and 40 m, water temperature gradually increased from May through the month of October, whereas below 40 m, the mean temperature increased slightly in the spring and remained nearly constant in the summer and fall. Because of the unusual pattern of mixing in the deep lake, seasonal variations in water temperature below a depth of 80 m were less than 1° C (Figs. 5 - 6), and only the upper 50 m of the water column exhibited major seasonal changes in temperature. The long-term pattern (between 1896 and 1990) of the near-surface water temperature for the month of August is presented in Figure 7.

#### pH

The mean hydrogen ion concentration (activity) of 384 water samples collected at Station 13 in Crater Lake between 1982 and 1990 was  $3.13 \times 10^{-8}$  gram-ions per liter with a standard error of  $1.66 \times 10^{-9}$  gram-ions per liter. The pH equivalent of this mean is 7.51. In the upper 20 m of the water column, pH equivalents of mean hydrogen ion concentrations

Table 5. Summary of the water quality of Crater Lake, 1982-1990. Data presented as maximum-minimum values for a period from late June or early July to mid-September. Values for pH, total alkalinity, and conductivity are for all samples obtained between the water surface and a depth of 550 m.

| Variable                        | 1982 <sup>1</sup> | 1983      | 1984                 | 1985      | 1986      | 1987      | 1988      | 1989                 | 1990      |
|---------------------------------|-------------------|-----------|----------------------|-----------|-----------|-----------|-----------|----------------------|-----------|
| <b>Temperature (C):</b>         |                   |           |                      |           |           |           |           |                      |           |
| Surface                         | 12.8-19.2         | 8.8-17.0  | 12.7-17.7            | 11.0-16.6 | 12.4-16.4 | 9.8-14.6  | 10.3-17.4 | 7.9-14.6             | 9.5-18.0  |
| 100 m                           | 3.5-4.2           | 3.9-4.2   | 3.9-4.0              | 4.0-4.3   | 3.8-4.0   | 3.9-4.1   | 4.0-4.2   | 3.9-4.0              | 4.2-4.3   |
| 250 m                           | ---               | 3.7       | 3.6-3.7              | 3.6-3.7   | 3.5-3.7   | 3.5-3.6   | 3.6-3.7   | 3.6-3.7 <sup>3</sup> | 3.7       |
| <b>pH</b>                       |                   |           |                      |           |           |           |           |                      |           |
|                                 | 7.5-7.9           | 6.9-7.9   | 7.0-7.9              | 7.4-8.7   | 7.4-7.9   | 7.4-7.9   | 7.3-8.0   | 7.1-7.9              | 7.4-7.9   |
| <b>Total Alkalinity (mg/l):</b> |                   |           |                      |           |           |           |           |                      |           |
|                                 | 28.8-30.6         | 29.9-30.7 | 27.1-30.5            | 26.5-29.1 | 25.7-27.5 | 26.0-29.1 | 26.8-29.2 | 26.5-28.5            | 24.3-31.1 |
| <b>Conductivity (μmhos/cm):</b> |                   |           |                      |           |           |           |           |                      |           |
|                                 | ---               | 80-122    | 100-125 <sup>2</sup> | 107-120   | 112-120   | 111-119   | 111-119   | 110-121              | 109-120   |
| <b>Dissolved Oxygen (mg/l):</b> |                   |           |                      |           |           |           |           |                      |           |
| Surface                         | 9.3-12.1          | 8.5-11.3  | 8.2-9.5              | 8.5-9.4   | 7.8-9.9   | 7.8-10.1  | 7.4-9.2   | 8.3-9.6              | 7.9-9.6   |
| 110m                            | 11.8-14.4         | 9.3-11.0  | 10.4-11.0            | 9.5-11.4  | 10.5-12.8 | 9.4-10.2  | 9.7-10.3  | 10.1-10.4            | 10.1-10.4 |
| 550m                            | ---               | ---       | ---                  | 10.0-10.4 | 9.2-10.0  | 9.0-9.5   | 9.1-9.2   | 9.2-9.4              | 9.3-9.5   |

<sup>1</sup> 0-300 m, except for temperature.

<sup>2</sup> One surface sample of 166 was omitted because of suspected contamination.

<sup>3</sup> 200 m.

## Temperature Profiles – 1990

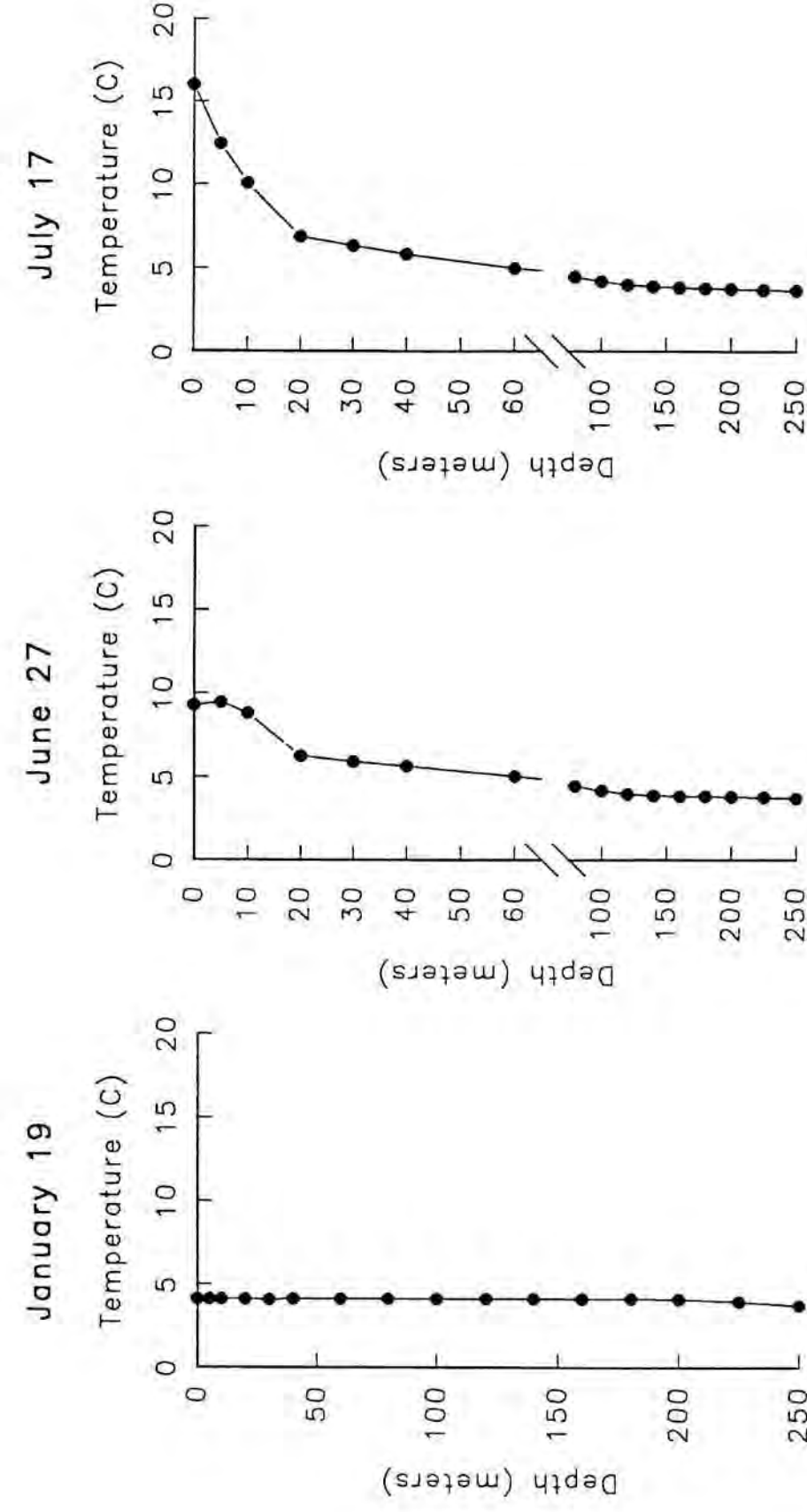


Figure 2. Temperature-depth profiles from the water surface to a depth of 250 m at Station 13 in January, June, and July 1990.

# Temperature Profiles – 1990

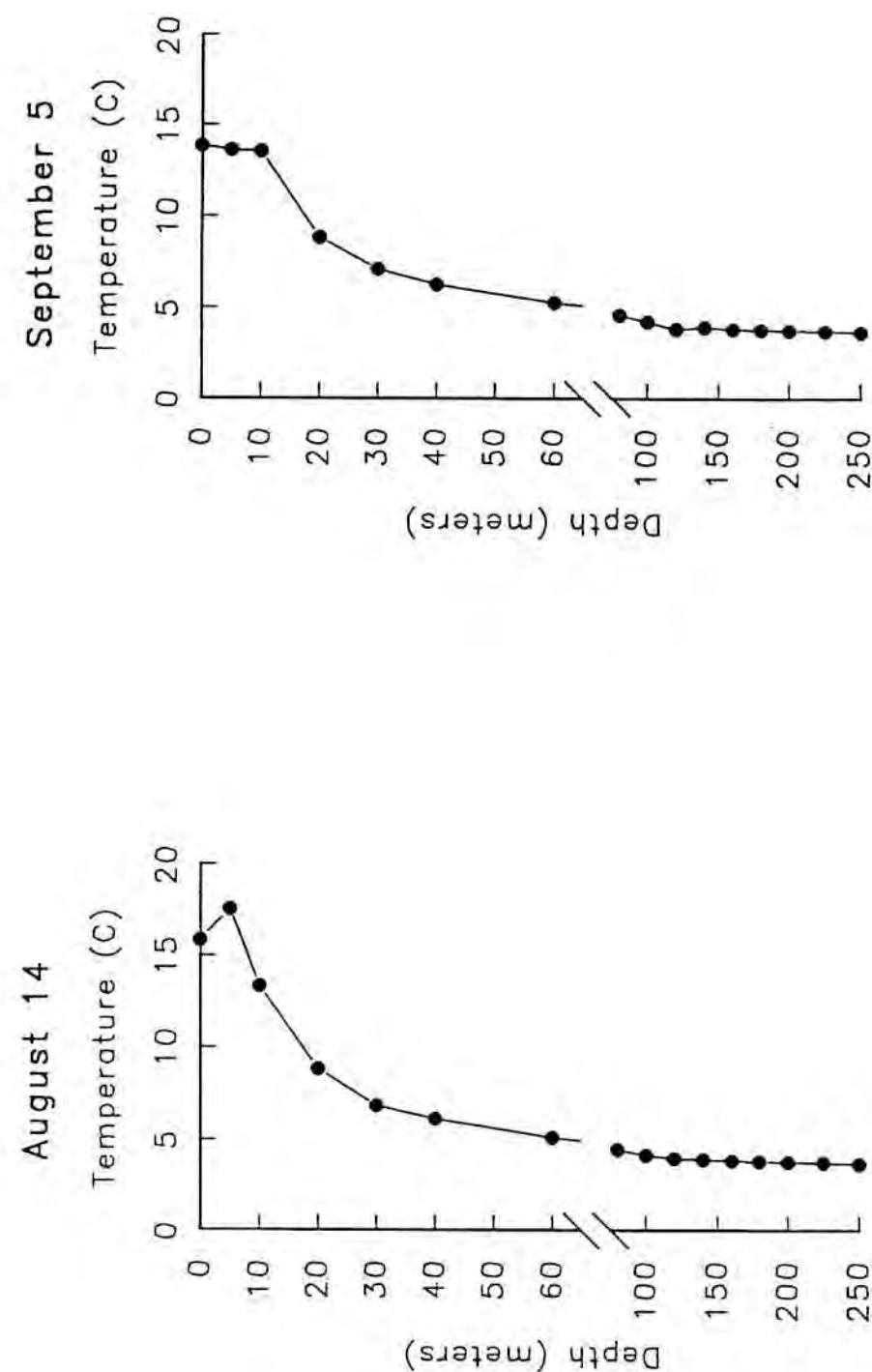


Figure 3. Temperature-depth profiles from the water surface to a depth of 250 m at Station 13 in August and September 1990.

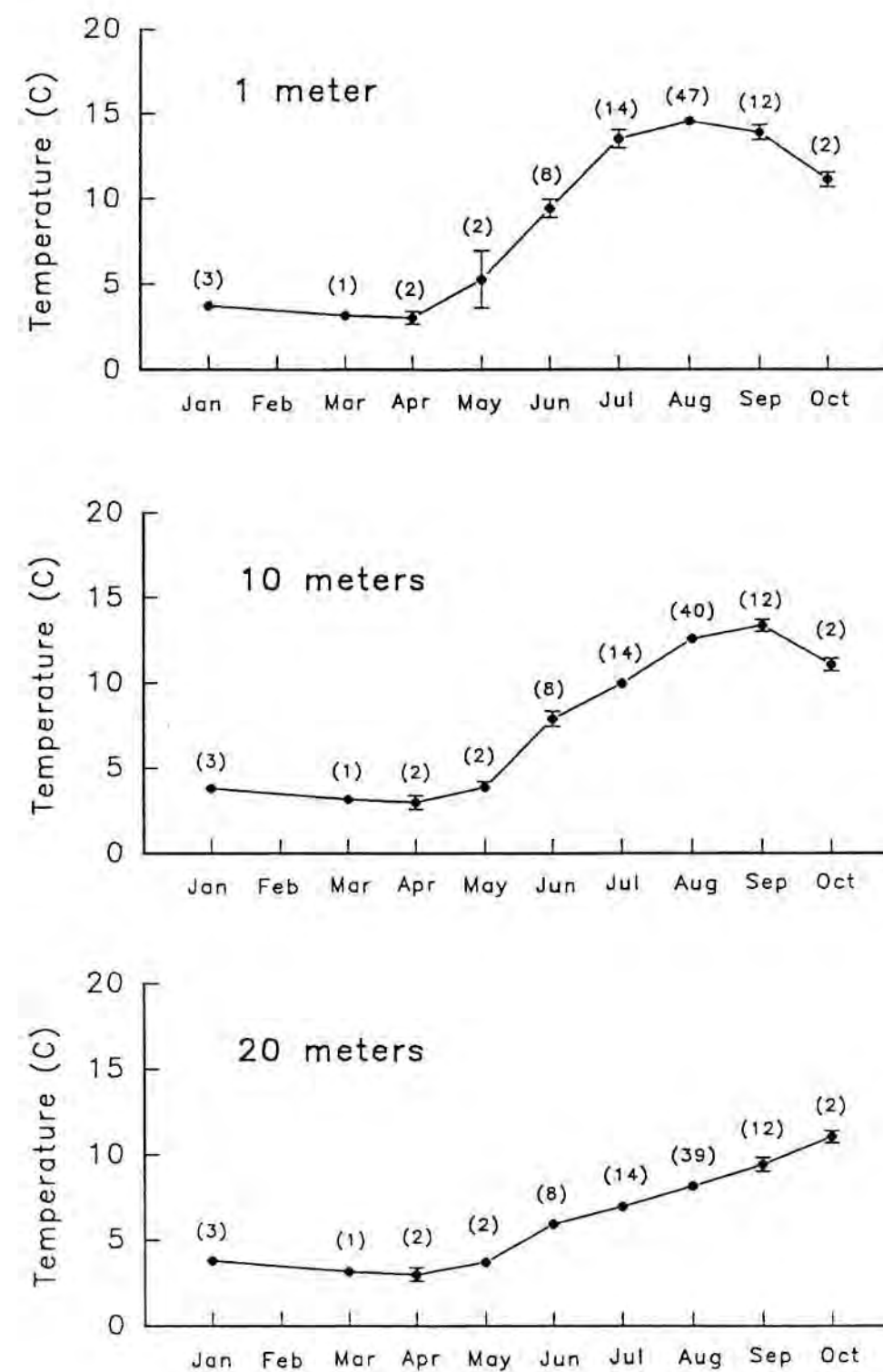


Figure 4. Mean monthly temperatures at the depths of 1 m, 10 m, and 20 m at Station 13 between 1982 and 1990.

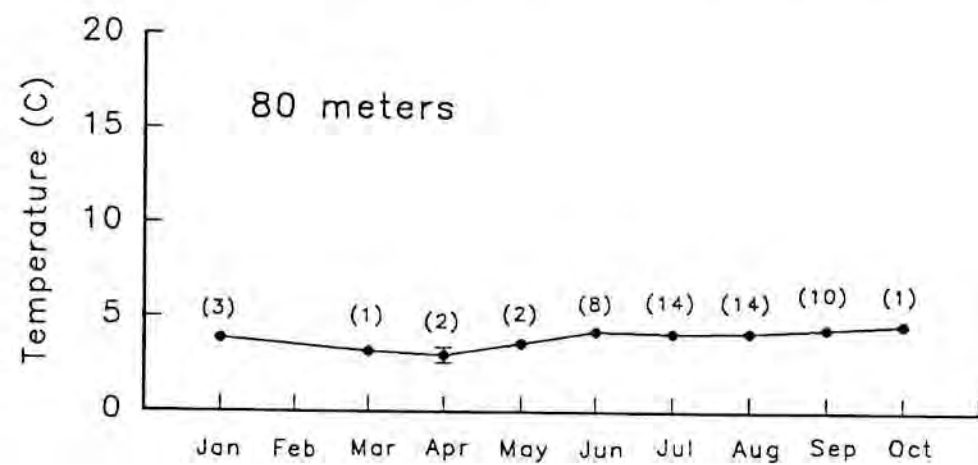
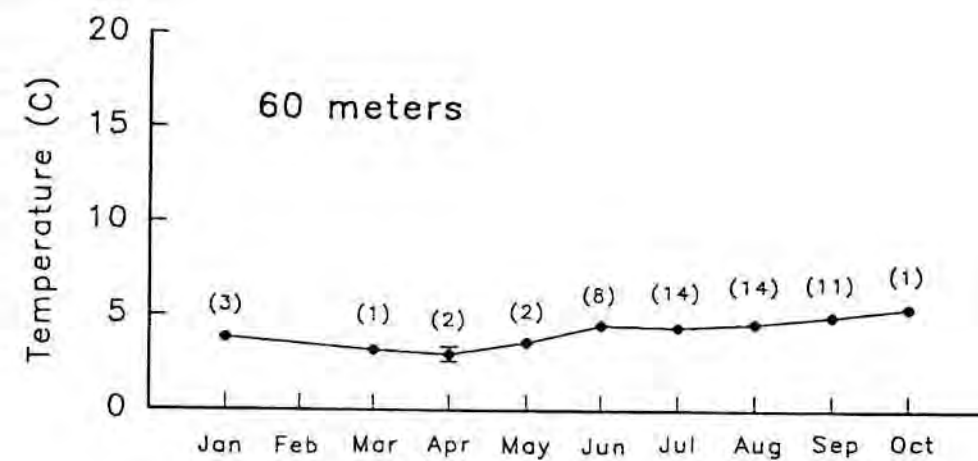
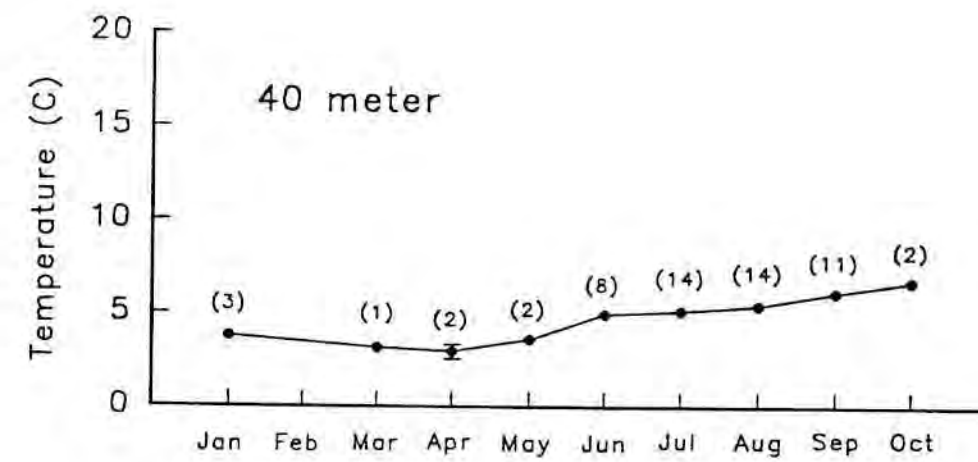


Figure 5. Mean monthly temperatures at the depths of 40 m, 60 m, and 80 m at Station 13 between 1982 and 1990.

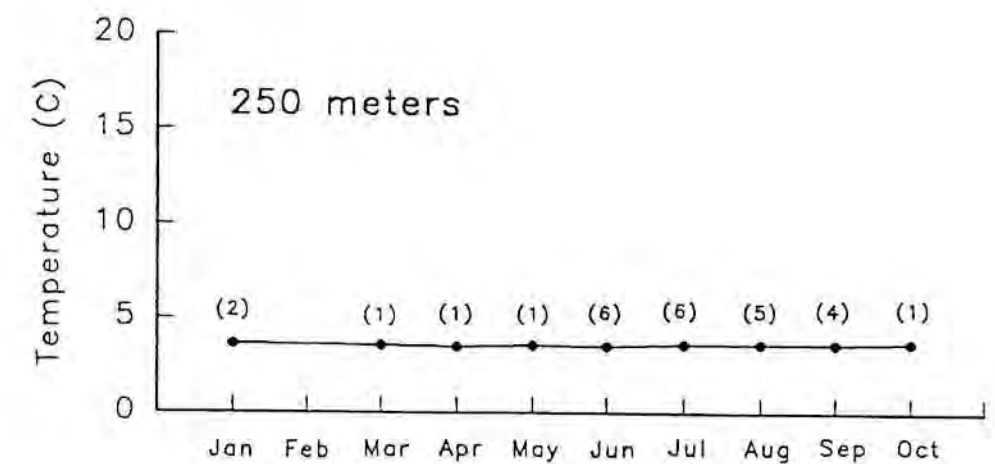
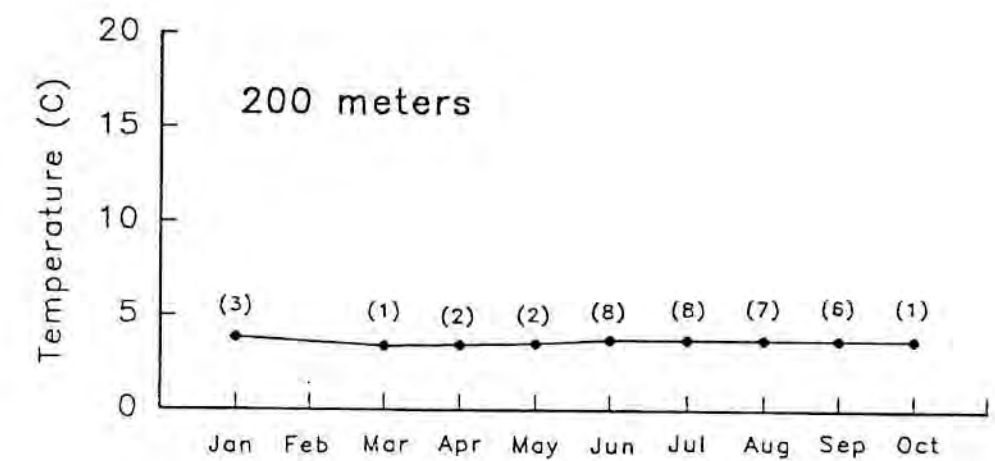
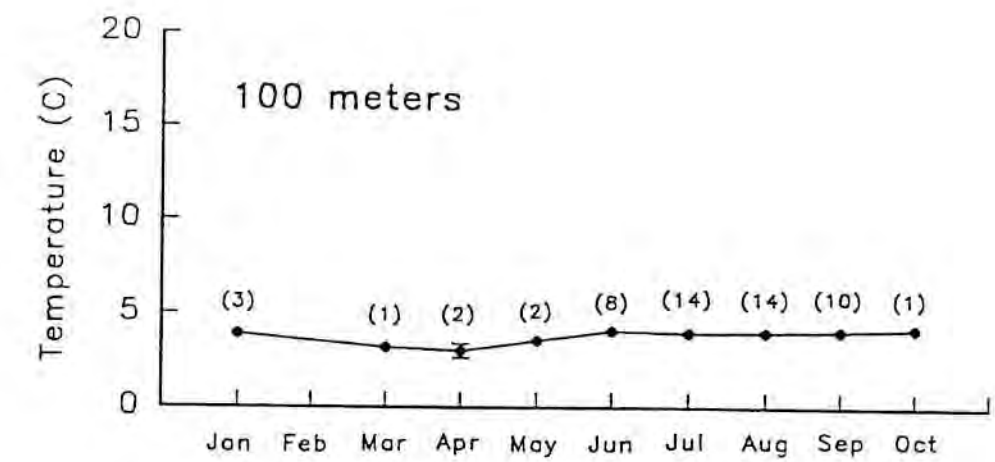


Figure 6. Mean monthly temperatures at the depths of 100 m, 200 m, and 250 m at Station 13 between 1982 and 1990.

## Crater Lake Near-Surface Water Temperature 1895–1990

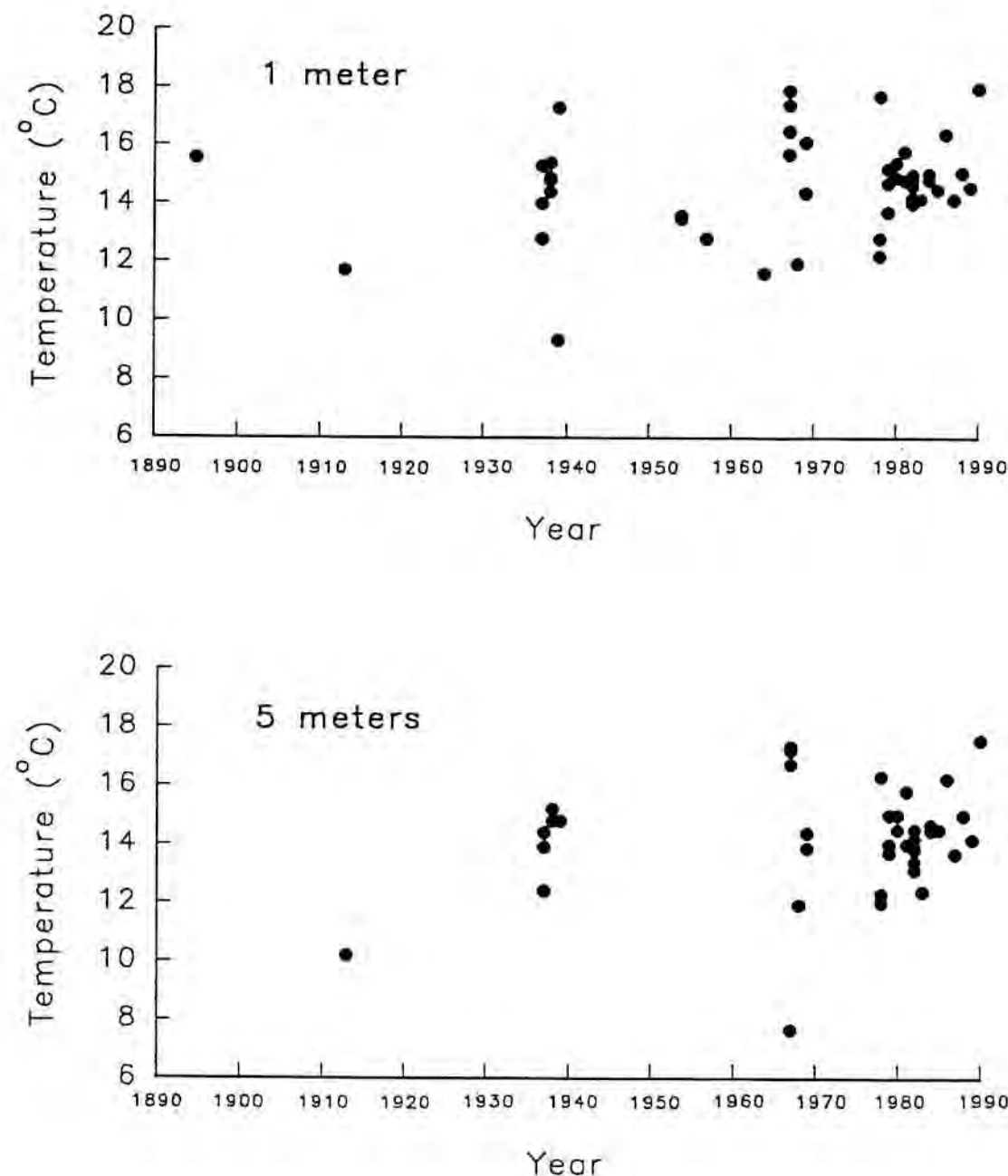


Figure 7. Water temperature in August at depths of 1 m and 5 m below the water surface of Crater Lake between 1895 and 1990.

ranged from about 7.6 to 7.7 (Fig. 8A), whereas in January 1987, 1988 and 1990, corresponding values near the water surface were more variable (Fig. 8B). Below a depth of 20 m, the mean hydrogen ion concentration gradually decreased to a minimum pH equivalent of about 7.3 at a depth of 550 m. The 10-year study (1982-1990) and earlier data collected by the U.S. Geological Survey indicated that there were no obvious changes in the pattern of hydrogen ion activity in the lake since 1961 (Tables 5 and 6).

### Total Alkalinity

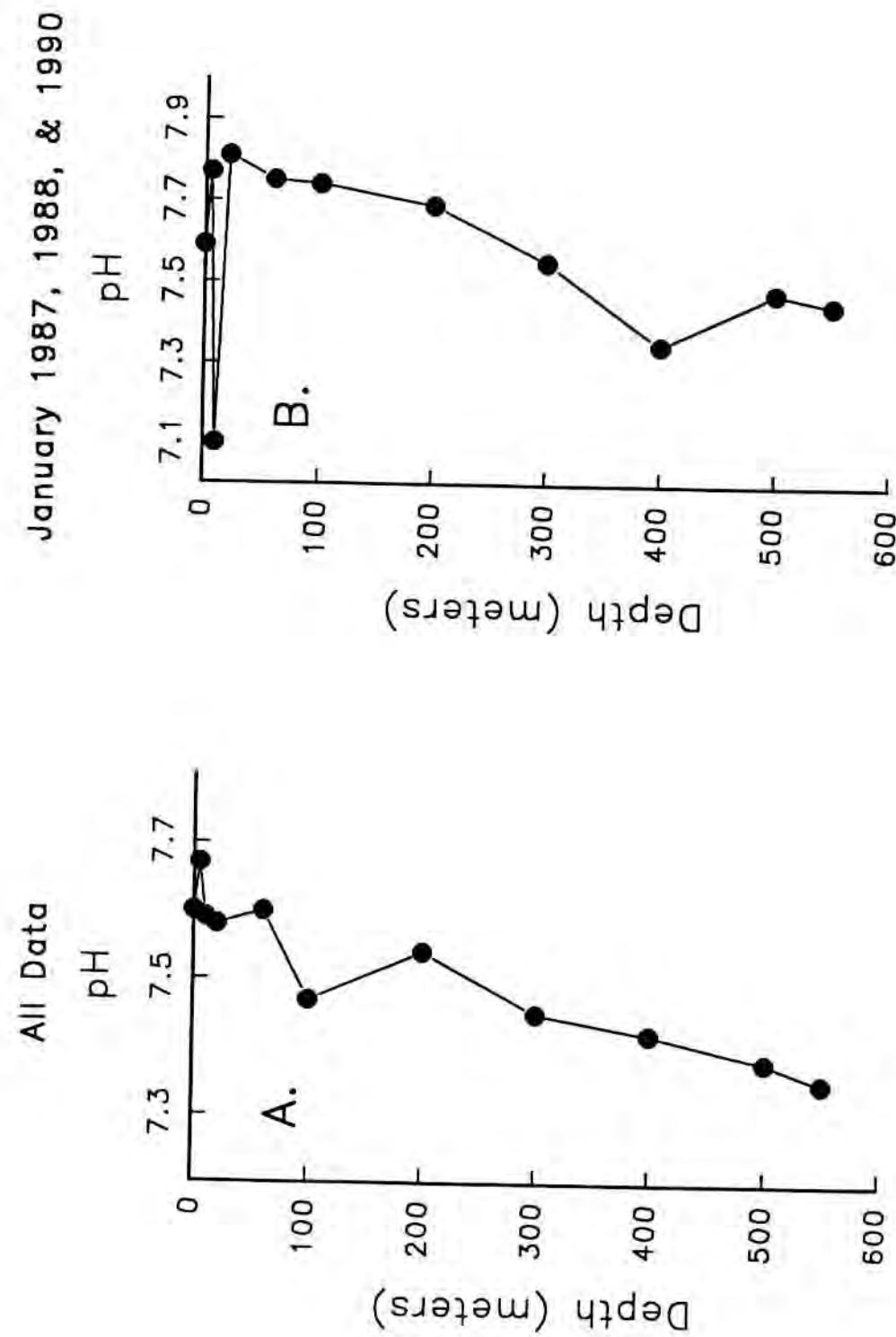
Mean total alkalinity of all water samples collected at Station 13 between 1982 and 1990 was 27 mg/l. The alkalinity of the near-surface water was slightly less than at greater depths, a difference that was more pronounced in the metalimnion during August (Fig. 9). In general, mean total alkalinity was almost constant in the water column between depths of 100 m and 550 m. Moreover, there were no obvious annual changes in the mean total alkalinity of the lake between 1982 and 1990 (Table 5).

### Conductivity

Mean conductivity of all water samples collected at Station 13 between 1982 and 1990 was 115.3  $\mu\text{hos/cm}$ . Conductivity increased between the depths of 200 m and 550 m, reaching a maximum mean value of about 118  $\mu\text{hos/cm}$  near the bottom of the lake (Fig. 10). In the winter and spring the near-surface conductivity was usually lower by 1 or 2  $\mu\text{hos/cm}$  than in the summer and fall when thermal stratification was evident. However, data collected between 1961 and 1990 (Tables 5 and 6) indicated that there were no significant annual changes in the mean conductivity of the lake during this period.

### Dissolved Oxygen

The mean concentration of dissolved oxygen was relatively uniform in the water column of Crater Lake in the spring of the year, while in August, when thermal



Note: Each value represents the pH equivalent of the mean hydrogen ion activity

Figure 8. Mean pH profile from the water surface to a depth of 550 m for all samples (A) and for the January samples (B) collected at Station 13 between 1982 and 1990.

Table 6. Range of selected water quality variables for samples obtained from Crater Lake between 1912 and 1990. All samples were taken near the lake surface from June through September. Conductivity is expressed as  $\mu\text{mhos/cm}$ , pH in standard units, and the elements as mg/l. Values for Ca, Mg, Na, K, and S from the present study were obtained since 1986; data for Si was obtained since 1983.

| Variable     | 1912<br>(Van Winkle & Finkbiner) | 1961-1981<br>(U.S.G.S.) | 1982-1990<br>(Present Work) |
|--------------|----------------------------------|-------------------------|-----------------------------|
| pH           | ---                              | 7.3-7.7                 | 7.1-7.9                     |
| Conductivity | ---                              | 115-118                 | 80-121 <sup>1</sup>         |
| Si           | 8.4                              | 8.0-8.9                 | 7.3-9.3                     |
| Ca           | 7.1                              | 6.7-7.3                 | 6.3-7.8                     |
| Mg           | 2.8                              | 2.6                     | 2.6-2.9                     |
| Na           | 11                               | 10-12                   | 10-11                       |
| K            | 2.2                              | 1.7-1.8                 | 1.5-1.9                     |
| S            | 3.7                              | 3.3-3.7                 | 3.1-3/6                     |

<sup>1</sup>Anomalously high value (166  $\mu\text{mhos/cm}$ ) measured in July 1984 was omitted.

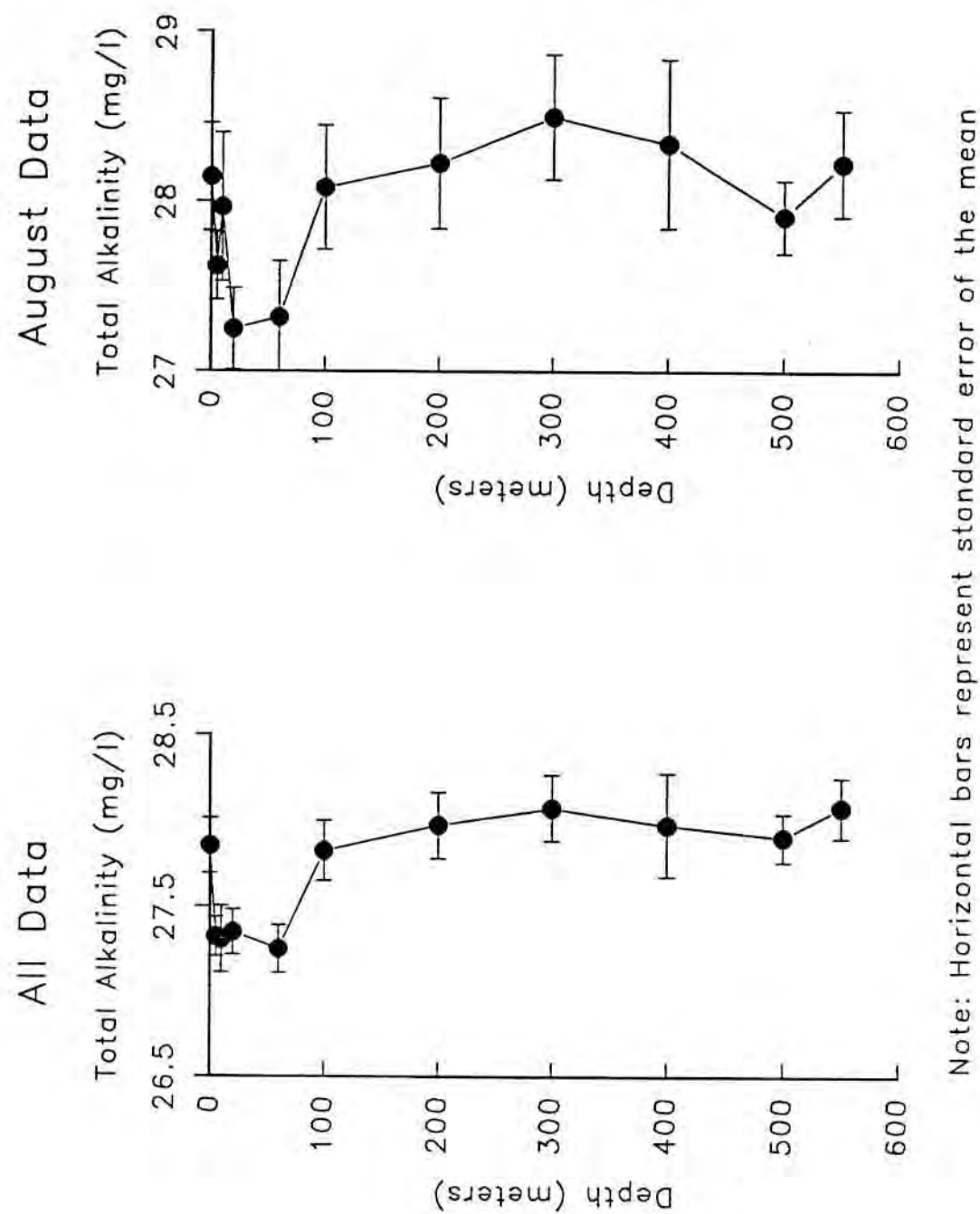


Figure 9. Mean total alkalinity depth profile from the water surface to a depth of 550 m for all samples and for the August samples collected at Station 13 between 1982 and 1990.

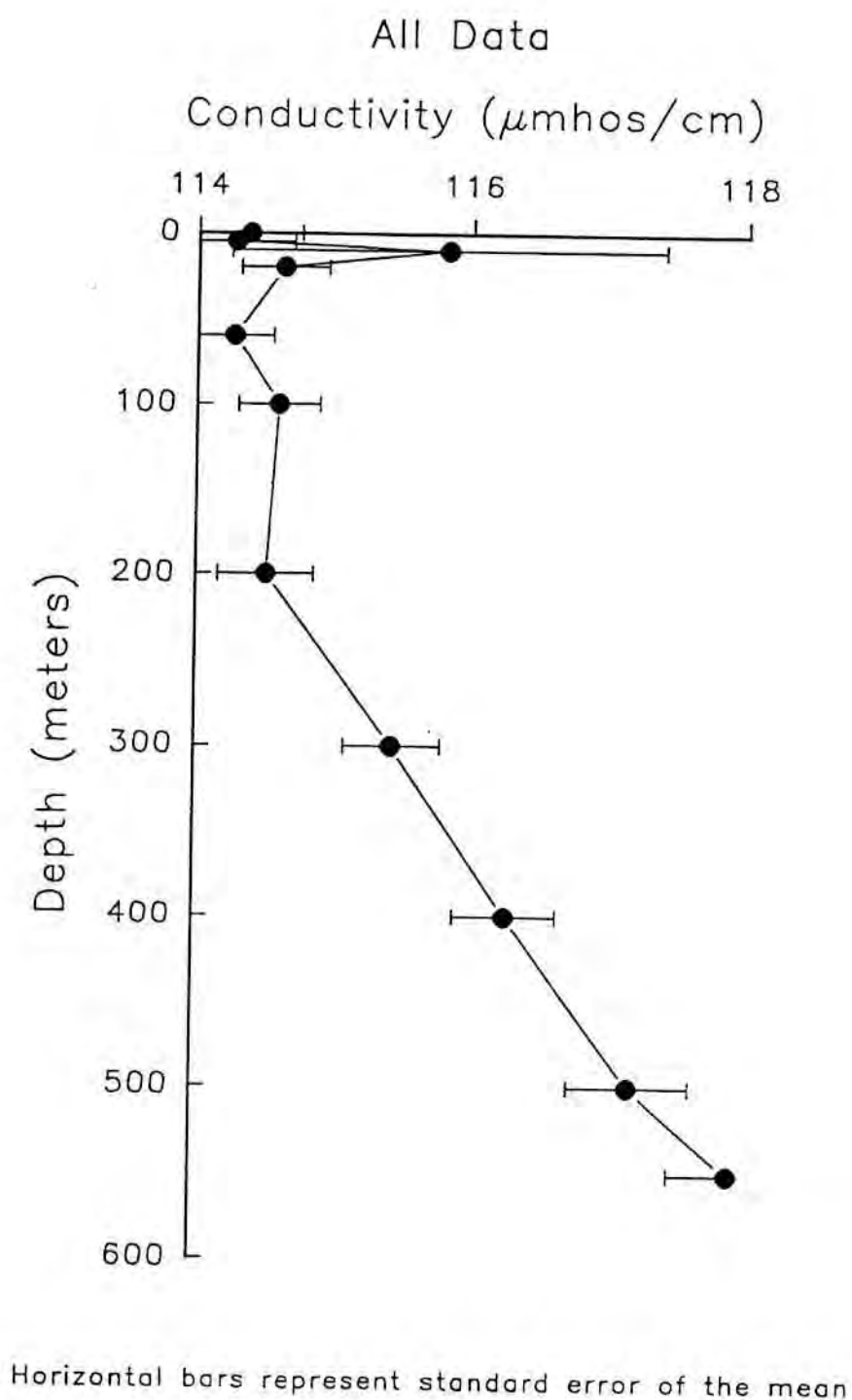


Figure 10. Mean conductivity depth profile from the water surface to a depth of 550 m for all samples collected at Station 13 between 1986 and 1991.

stratification was present, the mean concentration exhibited an orthograde profile in the upper 250 m of the water column (Fig. 11). Below a depth of 250 m, there was a slight decrease in the concentration of dissolved oxygen with increasing depth, a pattern that was more evident in the summer than at other seasons of the year. When thermal stratification occurred, the upper 20 m of the water column usually remained supersaturated with oxygen, often between 105% and 119%, whereas the percentage saturation below 100 m was slightly less than 100% and decreased with depth to about 90% near the bottom of the lake (Fig. 12). Furthermore, the spatial and seasonal patterns of dissolved oxygen in the lake did not exhibit appreciable changes between 1982 and 1990 (Table 5).

### Nutrients and Cations

Concentrations of nutrients and cations exhibited little temporal and spatial variation during the 10-year study (1982 - 1990). Orthophosphate phosphorus, nitrate nitrogen, sodium, magnesium, calcium, silicon, and sulfate sulfur increased in concentration with an increase in depth and reached maximum concentrations between a depth of 500 m and the lake bottom (Figs. 13 - 16, Table 7). Nitrate nitrogen was usually below the limits of detection in the upper 200 m of the water column, while Kjeldahl and organic nitrogen decreased in concentration between the depths of 100 m and 500 m (Figs. 13 and 14). All data collected from 1912 to 1990 indicate that there has been very little variation in the annual mean concentrations of nutrients and cations during the past 68 years (Table 6). Without a more intensive sampling regime than the one used in this study (i.e., monthly or biweekly throughout the year), the dynamics of these nutrient profiles is not possible to describe.

### Discussion

Crater Lake is unique among the lakes in the Cascade Mountains of Oregon in that it almost always remains free of ice and snow during winter months. Apparently, the large volume of water in the lake retains enough heat in the winter to keep it free of ice and

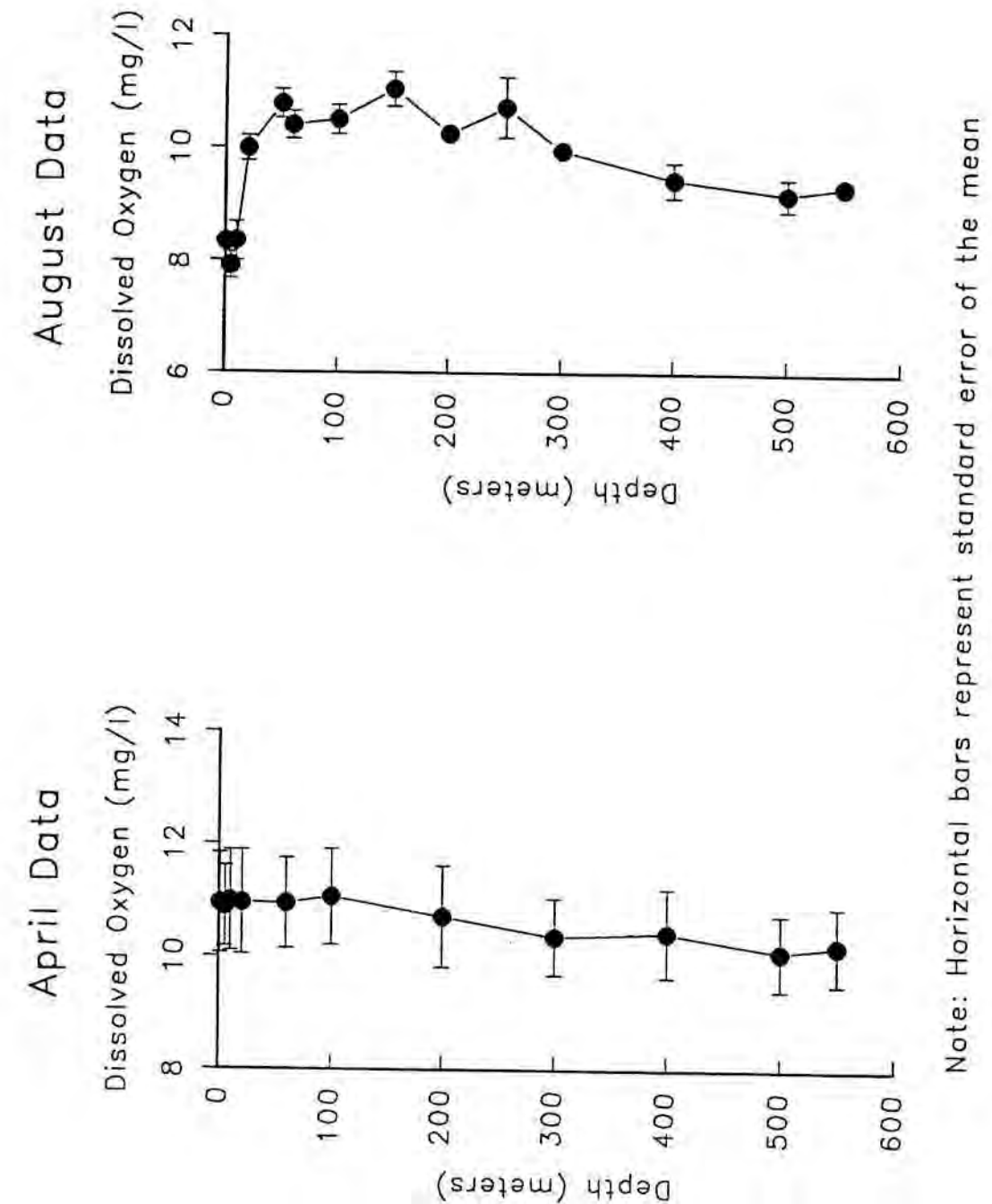
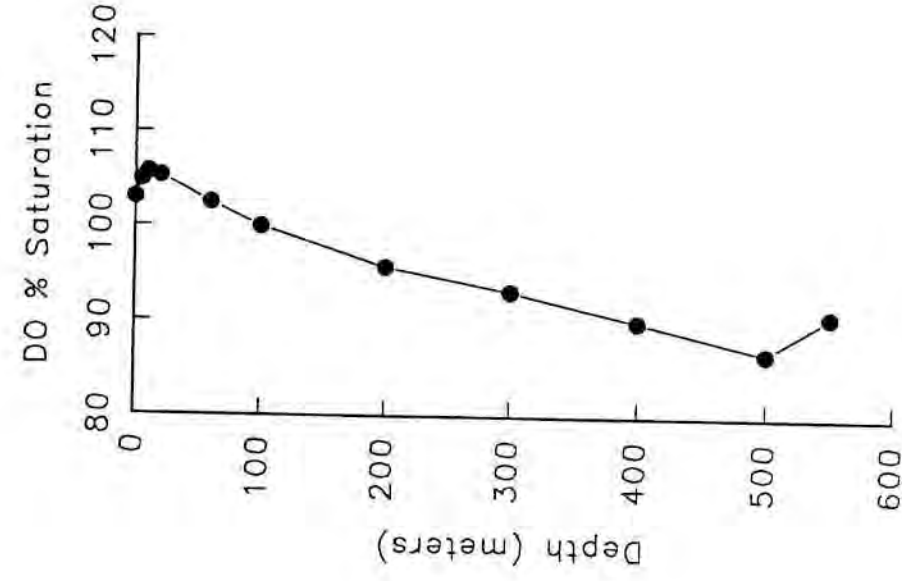


Figure 11. Mean dissolved oxygen depth profile from the water surface to a depth of 550 m for samples collected at Station 13 in April and August between 1982 and 1991.

July 17, 1990



August 14, 1990

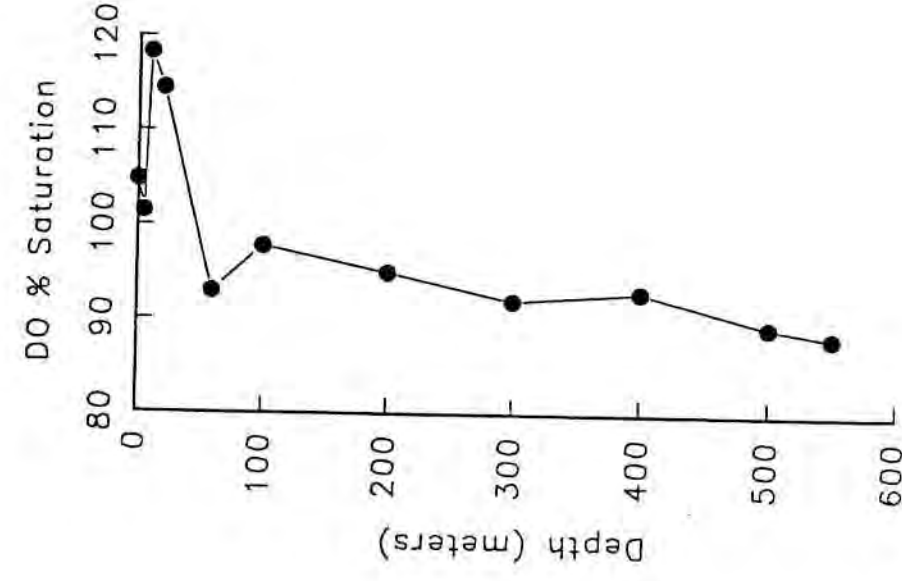
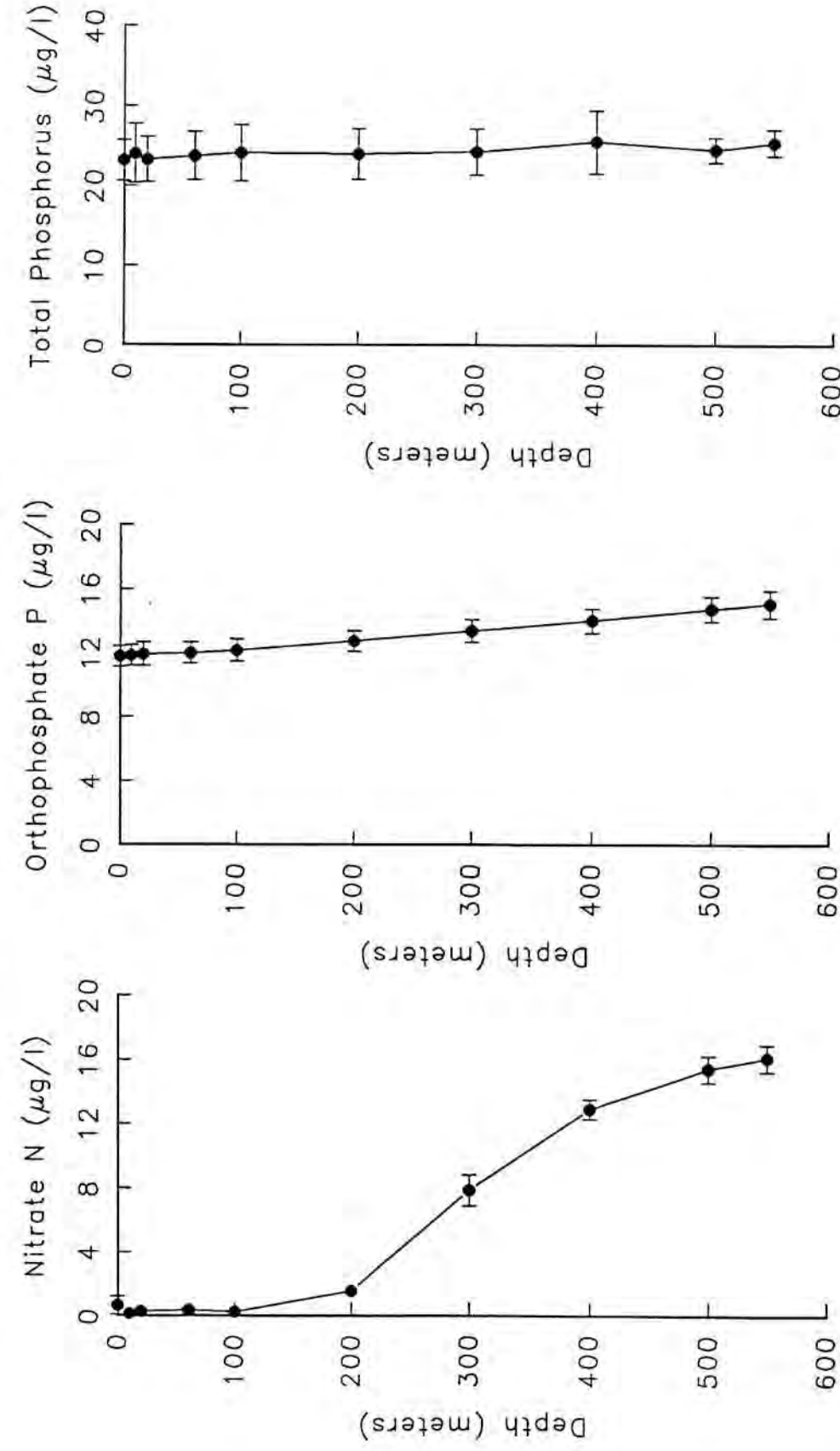


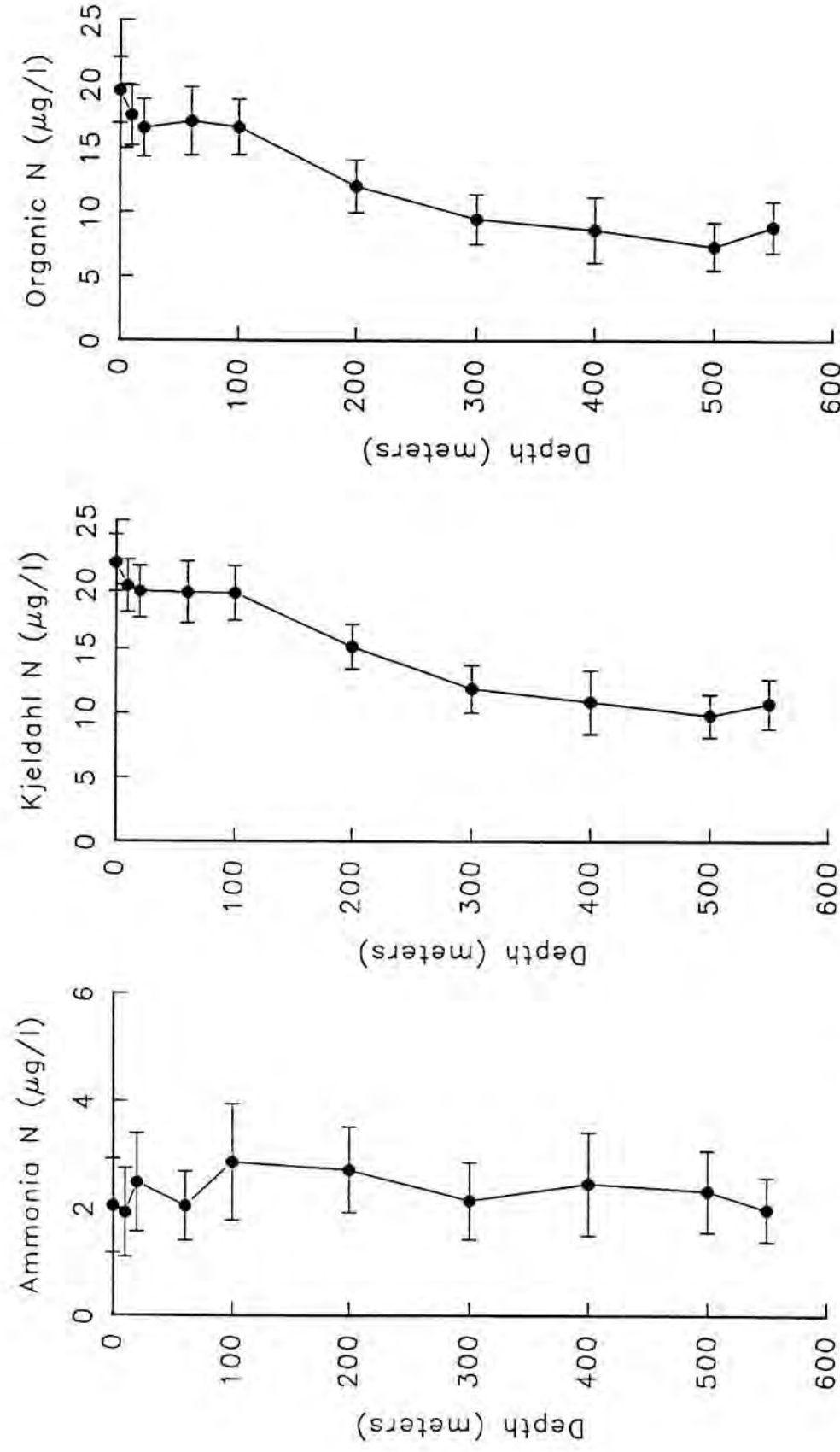
Figure 12. Dissolved oxygen depth profile, expressed as percentage saturation, from the water surface to a depth of 550 m for samples collected on July 17, 1990, and August 14, 1990, at Station 13.

## Water Column Nutrients 1983 - 1991



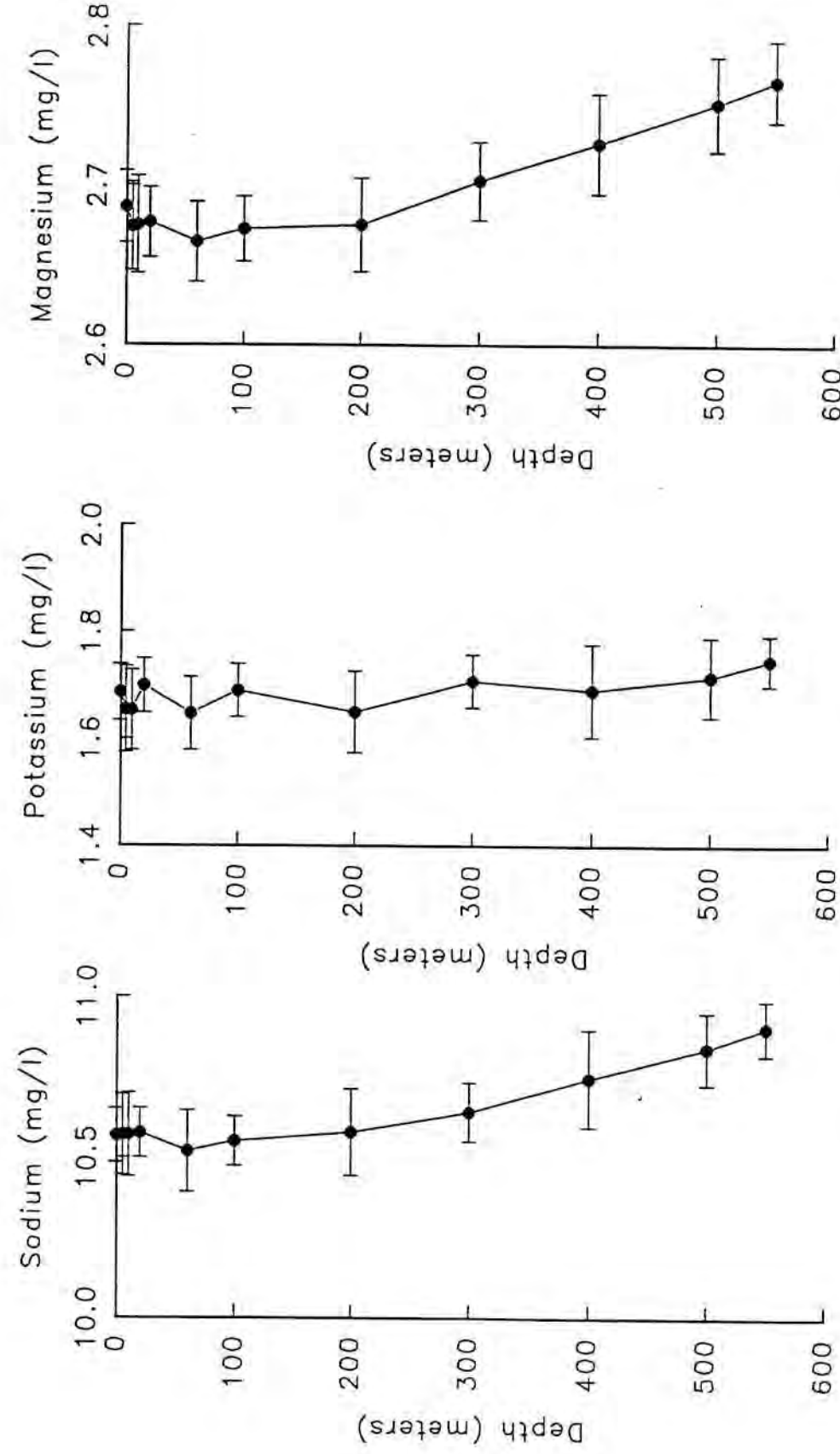
Note: Error bars represent 95% confidence interval

Figure 13. Depth profiles of mean concentrations of nitrate-N, orthophosphate-P and total phosphorus from the water surface to a depth of 550 m for all samples collected at Station 13 between 1983 and 1991.



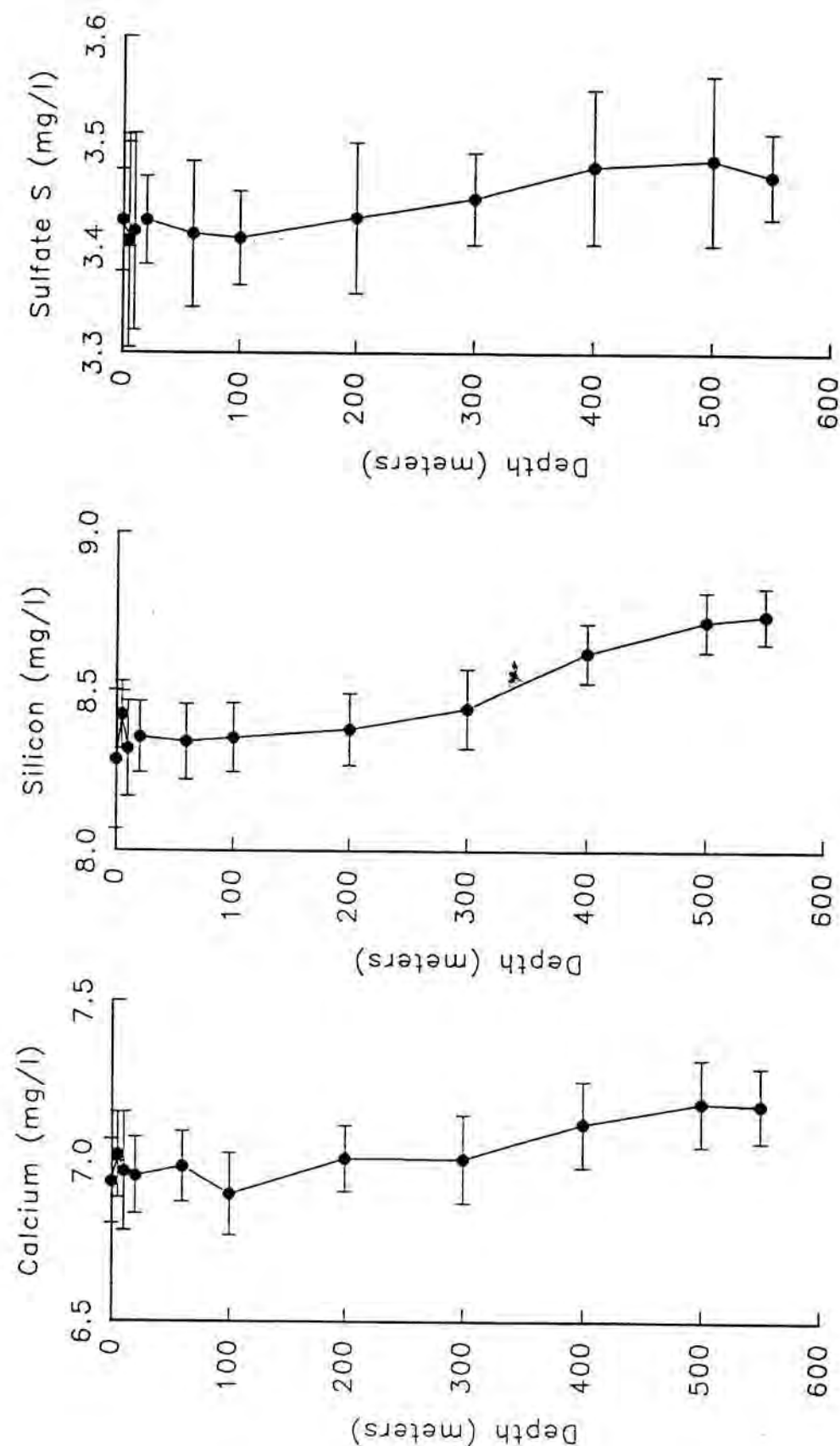
Note: Error bars represent 95% confidence interval

Figure 14. Depth profiles of mean concentrations of ammonia-N, Kjeldahl-N and organic-N from the water surface to a depth of 550 m for all samples collected at Station 13 between 1983 and 1991.



Note: Error bars represent 95% confidence interval

Figure 15. Depth profiles of mean concentrations of sodium, potassium and magnesium from the water surface to a depth of 550 m for all samples collected at Station 13 between 1986 and 1990.



Note: Error bars represent 95% confidence interval

Figure 16. Depth profiles of mean concentrations of calcium, silicon, and sulfate-S from the water surface to a depth of 550 m for all samples collected at Station 13 between 1983 and 1991.

Table 7. Mean concentrations of selected chemical variables for all samples obtained from the indicated depth intervals in Crater Lake, 1982-1990.

| Variable                             | Depth Interval (meters) |         |       |
|--------------------------------------|-------------------------|---------|-------|
|                                      | 0-200                   | 200-550 | 0-550 |
| Nitrate N ( $\mu\text{g/l}$ )        | 0.61                    | 10.62   | 6.98  |
| Ammonia-N ( $\mu\text{g/l}$ )        | 2.55                    | 2.34    | 2.41  |
| Kjeldahl-N ( $\mu\text{g/l}$ )       | 18.52                   | 11.55   | 14.08 |
| Organic N ( $\mu\text{g/l}$ )        | 15.68                   | 9.09    | 11.49 |
| Orthophosphate P ( $\mu\text{g/l}$ ) | 12.21                   | 13.88   | 13.27 |
| Total phosphorus ( $\mu\text{g/l}$ ) | 28.22                   | 29.59   | 29.09 |
| Sodium (mg/l)                        | 10.56                   | 10.72   | 10.66 |
| Calcium (mg/l)                       | 6.96                    | 7.09    | 7.04  |
| Magnesium (mg/l)                     | 2.67                    | 2.72    | 2.70  |
| Potassium (mg/l)                     | 1.67                    | 1.70    | 1.69  |
| Silicon (mg/l)                       | 8.36                    | 8.57    | 8.49  |
| Sulfate S (mg/l)                     | 3.42                    | 3.46    | 3.45  |

snow (Hutchinson 1957). The ice cover at times in 1985 and 1986 was unusual. The last reported occurrence of an ice cover prior to the 10-year study was in 1949 (unpublished park records). During the three recorded periods when ice was observed on the lake (i.e., winters of 1949, 1985, and 1986), the weather was described as clear and extremely cold, while the lake surface was flat and calm.

Wind action and cooling usually mixes the water column of Crater Lake to a depth of about 250 m. A similar depth of mixing has been reported in Lake Tahoe for most years (Goldman and de Amezaga 1975). However, unlike Crater Lake, the water column in Lake Tahoe undergoes complete mixing when certain weather conditions are present (i.e., very large storm events during February or March when the lake is isothermal). Also, the thermocline in Lake Tahoe occasionally is disrupted for short periods of time in summer when energy inputs from wind action are high enough to break down stratification. Complete mixing of the water column in the winter and disruption of thermal stratification in the summer was not observed in Crater Lake, probably because of the relatively short fetch (8 km), and small surface area (53.2 km<sup>2</sup>), and great depth of the lake.

According to Hutchinsons (1957) classification, Crater Lake is a meromictic lake because some water below the depth of 250 m remains partly unmixed with the main water mass when the lake circulates. However, there is some mixing in Crater Lake in the winter and early spring each year when the relatively cold, dense water near the surface sinks and exchanges positions with water in the deep basins of the lake. This process moves nutrient-rich water from locations in the deep lake to the upper 250 m of the water column (see Lake Circulation and Hydrothermal Properties sections), an upwelling phenomenon that is undoubtedly coupled to patterns of primary and secondary production. In addition, the relatively stable thermocline in Crater Lake affects patterns of primary productivity by preventing an occasional recirculation of recycled nutrients into the euphotic zone during the summer and early fall as observed in Lake Tahoe (Abbott et al. 1984). Also, because of the great clarity of the lake, the stability of the epilimnion probably has an important effect on the solar heating of the metalimnion and the vertical distribution of phytoplankton and zooplankton (see Phytoplankton and Zooplankton sections).

Oligotrophic lakes typically are more transparent and lower in concentrations of nutrients and dissolved salts than lakes of higher productivity (Wetzel 1975, Goldman

1983). In oligotrophic lakes, concentrations of dissolved oxygen and nitrate often exhibit orthograde depth profiles during thermal stratification, whereas total phosphorus and ammonia are relatively uniform in concentration throughout the water column (Wetzel 1975). Concentrations of total phosphorus and inorganic nitrogen in the epilimnion of oligotrophic lakes are usually less than 5 µg/l and 200 µg/l, respectively (Wetzel 1975). Chemical and physical properties of Crater Lake that are most consistent with typical oligotrophic characteristics include high transparency, orthograde dissolved oxygen and nitrate depth profiles, and low concentrations of nitrate in the epilimnion. However, cation concentrations in Crater Lake often exceed those in other eutrophic, mesotrophic, and oligotrophic lakes in the Cascade Mountains of Oregon, and are more similar to mean concentrations reported for the streams and lakes of the world (Table 8). High concentrations of cations in Crater Lake, as well as in the other two caldera lakes included in Table 8 (East Lake and Paulina Lake), are associated with inputs of hydrothermal fluids (see Chemical Solute Mass Balance and Hydrothermal Properties sections). However, in comparison to other caldera lakes, concentrations of cations in Crater Lake, East Lake, and Paulina Lake are low (Larson 1989). Furthermore, the relatively high concentrations of total phosphorus reported for Crater Lake are in the range usually associated with mesotrophic lakes (Wetzel 1975). Therefore, the chemical and physical properties of Crater Lake are unique and do not conform to the entire range of criteria usually associated with oligotrophic status.

## References

- Abbott, M. R., K. L. Denman, T. M. Powell, P. J. Richerson, R.C. Richards and C. R. Goldman. 1984. Mixing and the dynamics of the deep chlorophyll maximum in Lake Tahoe. *Limnology and Oceanography* 29: 862-878.
- Goldman, C. R., and E. de Amezaga. 1975. Spatial and temporal changes in the primary productivity of Lake Tahoe, California-Nevada between 1959 and 1971. *Verh. Internat. Verein. Limnol.* 19: 812-825.

Table 8. Concentrations of selected chemical variables in water samples from near surface waters of eutrophic (E), mesotrophic (M), and oligotrophic (O) lakes in the Cascade Mountains of Oregon. Data for the State of Oregon were obtained from Johnson et al. (1985), while worldwide averages were taken from a publication by Livingstone (1963).

| Lake                | Class | Elevation (m) | Area (ha) | Depth (m) | Alkalinity (mg/l) | Cond (µmhos/cm) | pH      | T-Phos (µg/l) | Na (mg/l) | K (mg/l) | Ca (mg/l) | Mg (mg/l) | Cl (mg/l) | Sulfate (mg/l) |
|---------------------|-------|---------------|-----------|-----------|-------------------|-----------------|---------|---------------|-----------|----------|-----------|-----------|-----------|----------------|
| Diamond             | E     | 1579.8        | 1300.7    | 15.8      | 15                | 29              | 9.5     | 61            | 3.2       | 0.8      | 2.3       | 1.1       | 0.9       | 0.3            |
| Suttle              | E     | 1047.9        | 102.4     | 22.9      | 15                | 50              | 8.4     | 24            | 2.5       | 0.8      | 4.0       | 1.8       | 0.6       | 1.6            |
| East                | M     | 1941.6        | 422.5     | 54.9      | 103               | 310             | 7.9     | 16            | 23.1      | 4.0      | 24.3      | 11.8      | 0.9       | 82.7           |
| Gold                | M     | 1467.0        | 38.9      | 13.1      | 16                | 33              | 7.3     | 47            | 2.1       | 0.8      | 3.2       | 1.0       | 0.5       | 0.7            |
| Marion              | M     | 1258.8        | 105.6     | 56.4      | 18                | 37              | 8.8     | 33            | 2.6       | 1.1      | 4.4       | 1.5       | 0.9       | 0.7            |
| Odeil               | M     | 1459.1        | 1449.6    | 86.0      | 13                | 32              | 9.3     | 28            | 2.4       | 0.8      | 2.8       | 0.9       | 0.7       | 0.3            |
| Paulina             | M     | 1929.7        | 619.6     | 76.2      | 340               | 560             | 8.3     | 45            | 4.5       | 5.4      | 25.9      | 36.4      | 3.5       | 5.1            |
| Big                 | O     | 1415.5        | 76.9      | 23.5      | <1                | 4               | 7.2     | 2             | 0.3       | 0.1      | 0.8       | 0.3       | 0.6       | <0.1           |
| Blue                | O     | 1052.5        | 21.9      | 95.7      | 16                | 50              | 6.9     | 29            | 2.6       | 0.9      | 4.3       | 2.0       | 0.6       | <0.1           |
| Breitenbush         | O     | 1676.4        | 26.3      | 7.6       | <1                | 6               | 7.6     | —             | 0.5       | 0.1      | 0.7       | 0.2       | 0.4       | 0.2            |
| Charlton            | O     | 1734.9        | 63.1      | 29.0      | 2                 | 6               | 6.8     | 4             | 0.4       | 0.1      | 0.5       | 0.1       | 0.4       | 0.8            |
| Crescent            | O     | 1474.9        | 1840.2    | 80.8      | 11                | 26              | 7.6     | 62            | 1.7       | 0.9      | 2.4       | 0.9       | —         | 0.8            |
| Deer                | O     | 1492.3        | 21.0      | 7.9       | 3                 | 12              | 6.5     | 17            | 0.9       | 0.3      | 1.1       | 0.4       | 0.7       | 0.7            |
| Devils              | O     | 1638.1        | 9.3       | 3.0       | 10                | 25              | —       | 72            | 2.4       | 0.9      | 1.4       | 0.9       | 0.7       | <0.1           |
| Doris               | O     | 1618.5        | 27.9      | 29.0      | <1                | 4               | —       | 3             | 0.3       | 0.1      | 0.5       | 0.1       | 0.6       | 0.4            |
| Hartette            | O     | 2057.4        | 16.2      | 24.1      | <1                | 3               | —       | 9             | 0.2       | 0.1      | 0.5       | 0.1       | 0.6       | 0.5            |
| Lost                | O     | 958.0         | 93.5      | 53.3      | 2                 | 12              | 6.6     | 6             | 0.8       | 0.1      | 1.1       | 0.4       | 1.6       | 0.3            |
| Ollalie             | O     | 1504.5        | 76.1      | 13.1      | <1                | 3               | —       | 8             | 0.3       | 0.0      | 0.4       | 0.1       | 0.5       | 0.1            |
| Summit              | O     | 1692.6        | 195.1     | 19.2      | <1                | 6               | 6.7     | 9             | 0.2       | 0.1      | 0.1       | 0.1       | 0.3       | 0.2            |
| Waldo               | O     | 1650.2        | 2848.8    | 128.0     | <1                | 3               | 6.3     | 9             | 0.2       | 0.0      | 0.4       | 0.1       | 0.6       | 0.3            |
| Crater              | O     | 1882.4        | 5317.4    | 588.9     | 40                | 108             | 7.2     | 17            | 11.0      | 1.8      | 9.3       | 2.7       | 9.0       | 12.4           |
| Crater <sup>1</sup> | O     | 1882.4        | 5317.4    | 588.9     | 26-30             | 80-121          | 7.1-7.9 | 13-43         | 10-11     | 1.5-1.9  | 6.3-7.8   | 2.6-2.9   | —         | 9.4-10.8       |
| Worldwide Mean      | —     | —             | —         | —         | —                 | —               | —       | —             | 6.3       | 2.3      | 15.0      | 4.1       | 7.8       | 11.2           |

<sup>1</sup>Data from the 10-year study.

- Goldman, C. R., and A. J. Horne. 1983. *Limnology*. McGraw-Hill, Inc., New York 464 pp.
- Hutchinson, G. E. 1957. *A Treatise on Limnology*. Vol. 1. Geography, Physics and Chemistry. John Wiley, New York. 1015 pp.
- Johnson, D. M., R. R. Peterson, D. R. Lycan, J. W. Sweet, and M. E. Neuhaus. 1985. *Atlas of Oregon Lakes*. Oregon State University Press, Corvallis. 317 pp.
- Larson, G. L. 1986. *Crater Lake limnological studies: 1985 annual report*. National Park Service, Cooperative Park Studies Unit, Oregon State University, Corvallis. 73 pp.
- Larson, G. L. 1987. *Crater Lake limnological studies: 1986 annual report*. National Park Service, Cooperative Park Studies Unit, Oregon State University, Corvallis. 81 pp.
- Larson, G. L. 1989. Geographical distribution, morphology, and water quality of caldera lakes: A review. *Hydrobiologia* 171: 23-32.
- Van Winkle, W., and N. M. Finkbiner. 1913. Composition of the water of Crater Lake, Oregon. *Journal of Industrial Engineering and Chemistry* 4: 158-199.
- Wetzel, R. G. 1975. *Limnology*. W. B. Saunders Company, Philadelphia, Penn. 743 pp.

## Water Chemistry of Caldera Springs

Stanley V. Gregory, Gary L. Larson, C. David McIntire, and Mark Buktenica

The caldera walls surrounding Crater Lake contain numerous ephemeral and perennial springs that deliver surface water into the lake. Sixty-three springs were identified in early hydrologic studies of Crater Lake by Diller and Patton (1902). These springs emerge at different heights above the lake surface, some running hundreds of meters before reaching the lake and others emerging less than 50 m above the lake. These caldera springs have extremely high gradient channels which range from 50-140% and flow over talus slopes and avalanche tracks (Gregory et al. 1990). The bed material and high gradients make these channels extremely unstable, and substrates shift readily and exhibit little armoring of the streambed.

The geology of the caldera rim is extremely complex, reflecting the multiple events that shaped Mount Mazama and Crater Lake starting more than 400,000 years before present (B.P.). Numerous andesitic and dacitic flows shaped the flanks of the mountain, and dykes reveal intrusions of magma such as the remnant of an old cone at Phantom Ship on the southeast corner of the lake (Bacon and Lanphere 1990). In addition, four major glacial episodes have modified the landforms of Mount Mazama, the most recent and evident associated with Pleistocene glaciation from 10,000-25,000 years B.P. (Cranson 1982).

Stream flow in the caldera springs is dominated by snowmelt hydrology, with maximum discharge occurring during late spring and low flows occurring from late summer through winter under snowpack. Early studies estimated a total discharge of 10.75 cfs (cubic feet per second) from all springs surrounding the lake during July 1901

(Diller and Patton 1902). No continuous hydrologic measurements are available for any caldera spring, but the U.S. Geological Survey has maintained a gaging station at Annie Spring on the outer flank south of the caldera since 1979. This stream exhibits runoff patterns typical of snowmelt hydrology.

Vegetation is sparse on most of the caldera rim because of the xeric conditions on the south-facing wall and the instability of the steep slopes. Most of the springs on the north portion of the caldera have little terrestrial vegetation, and the majority of springs on the south rim are lined by narrow fringes of shrubs and herbaceous plants or occasional thickets of Sitka alder (*Alnus sinuata*). Mature conifer forests of mountain hemlock (*Abies mertensiana*), red fir (*Abies procera*), and white bark pine (*Pinus albicaulis*) are found on the southwest caldera wall. Soils are poorly developed, and soil formation is limited by the high rates of erosion and mass failure.

#### Methods

The National Park Service has identified 61 springs around the lake and has numbered them sequentially in a clockwise direction starting at Cleetwood Cove on the north wall. Ten perennial springs were selected for this study of surface water chemistry, starting with Spring 2 on the east wall and extending around to Spring 49 on the northwest wall (Fig. 1; Table 1). This study is based on water samples collected during 1984-1989.

Samples were collected from the springs several meters above their point of entry into the lake. Water samples were collected in two 1-liter acid-washed polypropylene bottles, held on ice in darkness, filtered through Whatman GF/F fiber filters, frozen within 8 hours of collection, and taken to the Cooperative Chemical Analytical

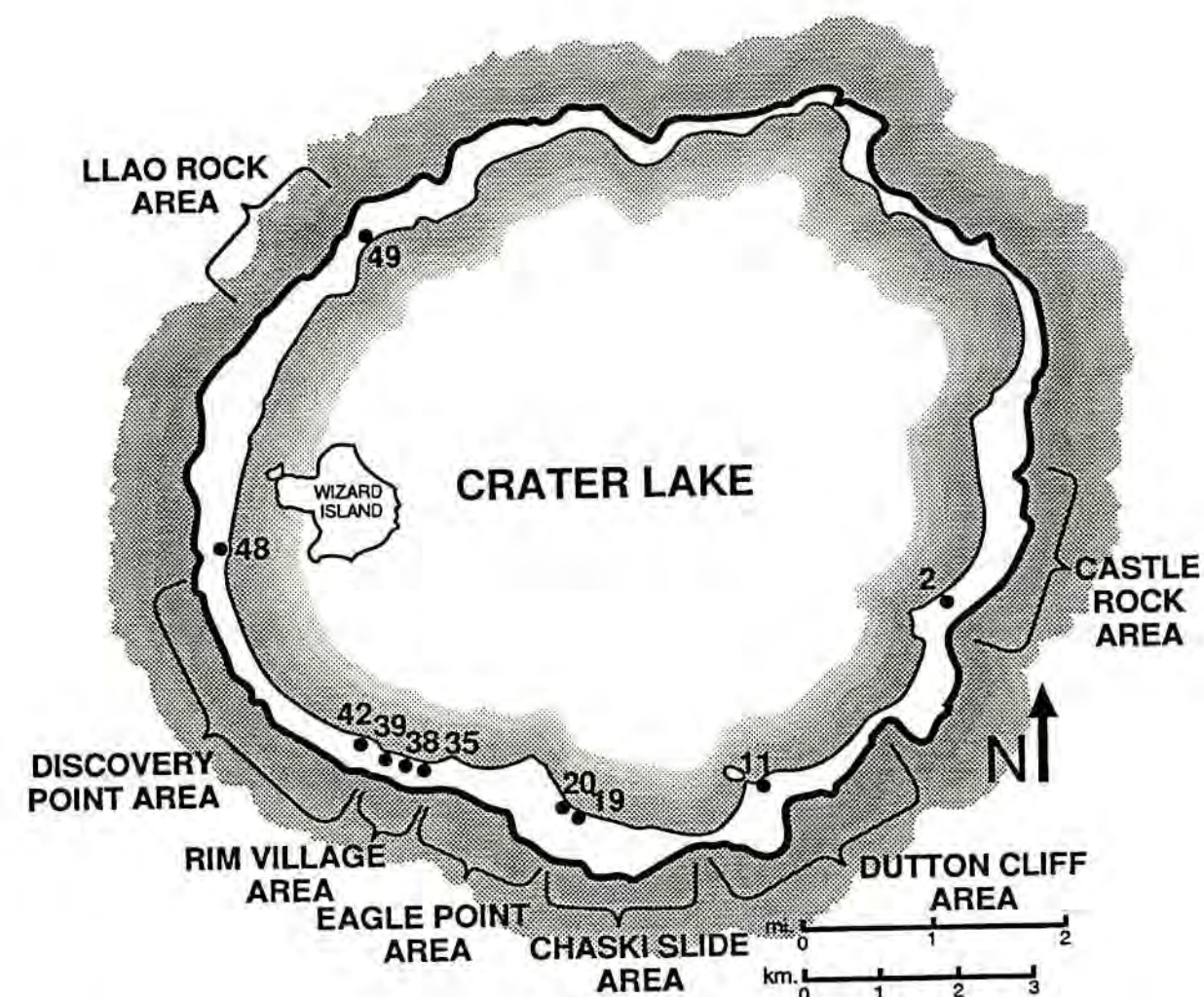


Figure 1. Locations of springs within the caldera of Crater Lake.

Table 1. Characteristics of selected springs in the caldera rim of Crater Lake. Rim locations refer to the compass bearing of the springs around the perimeter of the lake from the perspective of the center of the lake. Point of emergence refers to the position on the caldera wall above the lake surface from which the springs emerge as surface flow.

| Spring Number | Area of Caldera | Rim Location | Point of Emergence | Dominant Vegetation                   |
|---------------|-----------------|--------------|--------------------|---------------------------------------|
| 2             | Castle Rock     | E            | Intermediate       | Shrub with some alder                 |
| 11            | Dutton Cliff    | SSE          | Intermediate       | Sparse                                |
| 19            | Chaski Slide    | S            | Intermediate       | Shrub                                 |
| 20            | Chaski Slide    | S            | Intermediate       | Shrub                                 |
| 35            | Eagle Point     | SSW          | High               | Shrub with some alder                 |
| 38            | Rim Village     | SW           | High               | Alder thicket, conifer forest patches |
| 39            | Rim Village     | SW           | High               | Alder thicket, conifer forest patches |
| 42            | Rim Village     | WSW          | Low                | Mature conifer forest                 |
| 48            | Discovery Point | W            | High               | Mature conifer forest                 |
| 49            | Llao Rock       | NW           | Intermediate       | Sparse                                |

Laboratory for analysis. Methods for analysis, determination of standards, and quality assurance are described in the chapter on the quality assurance program of this laboratory.

Water chemistry is presented for all sampling dates during the six-year study period. Data are incomplete for the full suite of chemical parameters and all springs for the study period, but the database is complete for 1987-1988. Detailed analysis of water chemistry for all springs is based on this shorter record of complete information.

## Results

### Discharge

Discharge regimes of the caldera springs are strongly influenced by snowmelt, as evidenced by the hydrologic record from Annie Springs (Fig. 2; USGS Water Records 1979-1991). Annie Springs emerges 50 m below the surface of Crater Lake on the outer

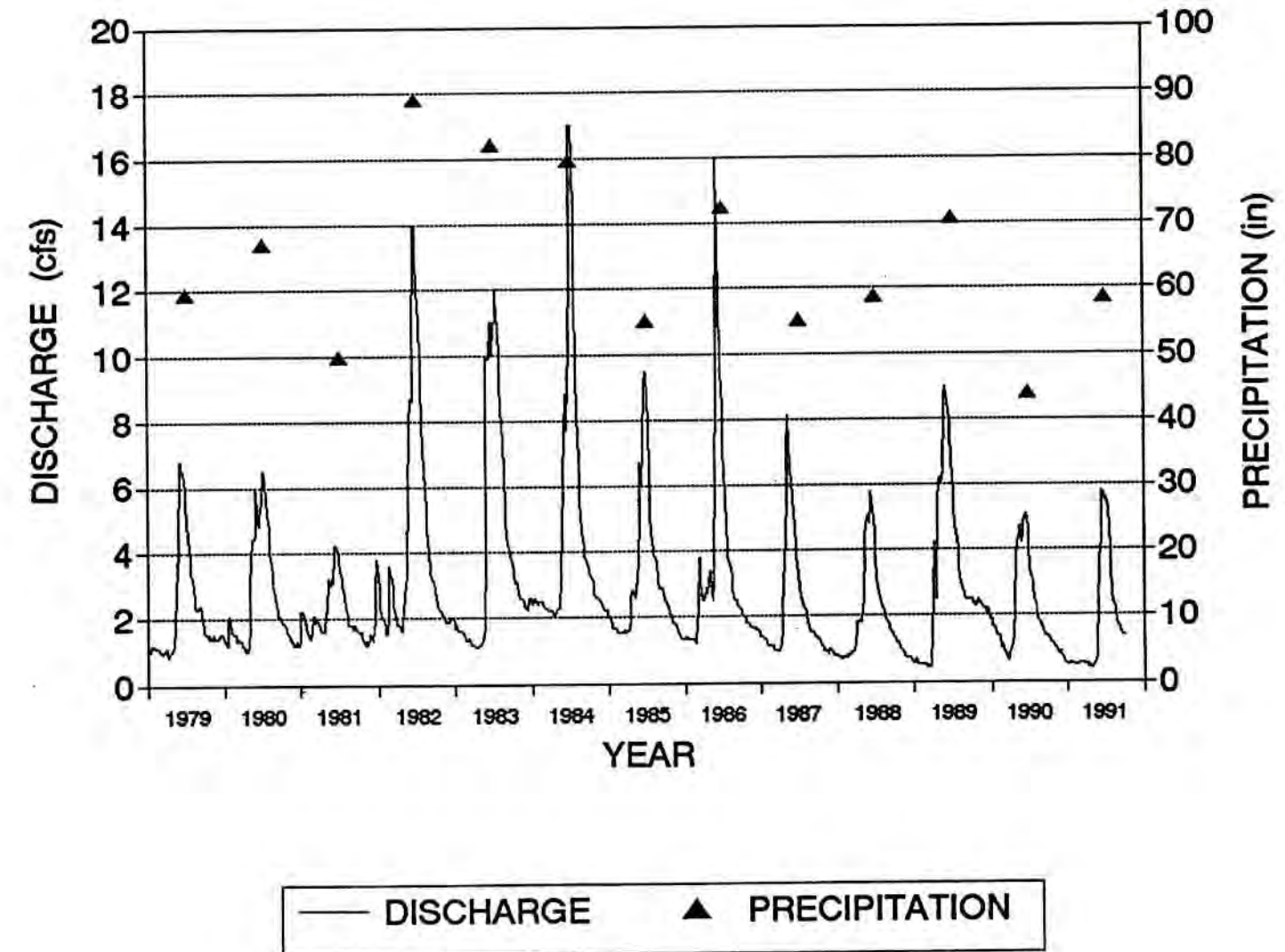


Figure 2. Hydrograph of daily discharge in Annie Springs for the period from October 1979 through September 1991.

flank of the south rim. Though this spring is not inside the caldera, temporal patterns of streamflow should be similar to the hydrologic regimes of the caldera springs because precipitation, climate, and geology are essentially identical. The study period from 1984-1989 is characterized by decreasing precipitation and associated declines in both maximum and minimum discharges. Annual precipitation strongly influences maximum discharges because of the overwhelming influence of snowpack on peak runoff during snowmelt (Fig. 3). Consequently, potential dilution and transport of dissolved material in soil solution is greatest during the spring and early summer season.

#### General Water Chemistry

Conductivity of spring waters ranged from 5 to 157  $\mu\text{S}/\text{cm}$ , with the maximum conductivities observed in the Chaski Slide and Eagle Point areas (Table 2). Minimum ionic strengths were observed during early summer snowmelt in each caldera spring except springs 2 and 49 on the more xeric slopes.

Typical of surface waters in regions of volcanic geology, buffering capacity of the caldera springs was relatively low (Table 2). Alkalinities did not differ substantially between springs, with the exception of low alkalinity in springs 39 and 49 (Fig. 4). Spring 39 exhibited the lowest average total alkalinity of 0.11 meq/l, and nearby Spring 42 exhibited the highest total alkalinity of 0.36 meq/l. As observed for many other chemical species, the lowest concentrations of inorganic carbon occurred during snowmelt. For all streams, pH was relatively constant and generally averaged slightly above 7.5. The first pH sample collected in 1985 exceeded 8.0 for most springs, and this level of hydrogen ion activity never was observed again. Water chemistry data

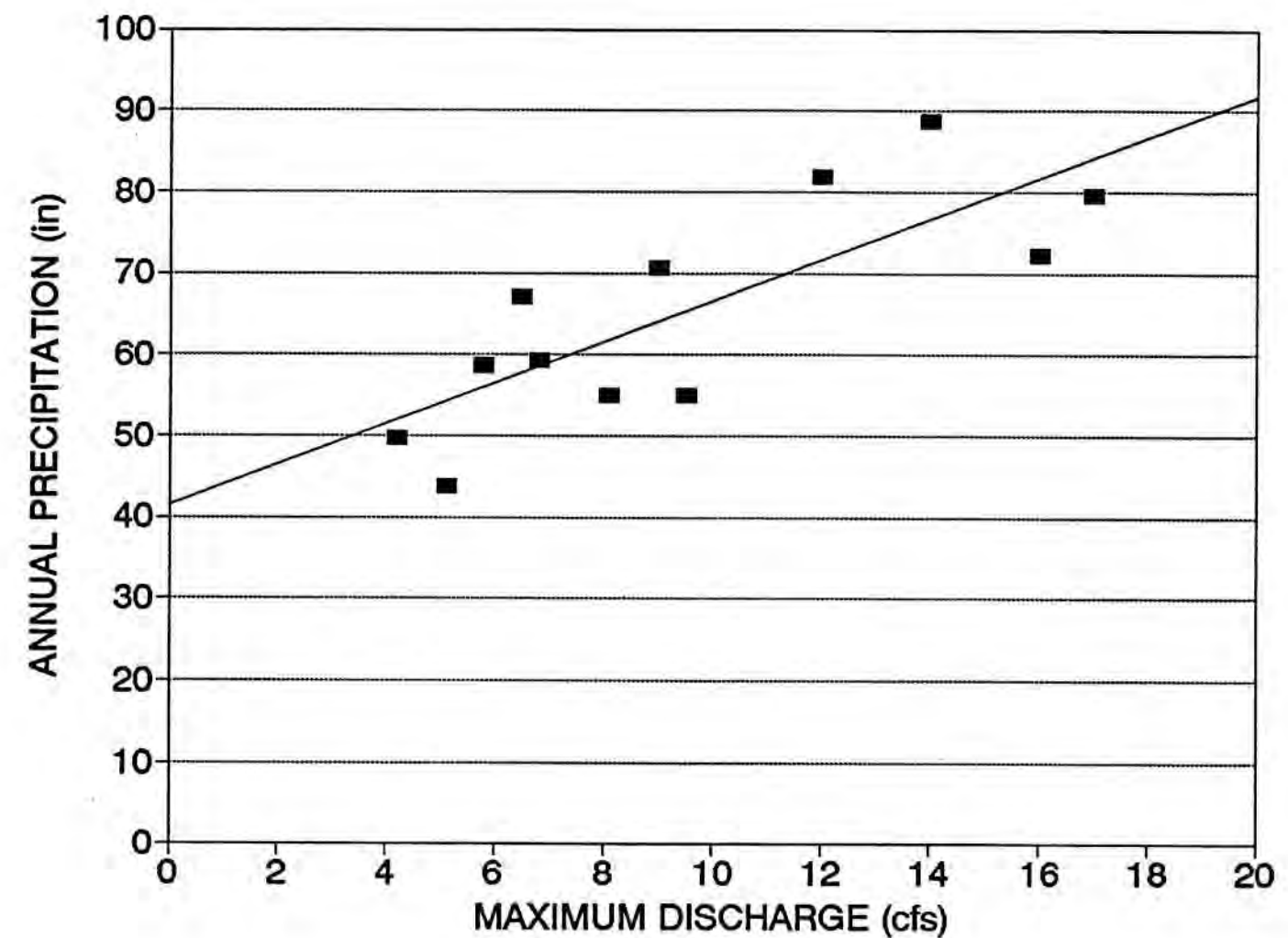


Figure 3. Relationship between annual precipitation and annual maximum discharge in Annie Springs.

Table 2. Average concentration (mg/l) and normality (meq/l) for major chemical species, pH, and temperature for caldera springs from 1984-1989. Alkalinity is expressed as mg CaCO<sub>3</sub>/l. Conductivity is measured as  $\mu$ S/cm. TKN is Kjeldahl nitrogen (ammonium + organic nitrogen). TP is total phosphorus (orthophosphate + organic phosphorus).

| SPRING                      | Ca     | Mg    | K     | Na    | Si     | SO <sub>4</sub> -S | Cl    | NH <sub>4</sub> -N | NO <sub>3</sub> -N | TKN   | PO <sub>4</sub> -P | TP    | Fe    | pH   | ALK    | COND   | TEMP |
|-----------------------------|--------|-------|-------|-------|--------|--------------------|-------|--------------------|--------------------|-------|--------------------|-------|-------|------|--------|--------|------|
| <b>Concentration (mg/l)</b> |        |       |       |       |        |                    |       |                    |                    |       |                    |       |       |      |        |        |      |
| 2                           | 2.419  | 0.907 | 1.078 | 2.980 | 17.876 | 0.228              | 0.663 | 0.005              | 0.026              | 0.024 | 0.055              | 0.083 | 0.000 | 7.34 | 14.361 | 39.986 | 5.4  |
| 11                          | 1.767  | 0.989 | 0.506 | 4.604 | 16.203 | 0.134              | 0.680 | 0.005              | 0.004              | 0.018 | 0.064              | 0.088 | 0.024 | 7.67 | 17.967 | 42.450 | 7.1  |
| 19                          | 10.506 | 2.923 | 0.310 | 3.776 | 10.561 | 8.808              | 0.516 | 0.004              | 0.051              | 0.014 | 0.048              | 0.066 | 0.003 | 7.71 | 16.227 | 99.225 | 4.3  |
| 20                          | 6.165  | 1.450 | 0.930 | 2.597 | 11.730 | 4.344              | 0.385 | 0.004              | 0.068              | 0.013 | 0.040              | 0.059 | 0.001 | 7.52 | 13.200 | 59.468 | 4.6  |
| 35                          | 6.861  | 1.960 | 0.969 | 2.292 | 12.518 | 4.708              | 0.449 | 0.004              | 0.047              | 0.033 | 0.075              | 0.096 | 0.007 | 7.57 | 15.193 | 71.683 | 6.3  |
| 38                          | 6.412  | 1.930 | 0.809 | 2.798 | 12.730 | 4.410              | 0.497 | 0.004              | 0.025              | 0.028 | 0.048              | 0.068 | 0.005 | 7.54 | 15.685 | 71.113 | 4.7  |
| 39                          | 2.007  | 0.417 | 0.460 | 1.479 | 8.919  | 1.073              | 0.427 | 0.005              | 0.089              | 0.029 | 0.023              | 0.041 | 0.000 | 7.13 | 5.579  | 24.927 | 4.8  |
| 42                          | 4.184  | 1.195 | 1.564 | 2.575 | 16.620 | 0.406              | 0.698 | 0.006              | 0.242              | 0.006 | 0.048              | 0.072 | 0.005 | 7.62 | 18.105 | 47.643 | 2.9  |
| 48                          | 2.359  | 0.559 | 1.340 | 2.498 | 16.278 | 0.135              | 0.494 | 0.003              | 0.021              | 0.011 | 0.041              | 0.065 | 0.001 | 7.53 | 14.060 | 33.532 | 4.1  |
| 49                          | 0.940  | 0.514 | 0.605 | 2.226 | 12.285 | 0.092              | 1.327 | 0.003              | 0.002              | 0.017 | 0.030              | 0.053 | 0.000 | 7.53 | 9.989  | 23.178 | 10.7 |
| <b>Normality (meq/l)</b>    |        |       |       |       |        |                    |       |                    |                    |       |                    |       |       |      |        |        |      |
| 2                           | 0.121  | 0.033 | 0.028 | 0.130 | 0.636  | 0.014              | 0.019 | 0.000              | 0.002              | 0.002 | 0.002              | 0.003 | 0.000 | 7.34 | 0.287  | 39.986 | 5.4  |
| 11                          | 0.088  | 0.036 | 0.013 | 0.200 | 0.577  | 0.008              | 0.019 | 0.000              | 0.000              | 0.001 | 0.002              | 0.003 | 0.000 | 7.67 | 0.359  | 42.450 | 7.1  |
| 19                          | 0.524  | 0.106 | 0.008 | 0.164 | 0.376  | 0.549              | 0.015 | 0.000              | 0.004              | 0.001 | 0.002              | 0.002 | 0.000 | 7.71 | 0.324  | 99.225 | 4.3  |
| 20                          | 0.308  | 0.053 | 0.024 | 0.113 | 0.418  | 0.271              | 0.011 | 0.000              | 0.005              | 0.001 | 0.001              | 0.002 | 0.000 | 7.52 | 0.264  | 59.468 | 4.6  |
| 35                          | 0.342  | 0.071 | 0.025 | 0.100 | 0.446  | 0.294              | 0.013 | 0.000              | 0.003              | 0.002 | 0.002              | 0.003 | 0.000 | 7.57 | 0.304  | 71.683 | 6.3  |
| 38                          | 0.320  | 0.070 | 0.021 | 0.122 | 0.453  | 0.275              | 0.014 | 0.000              | 0.002              | 0.002 | 0.002              | 0.002 | 0.000 | 7.54 | 0.313  | 71.113 | 4.7  |
| 39                          | 0.100  | 0.015 | 0.012 | 0.064 | 0.318  | 0.067              | 0.012 | 0.000              | 0.006              | 0.002 | 0.001              | 0.001 | 0.000 | 7.13 | 0.111  | 24.927 | 4.8  |
| 42                          | 0.209  | 0.043 | 0.040 | 0.112 | 0.592  | 0.025              | 0.020 | 0.000              | 0.017              | 0.000 | 0.002              | 0.002 | 0.000 | 7.62 | 0.362  | 47.643 | 2.9  |
| 48                          | 0.118  | 0.020 | 0.034 | 0.109 | 0.579  | 0.008              | 0.014 | 0.000              | 0.002              | 0.001 | 0.001              | 0.002 | 0.000 | 7.53 | 0.281  | 33.532 | 4.1  |
| 49                          | 0.047  | 0.019 | 0.015 | 0.097 | 0.437  | 0.006              | 0.037 | 0.000              | 0.000              | 0.001 | 0.001              | 0.002 | 0.000 | 7.53 | 0.200  | 23.178 | 10.7 |

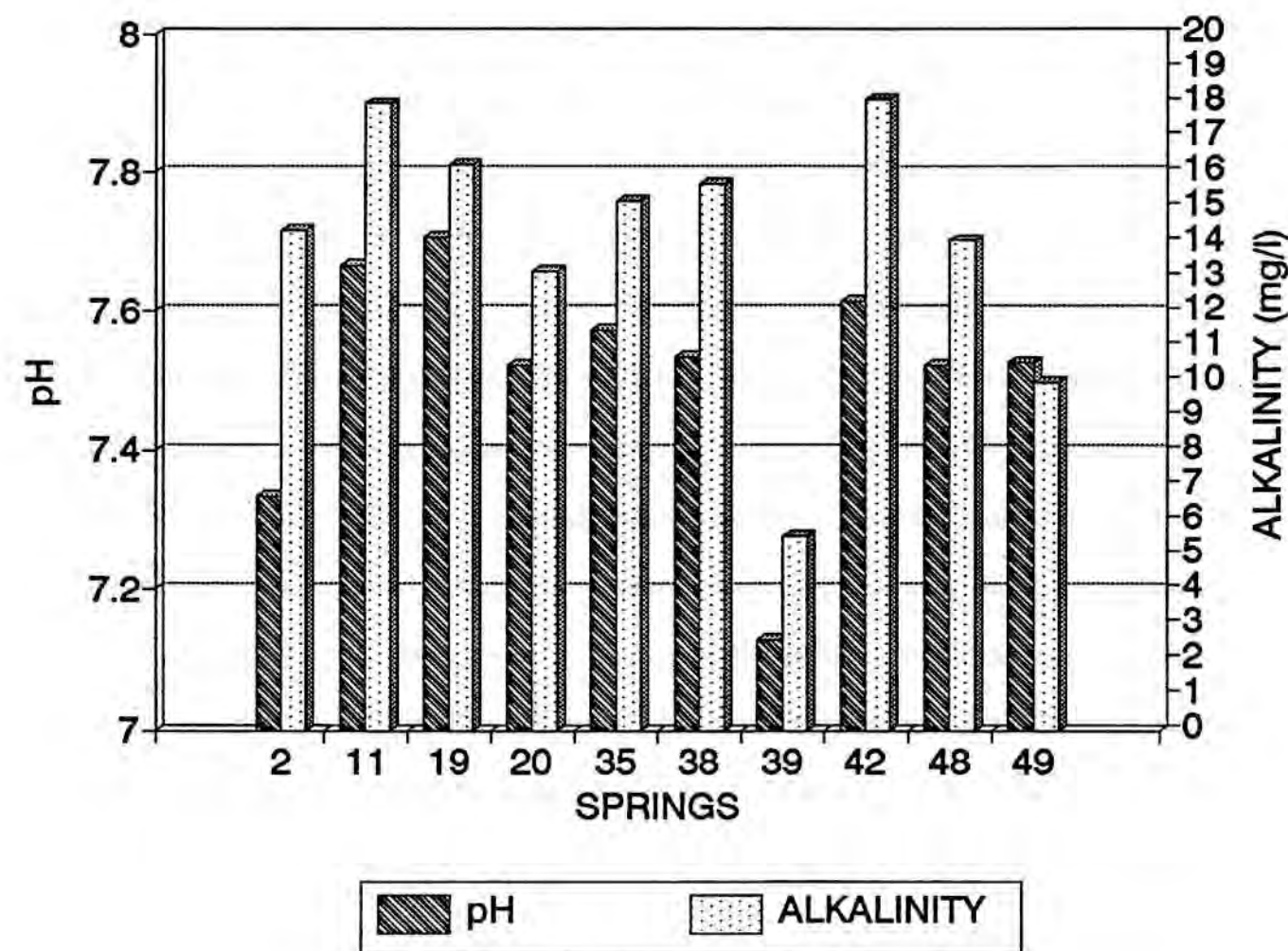


Figure 4. Average pH and total alkalinity (mg CaCO<sub>3</sub>/l) in caldera springs.

from this one date may be erroneous and inconsistent with the patterns observed during the six-year study.

The volcanic geology results in relatively high concentrations of silica in the caldera springs (Table 2). Silica averaged more than 12 mg/l for most springs around Crater Lake, but springs 19 and 39 exhibited concentrations of 10.6 and 8.9 mg/l. The range of silica concentrations between springs illustrates the complex patterns of geology, hydrologic routing, and alteration of the parent geology in the steep caldera rim.

Total charge balance of cations (Ca, Mg, K, Na, NH<sub>4</sub>) and anions (HCO<sub>3</sub>, CO<sub>3</sub>, NO<sub>3</sub>, organic N, PO<sub>4</sub>, organic P, Cl, and SO<sub>4</sub>) were analyzed for all springs during the period from 1987-1988. The plot of cations versus anions revealed a relationship close to 1:1 for all springs (cations = -0.041 + 1.070\*anions;  $r^2 = 0.99$ ), indicating that the chemical species analyzed account for most of the charge balance (Fig. 5). Equivalence of cations generally was within 5% of anion equivalences for most springs, but cations were 10%-15% lower than anions in springs 11, 38, and 49 (Fig. 6). These three springs also contained lower concentrations of the dominant cation, calcium. The discrepancies between cation and anion charge balances in these springs may reflect either analytical errors or omission of a cation in the analyses. As Nathenson and Thompson (1990) observed, bicarbonate accounts for most of the anionic charge in the caldera springs, and the ratio largely represents cations versus bicarbonate.

Cations were comprised primarily of calcium, and potassium was the least abundant cation in all springs. Normalities of sodium and magnesium were approximately equal in most springs, though sodium was the most abundant cation in springs 2 and 49 in the north half of the caldera. Cation concentrations were strongly

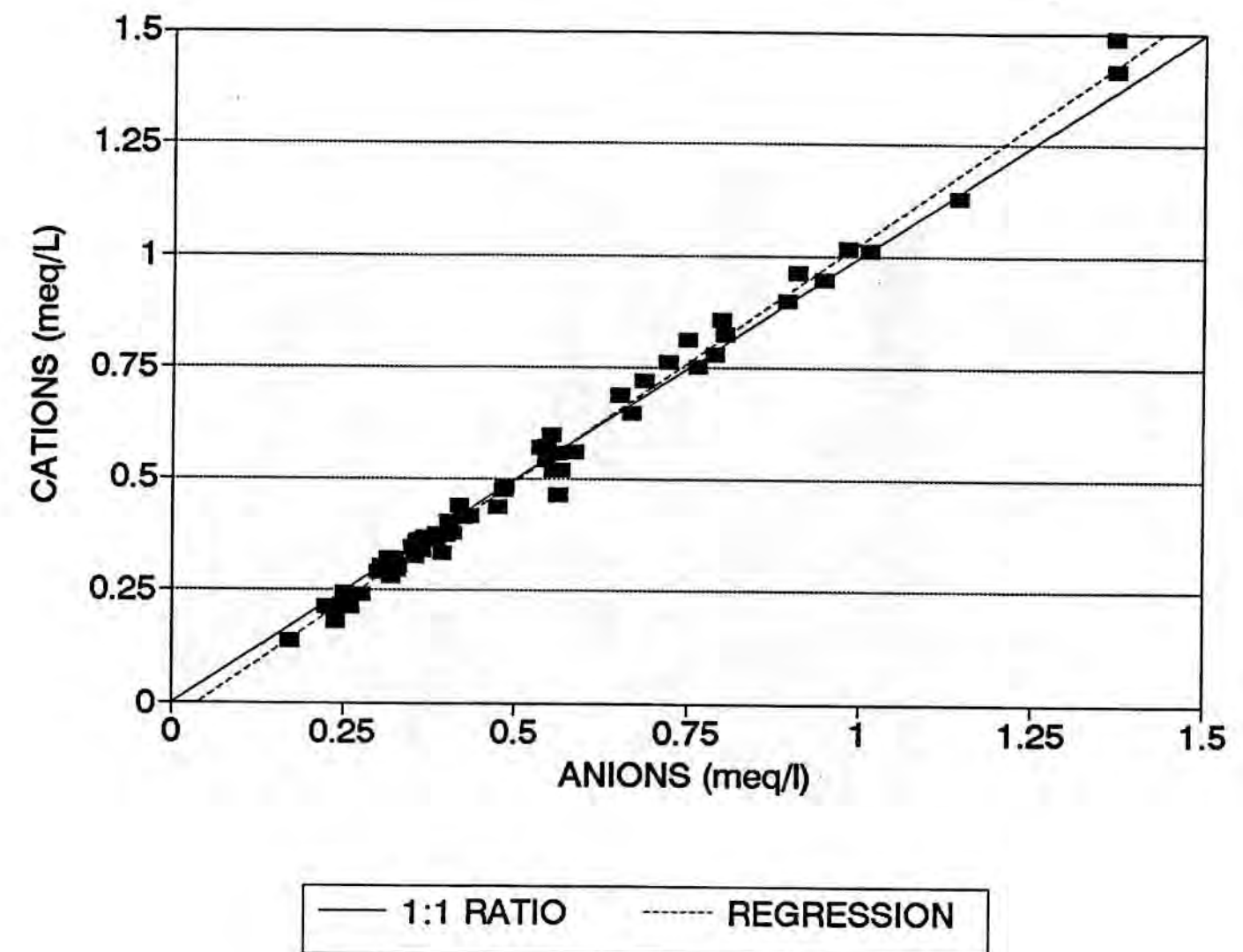


Figure 5. Relationship between cations and anions in caldera springs for water year 1987-88 (meq/l). Water year is October through September.

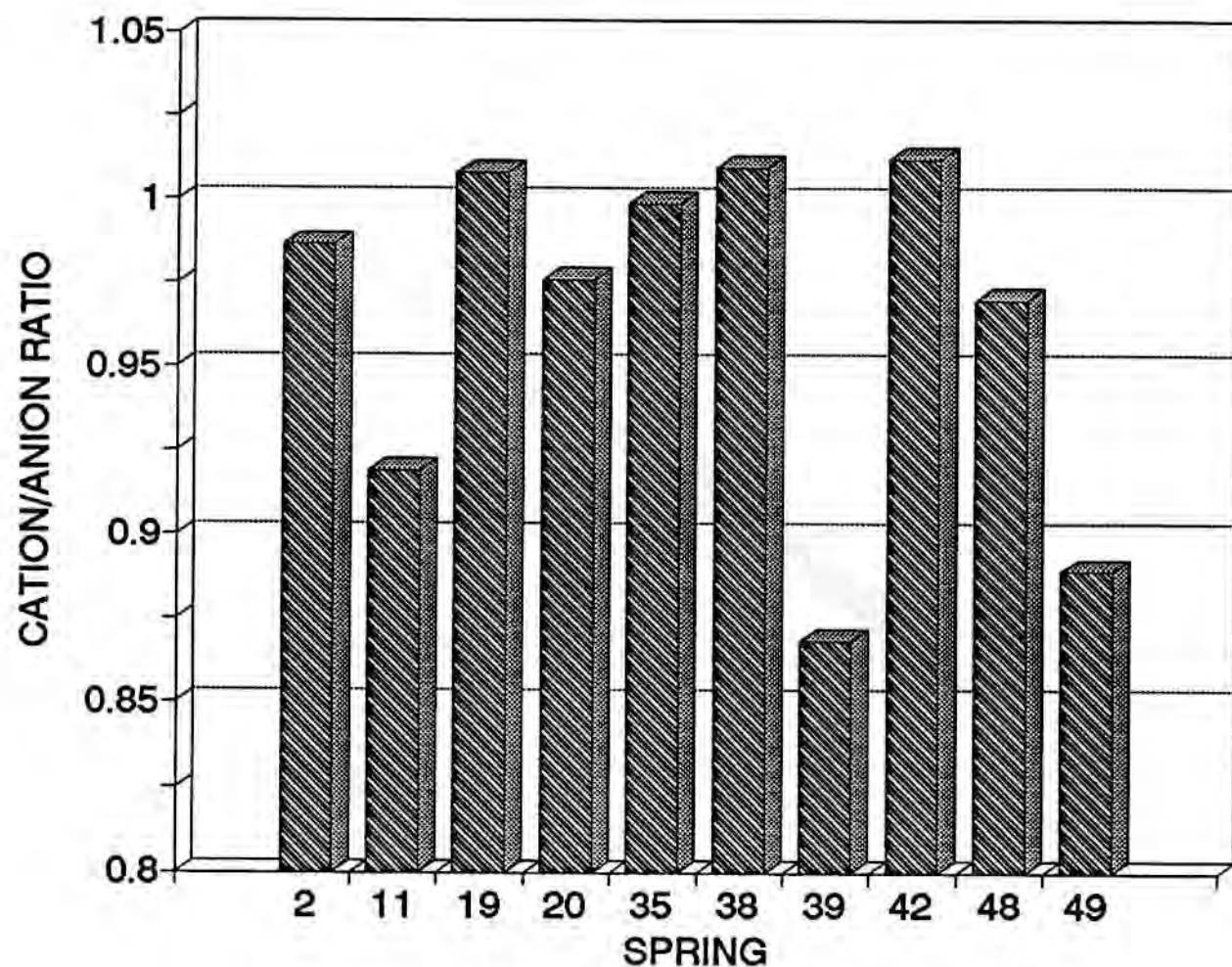


Figure 6. Average ratios of cations to anions (meq/l) for caldera springs during 1984-1989.

influenced by discharge, and the dilution at high discharge was reflected in the minimum concentrations observed during spring snowmelt.

#### Nitrogen and Phosphorus

Nitrate was the dominant form of nitrogen in most springs, and ammonium concentrations were extremely low (Table 2). The spring immediately below and slightly to the west of Rim Village exhibited much higher concentrations of nitrate than any other spring. Nitrate concentrations in Spring 42 averaged approximately  $240 \mu\text{g NO}_3\text{-N/l}$  (Fig. 7), and maximum concentrations of more than  $300 \mu\text{g NO}_3\text{-N/l}$  were observed in late summer and under winter snowpack. This seasonal periodicity was observed in springs 20 through 48 along the southwest rim of the caldera. Concentrations of organic nitrogen in Spring 42 were also distinctive, averaging  $9 \mu\text{g NO}_3\text{-N/l}$ , which is below the minimum level of detection. Organic nitrogen was generally less abundant than nitrate, though organic nitrogen was the dominant form in springs 11, 38, and 49. Springs in which organic nitrogen approached or exceeded nitrate concentrations averaged less than  $20 \mu\text{g NO}_3\text{-N/l}$ .

Orthophosphate was the dominant form of phosphorus in all springs, averaging from  $23\text{-}75 \mu\text{g PO}_4\text{-P/l}$  (Table 2) and differing little between springs (Fig. 8). Concentrations of phosphorus varied seasonally but did not exhibit as strong a response to snowmelt as was observed for cations, bicarbonate, and nitrogen.

#### Other Chemical Species

Chloride and sulfate were the other major anions found in spring water at Crater Lake (Table 2). Concentrations of sulfate were much higher in the Chaski Slide and Eagle Point areas of the lake, generally exceeding concentrations in the other springs by

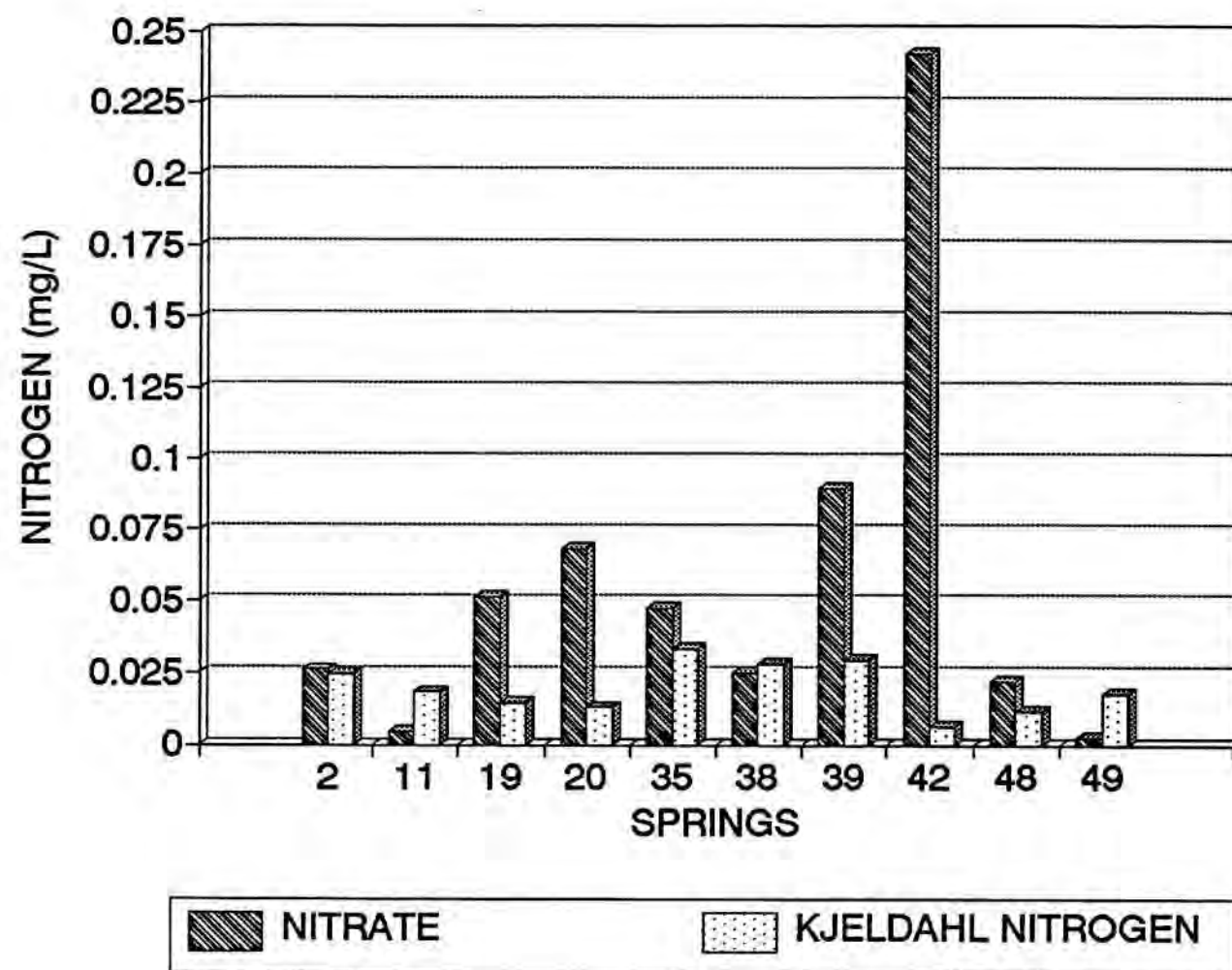


Figure 7. Average nitrate and Kjeldahl nitrogen concentrations (mg  $\text{NO}_3\text{-N/l}$ ; mg Kjeldahl N/l) in caldera springs from 1984-1989.

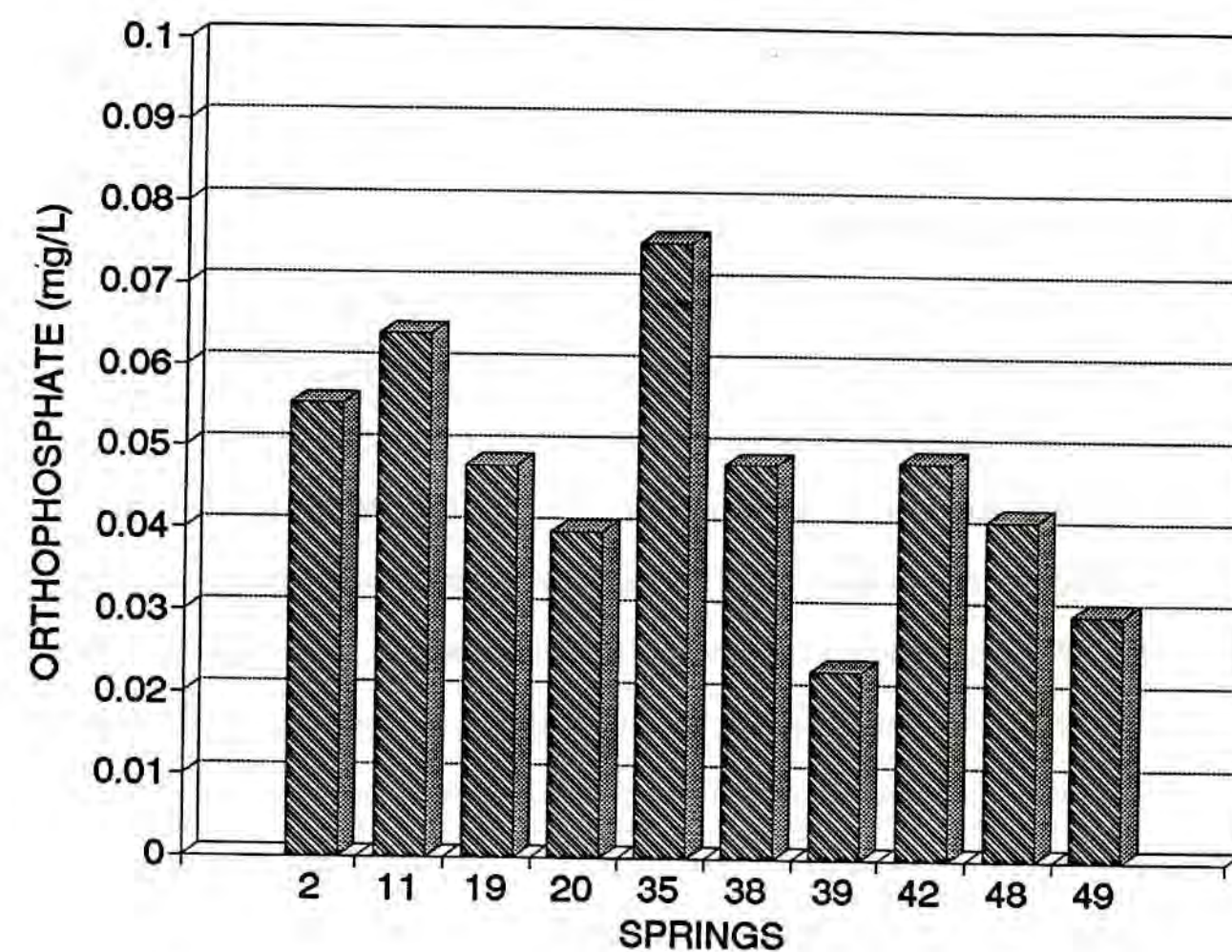


Figure 8. Average orthophosphate concentrations (mg  $\text{PO}_4\text{-P/l}$ ) in caldera springs from 1984-1989.

more than an order of magnitude (Fig. 9). Sulfate commonly exceeded the concentrations of chloride (in terms of meq/l) in springs, but chloride equalled or exceeded sulfate concentrations in springs in the more xeric extremes of the caldera (Spring 2 and Spring 49) and in Spring 42. Chloride concentrations in springs on the south rim (20,35,38,39, 48) averaged 0.494 mg/l, but chloride in Spring 42 was 0.2 mg/l higher (Fig. 9).

#### Patterns of Chemistry Within the Caldera

Systematic patterns of major cations and anions in spring chemistry were illustrated in modified Schoeller plots (Nathenson and Thompson 1990). Several general characteristics of groups of springs emerged through this analysis (Figs. 10-13). The springs in the north half of the caldera (springs 2, 11, 49) exhibited similar relative abundances of cations and anions (Fig. 10), with sodium being the dominant cation. Spring 19 was unlike any other spring in its relative chemical properties, characterized by extremely high amounts of calcium and sulfate (Fig. 11). Patterns of relative ionic concentrations in springs 20 and 35 also exhibited elevated amounts of calcium and sulfate, though not to the extent seen in Spring 19. Springs 38 and 39 were immediately adjacent to each other and exhibited drastically different chemistry (Fig. 12). Spring 38 was higher in all cations and anions, with the exception of potassium and chloride, and the ionic strength of Spring 38 was three times greater than that of Spring 39 (Table 2). Springs 42 and 48 in the west edge of the Rim Village area and the Discovery Point area were characterized by high concentrations of bicarbonate and silica (Fig. 13).

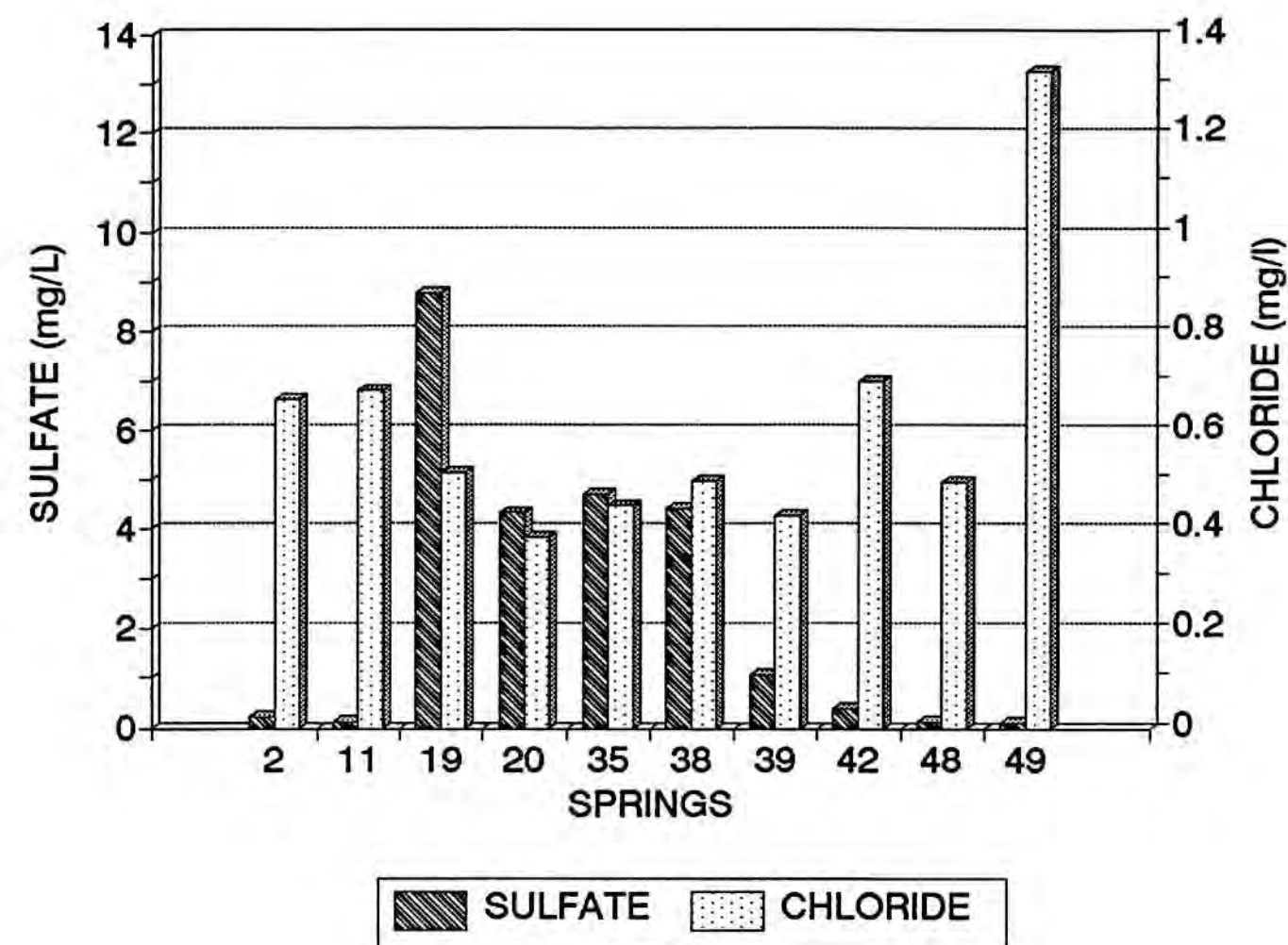


Figure 9. Average sulfate and chloride concentrations (mg SO<sub>4</sub>-S/l, mg Cl/l) in caldera springs from 1984-1989.

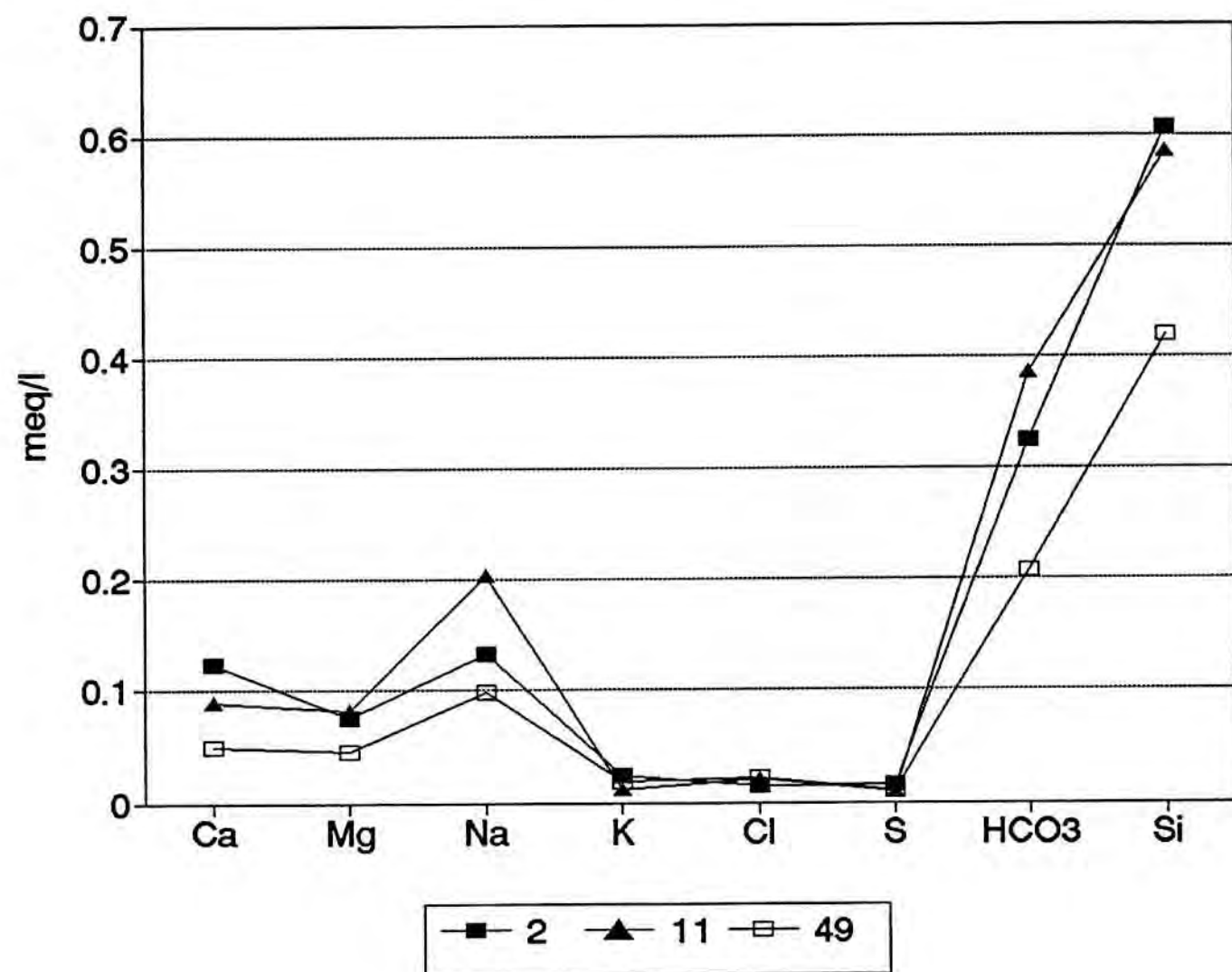


Figure 10. Modified Schoeller plots of major cations and anions for springs 2, 11, and 49 during water year 1987-1988.

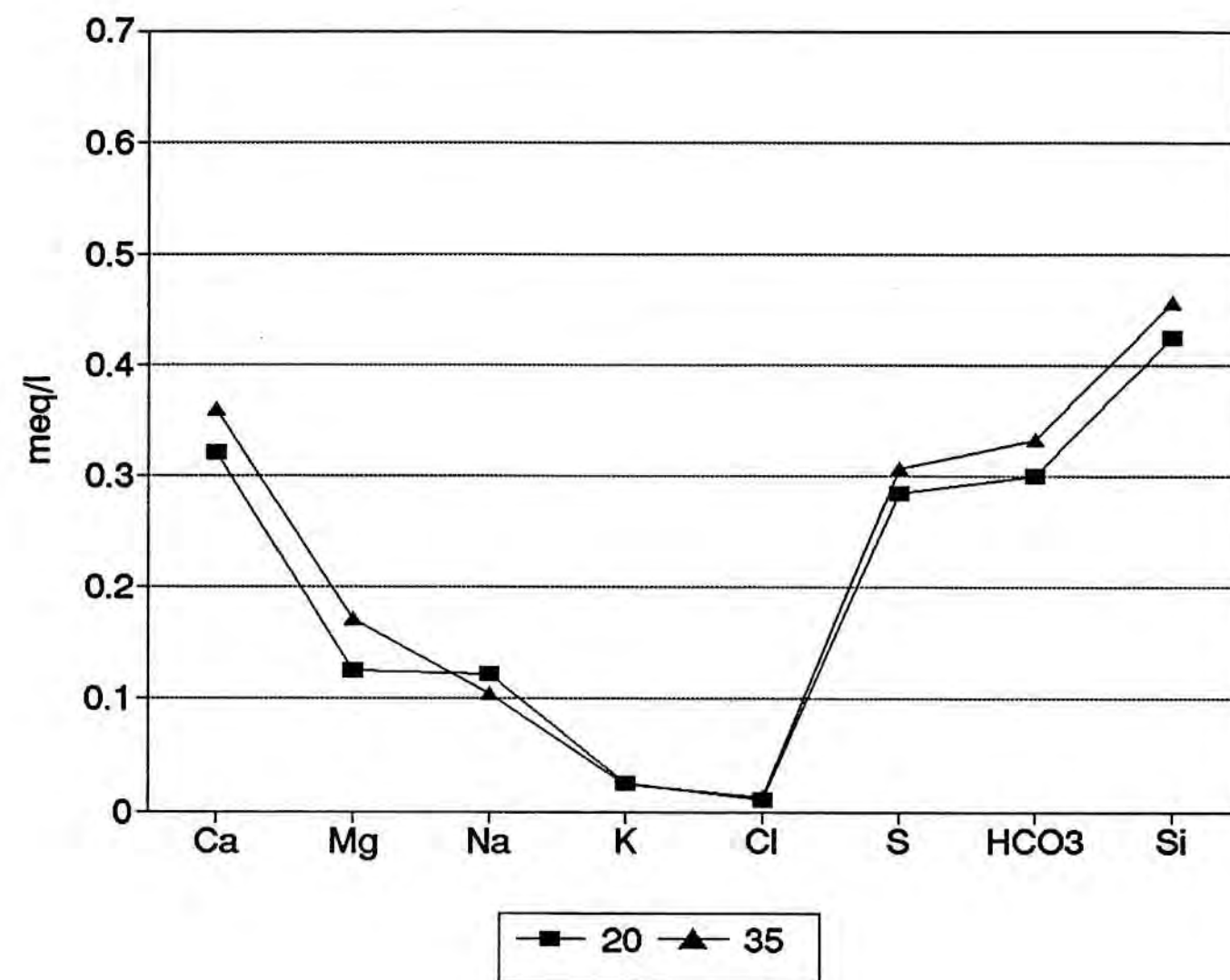


Figure 11. Modified Schoeller plots of major cations and anions for springs 20 and 35 during water year 1987-1988.

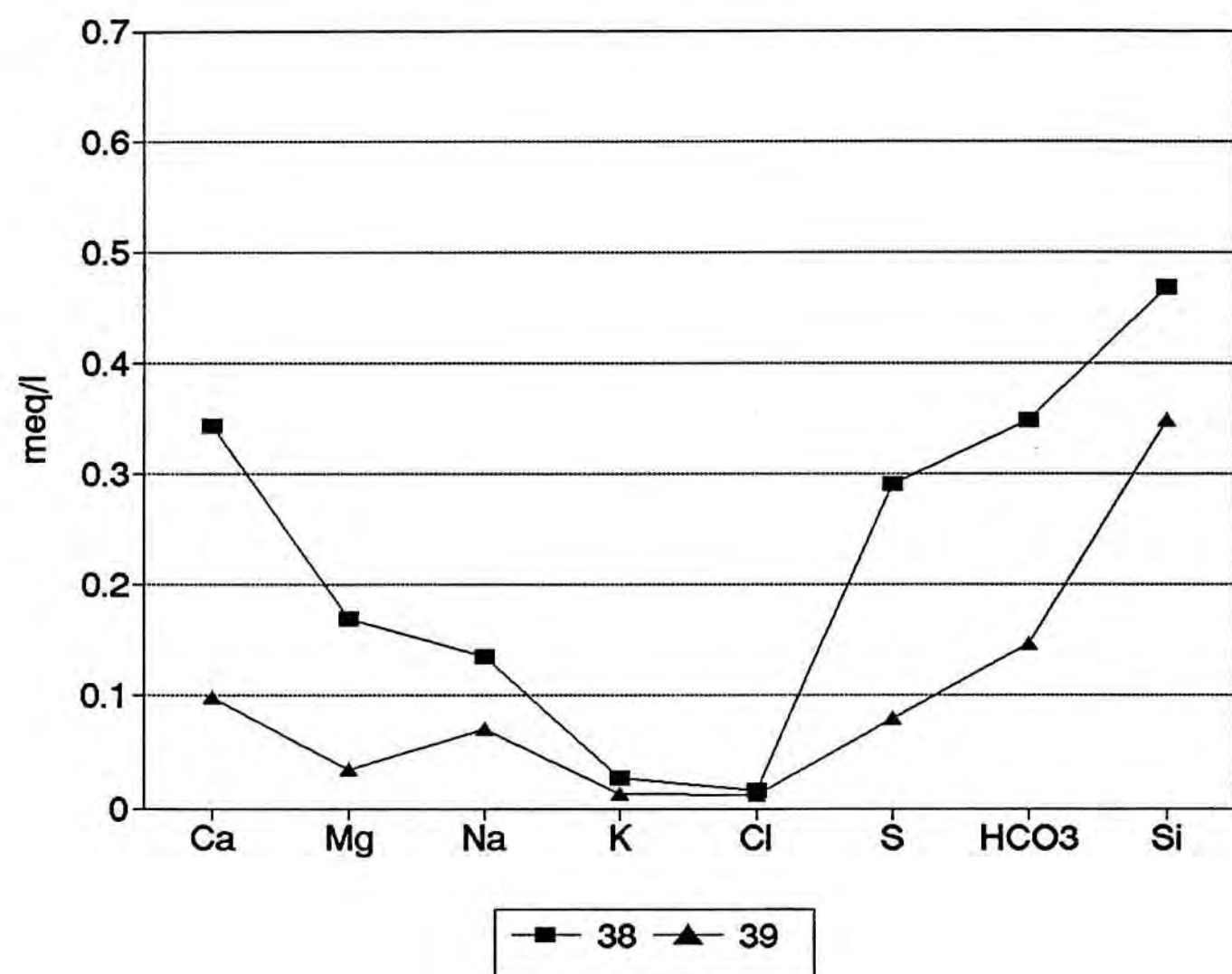


Figure 12. Modified Schoeller plots of major cations and anions for springs 38 and 39 during water year 1987-1988.

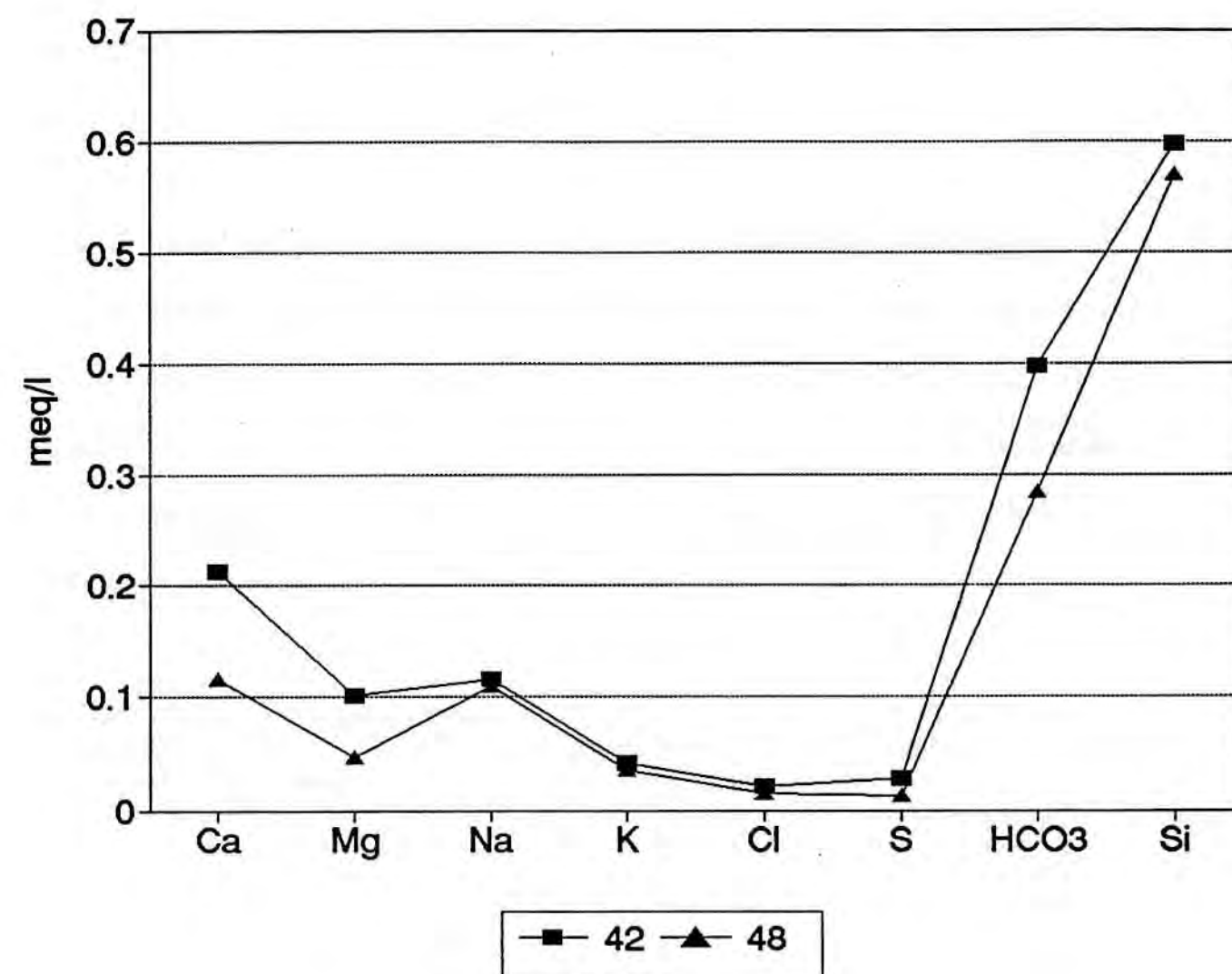


Figure 13. Modified Schoeller plots of major cations and anions for springs 42 and 48 during water year 1987-1988.

Patterns of spring chemistry were evaluated by multivariate data analysis (see Phytoplankton section for description of analytical methods). Major ionic components (cations, conductivity, pH, and alkalinity) and nutrients (ammonium, nitrate, orthophosphate, and silica) were examined. All samples with complete information on all chemical species were included from the 1984-1989 data.

Analysis of major ionic components indicated that a five-cluster structure was the most interpretable configuration (Fig. 14). The first cluster was characterized by intermediate concentrations of most cations but high concentrations of potassium (Table 3). The majority of samples in the first cluster came from springs 2, 11, 42, and 48. Conductivity and concentrations of calcium, magnesium, and bicarbonate were high in the second cluster, which was comprised primarily of late-season samples from springs 35 and 38. The third cluster contained samples from every spring, particularly from the

Table 3. Mean concentrations of cations, conductivity, pH, and alkalinity and cluster sizes for the ten caldera springs from 1984-1989. Alkalinity and cation concentrations are reported as mg/l, and conductivity is reported as  $\mu\text{S}/\text{cm}$ .

| Cluster | Size | pH   | Alk  | Cond  | Ca     | Mg    | K     | Na    |
|---------|------|------|------|-------|--------|-------|-------|-------|
| 1       | 66   | 7.61 | 16.5 | 42.6  | 3.007  | 0.952 | 1.153 | 3.068 |
| 2       | 26   | 7.59 | 17.4 | 85.5  | 8.566  | 2.377 | 0.967 | 3.203 |
| 3       | 44   | 7.40 | 10.2 | 37.0  | 3.179  | 0.898 | 0.656 | 1.925 |
| 4       | 11   | 7.74 | 17.8 | 118.3 | 13.313 | 3.699 | 0.173 | 4.601 |
| 5       | 10   | 6.81 | 4.5  | 23.2  | 1.869  | 0.387 | 0.124 | 1.089 |

## Crater Lake Springs Cation Analysis

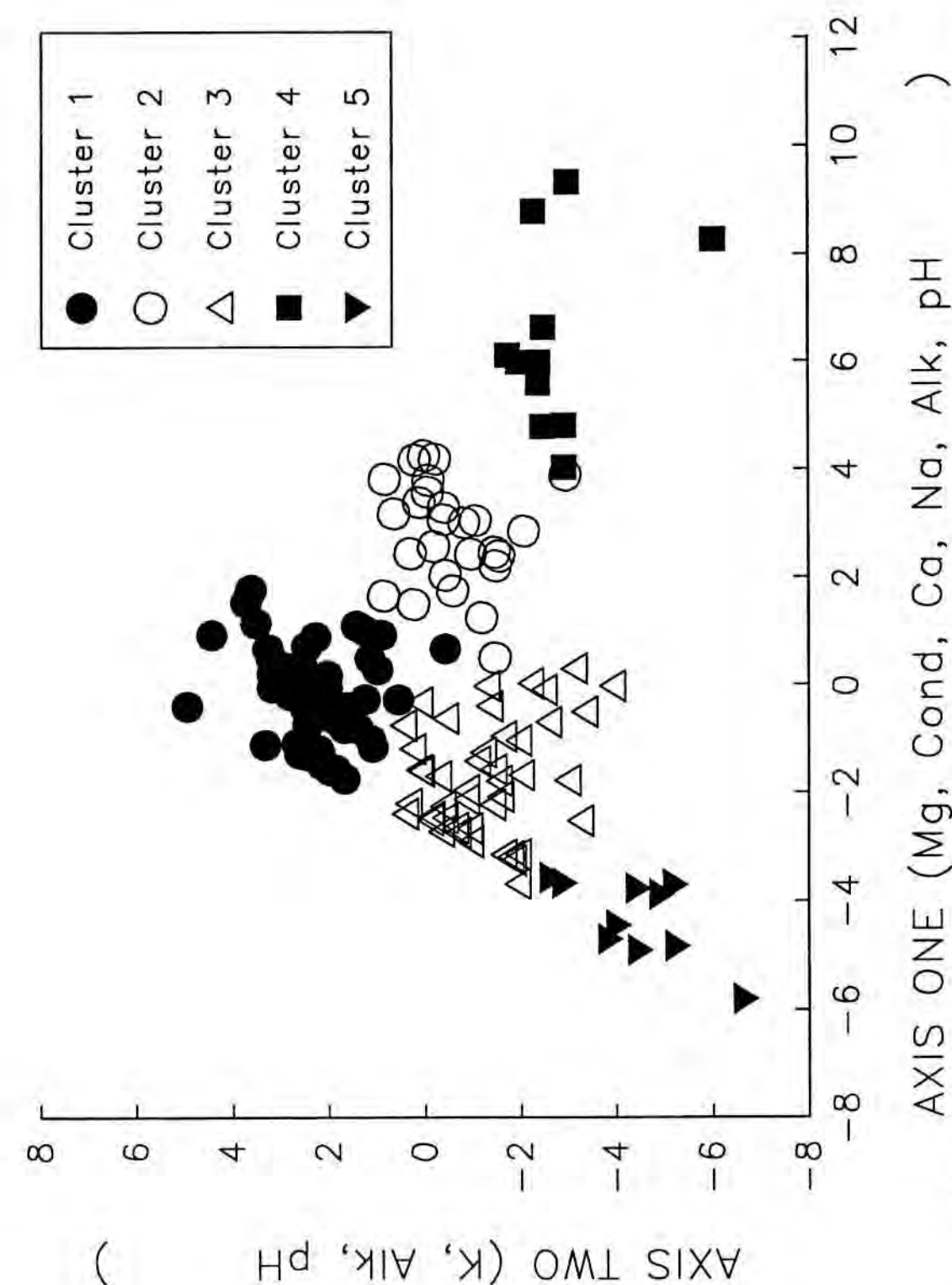


Figure 14.

Cluster analysis of major ionic components (cations, conductivity, pH, alkalinity) for caldera springs from data collected during 1984-1989.

late-spring and early summer period. This cluster of samples exhibited low alkalinity and pH approaching 7.5. Only samples from Spring 19 were found in the fourth cluster, which contained extremely high concentrations of calcium and magnesium and high conductivity. Low concentrations of all chemical parameters were characteristic of samples in the fifth cluster. This cluster was comprised of samples from Springs 38 and 39 in the snowmelt period of the year.

Nutrients in the caldera springs also were best characterized by a five-cluster structure (Table 4). Samples with high silica concentrations made up the first cluster, which was comprised primarily of samples from springs 2, 38, and 48. The second cluster consisted solely of samples from Spring 42 during late summer and winter. Low concentrations of orthophosphate and silica were typical of samples in the third cluster, and this cluster was made up primarily of springs 19, 20, 39, and 49. All springs were represented in the fourth cluster, which exhibited elevated concentrations of ammonium. The fifth cluster was characterized by high orthophosphate concentrations, primarily comprised of samples from Spring 35.

## **Discussion**

### **Potential Influences of Geology**

Springs emerging from the caldera walls around Crater Lake displayed a wide array of chemical characteristics across relatively short distances. Though surface water chemistry exhibited distinct patterns related to location around the caldera rim, springs in close proximity often had extremely different chemical properties. Springs 38 and 39 are immediately adjacent in the Rim Village area and are comparable in slope, aspect, vegetation, and approximate drainage area. These two springs were the most similar of

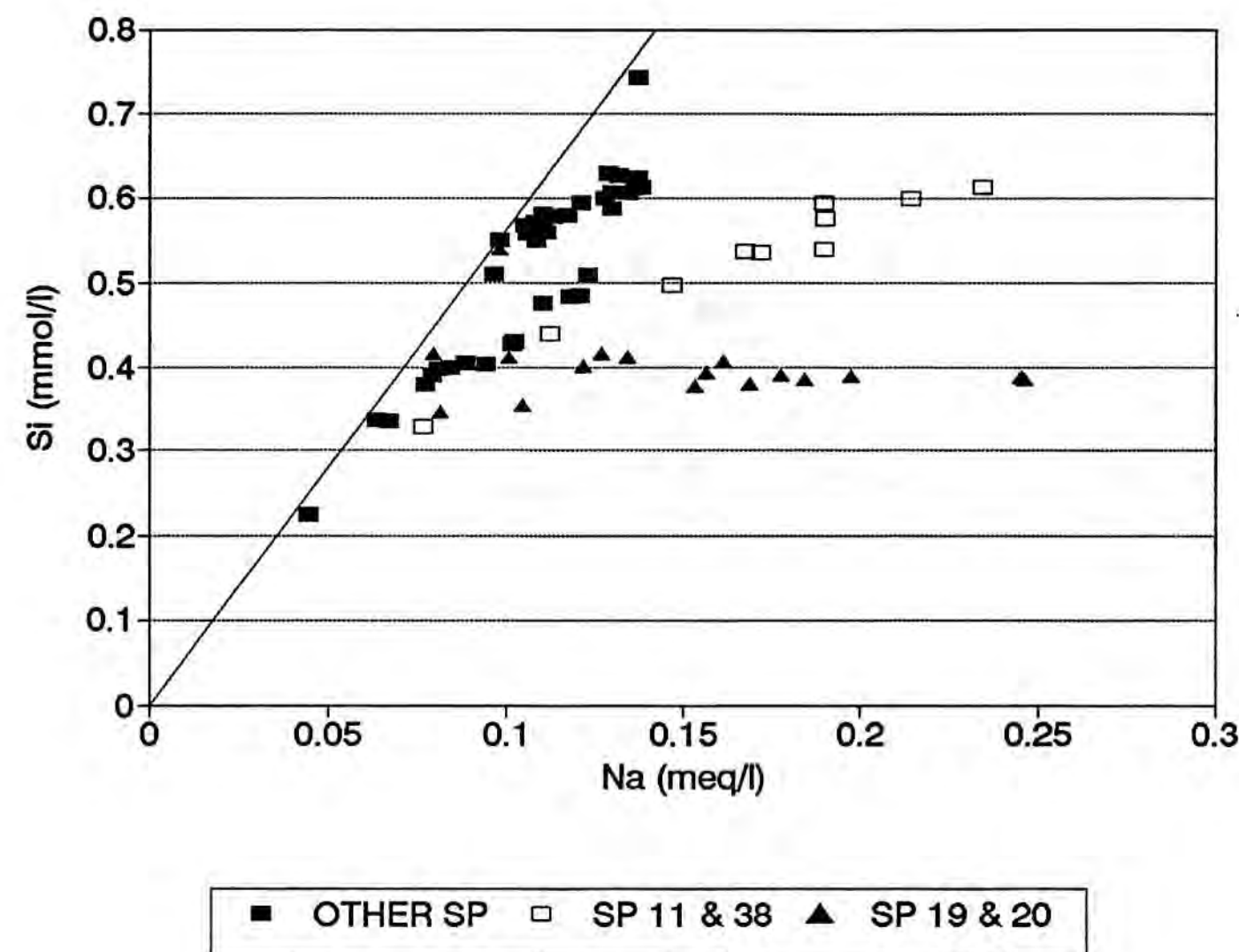
Table 4. Mean concentrations of nutrients (mg/l) and cluster sizes for the ten caldera springs from 1984-1989.

| <u>Cluster</u> | <u>Size</u> | <u>NH<sub>4</sub>-N</u> | <u>NO<sub>3</sub>-N</u> | <u>PO<sub>4</sub>-P</u> | <u>Silica</u> |
|----------------|-------------|-------------------------|-------------------------|-------------------------|---------------|
| 1              | 74          | 0.003                   | 0.020                   | 0.051                   | 16.391        |
| 2              | 25          | 0.003                   | 0.283                   | 0.048                   | 17.198        |
| 3              | 99          | 0.002                   | 0.058                   | 0.034                   | 10.179        |
| 4              | 39          | 0.009                   | 0.060                   | 0.047                   | 13.223        |
| 5              | 27          | 0.003                   | 0.035                   | 0.079                   | 13.642        |

the 10 study streams in physical and many ecological respects (Gregory et al. 1990), but they were very different streams in terms of water chemistry. Ionic strength of Spring 38 was approximately triple that of Spring 39. In contrast, nitrate concentrations in Spring 39 were almost an order of magnitude greater than nitrate concentrations in Spring 38, but phosphorus concentrations were greater in Spring 38. William's (1942) geological analysis of Crater Lake identified a dike that runs transversely from west to east and intersects the lake surface approximately at the base of Spring 39. Spring 42 emerges low on the caldera wall below the west face of the dike. This geologic discontinuity may influence the marked differences in spring chemistry in the Rim Village area. Our understanding of the mechanisms responsible for patterns of spring chemistry around the caldera are preliminary, and this analysis will serve as a basis for development of hypotheses and experimental approaches to understanding the complex flow patterns and chemistry of surface waters flowing into Crater Lake.

Nathenson and Thompson (1990) developed reactions for the weathering of minerals in the volcanic geology of Mount Mazama from glass to kaolinite clay. Based on these reaction, proportions of major chemical constituents can be predicted, and differences in chemical ratios can assist in the interpretation of weathering processes. Silica is a major component of volcanic minerals or glass and would be approximately 5.4 times more abundant than sodium based on the reaction from glass to kaolinite. Most of the caldera springs of Crater Lake exhibit chemical patterns that are consistent with this model (Fig. 15). The samples with much higher sodium concentrations than expected at silica concentrations of approximately 0.4 meq/l are from springs 19 and 20, and the high sodium samples at silica concentrations of 0.6 meq/l are from springs 11 and 38. Deviations from predicted ratios of silica and sodium in these two springs may reflect major changes in the local mineralogy. Their proximity on the south rim of the caldera supports the hypothesis of a local geologic influence on spring chemistry. Nathenson and Thompson (1990) indicated that the source of high concentrations of calcium, magnesium, and sulfate in springs of the Chaski Slide area is likely to be a large block of hydrothermally altered volcanic rock in that area of the caldera. Similarities in the chemistry of springs 11, 19, 20, 35, and 38 may indicate a common geologic composition of the Chaski Slide, Eagle Point, and part of the Rim Village areas.

The ratio of silica and carbonate in the caldera springs are also indicative of the weathering process (Nathenson and Thompson 1990). Ratios of silica and bicarbonate indicate that caldera springs around Crater Lake contain more bicarbonate than would be expected (Fig. 16). Samples that deviate most from the expected ratio at 0.4 and 0.6 meq Si/l are from Spring 19 and Spring 42, respectively. This further corroborates the possibility that the local geology around Spring 19 differs from that of other springs and



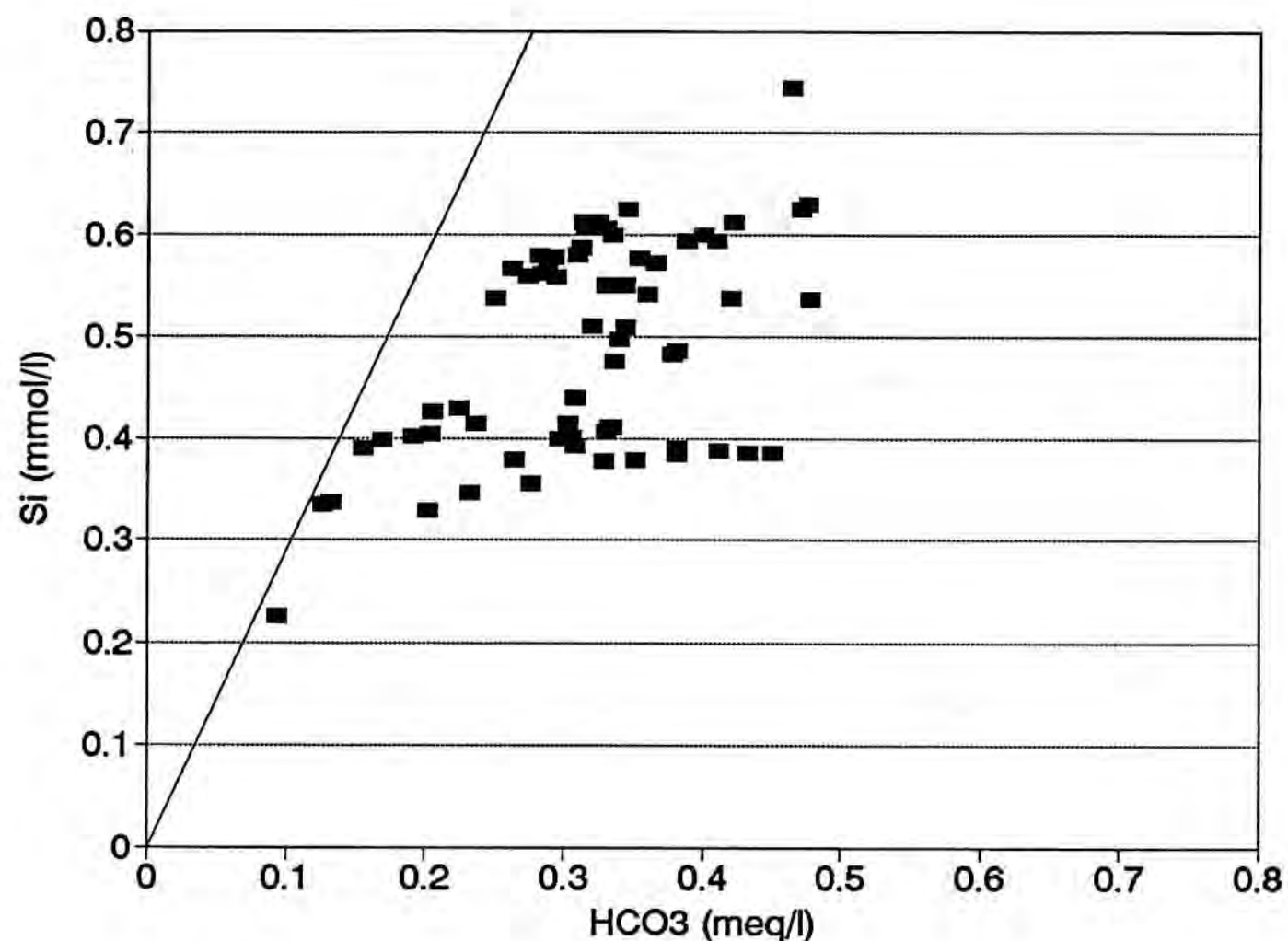


Figure 16. Relationship between silicate concentration and alkalinity (mmol Si/l; meq  $\text{HCO}_3/\text{l}$ ) in caldera springs during water year 1987-1988.

may reflect a different geological source, alteration of the parent material, or different duration of subsurface flow.

### Nitrogen Chemistry

Springs in the Crater Lake caldera are characterized by relatively low concentrations of nitrogen and high concentration of phosphorus, reflecting the influence of the volcanic geology. Ratios of inorganic nitrogen (ammonium and nitrate) to inorganic phosphorus are known as the Redfield ratio, and ratios less than 16 indicate nitrogen limitation of primary production (Redfield 1958). N:P ratios in the caldera springs are extremely low, generally less than one (Fig. 17). Biological production in the springs is clearly limited by the availability of nitrogen, even in Spring 42 with average nitrate concentrations of  $242 \mu\text{g NO}_3\text{-N/l}$  (Gregory et al. 1990).

Nitrogen chemistry of the caldera springs has received much attention because of the possible implications for eutrophication of Crater Lake (Larson 1984). Early observations of higher concentrations of nitrate in Spring 42 below Rim Village raised concerns about possible contamination of groundwater and Crater Lake by sewage (Larson 1984, Larson et al. 1990). Prior to 1990, a septic gallery ran from the Rim Village facilities to a leachfield in the headwaters of Dutton Creek on the south slope of the rim. Inspection of pipes revealed cracks or ruptures in the lines, making it possible for release of sewage over a broader area. In 1975, sewage lines overflowed into Munson Springs and contaminated the drinking water for the Crater Lake Lodge and Park Headquarters (Craun 1981). Evaluation of evidence of anthropogenic sources was a major impetus for monitoring the chemistry of the large caldera streams in this study.

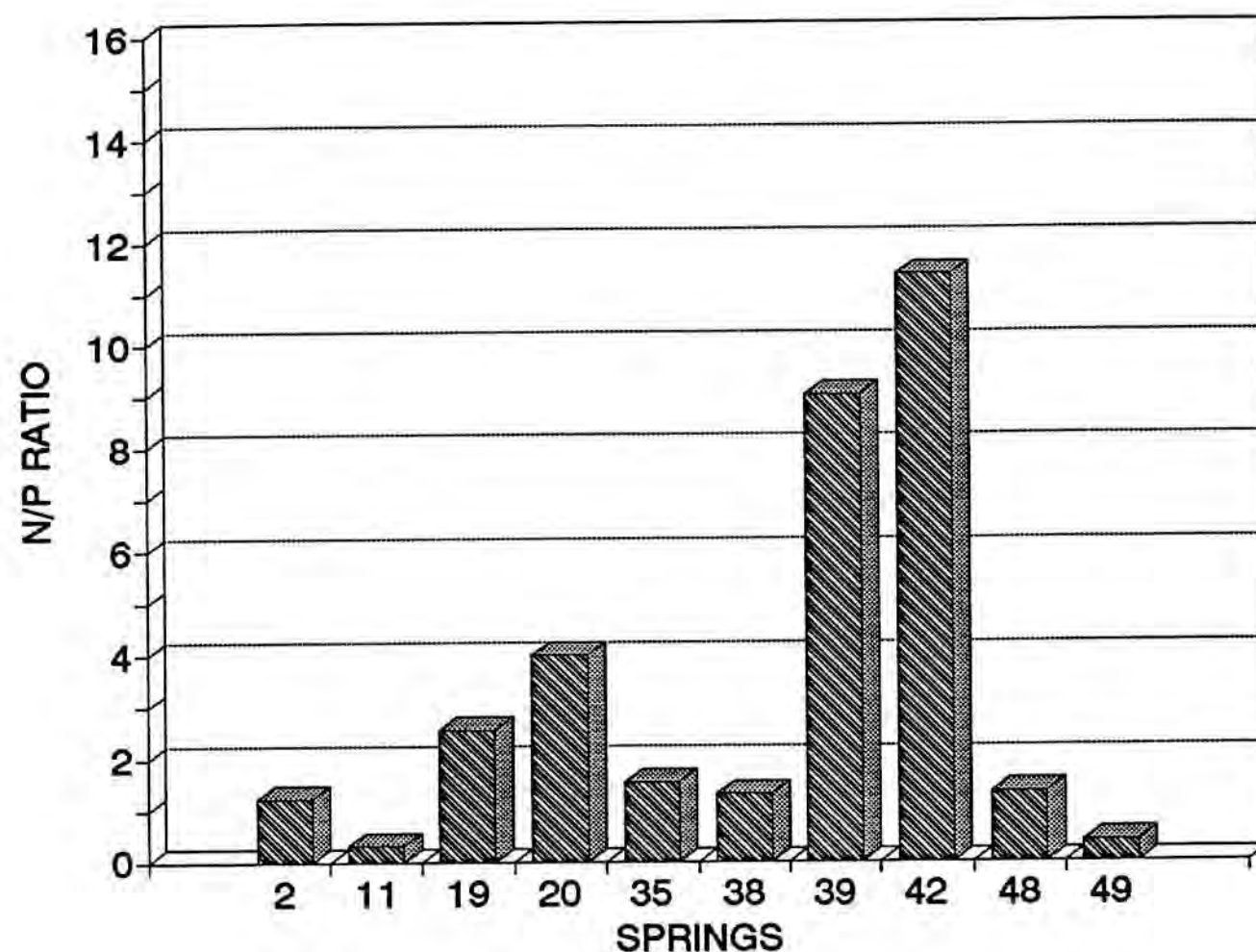


Figure 17. Average N:P ratios for caldera springs during 1984-1989.

Larson et al. (1990) estimated that approximately 2,500 kg of nitrogen could have been loaded into the drainfield each summer. This represents a worst-case scenario and the conservative assumption that all 600,000 visitors would contribute their total daily human waste load into the Rim Village septic system. The potential contribution of nitrogen into the watershed of Spring 42 would be substantially less because of several factors. Maximum capacity in the Rim Village facilities was approximately 300 persons per night when the lodge and dormitory were operating. Maximum annual overnight visitation would be approximately 30,000. It is unlikely that the remaining 570,000 visitors would contribute more than one-third of the daily waste load in the Rim Village septic system. In addition, the Rim Village area drains into the Munson Creek, Dutton Creek, Spring 39, and Spring 42 watersheds, and the leachfield is in the headwaters of Dutton Creek. These factors would reduce the potential load by approximately 33% for human use and 25% for watershed distribution. As a result, human activity could be expected to deliver approximately 200 kg of nitrogen annually into the upper watershed of Spring 42.

Several physical and chemical properties of the caldera springs provide a critical context for evaluating the potential anthropogenic influences on the nitrogen chemistry of Spring 42. These factors include: 1) nitrogen chemistry of the springs, 2) seasonal trends in spring chemistry, 3) nitrate concentrations in winter, 4) residence time of subsurface water, 5) other chemical species, 6) position of springs on caldera above the lake, and 7) examples from other springs in the Pacific Northwest.

Nitrogen chemistry of the springs. Nitrate concentrations in Spring 42 are distinctly higher than those of other caldera springs (Fig. 7). Springs on the southwest caldera rim all show higher nitrate concentrations than the other springs, though none to