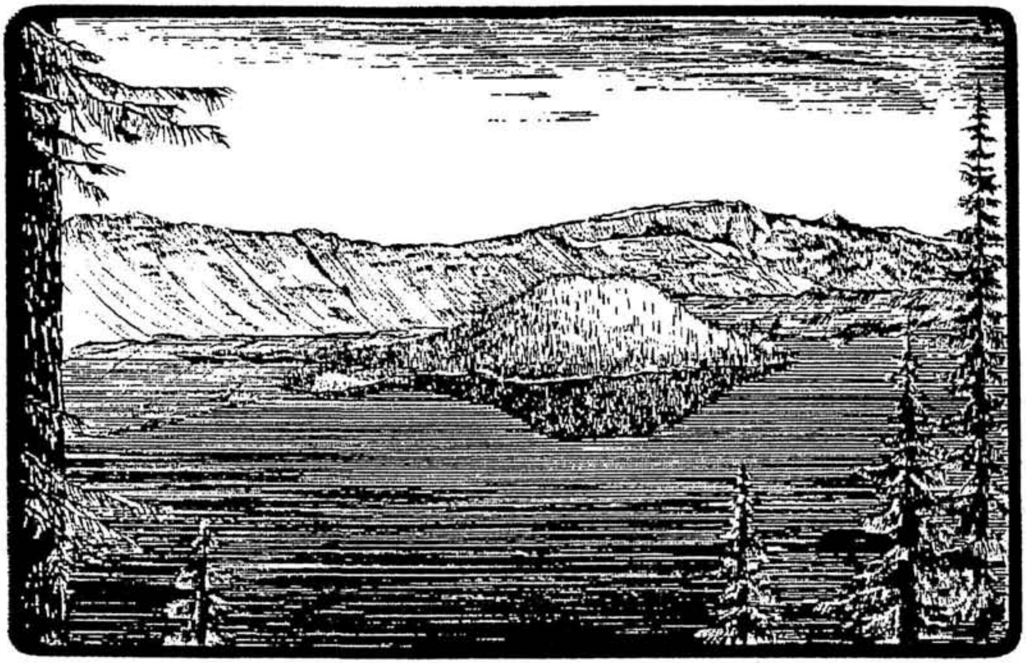
CRATER LAKE

LIMNOLOGICAL STUDIES
FINAL REPORT

Executive Summary • Abstract • Long-term Monitoring Program



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

TABLE OF CONTENTS

Three sections of the Final Report of Limnological Studies at Crater Lake, Oregon (July 1993) are provided in this publication. The full citation of the final report is: Larson, G.L., C.D. McIntire, and R.W. Jacobs, Editors. 1993. Crater Lake Limnological Studies Final Report. Technical Report NPS/PNROSU/NRTR-93/03. National Park Service, Pacific Northwest Region, Seattle, Washington. 722 pages.

Copies of the entire report are available from the following:

Technical Information Center (303) 969-2130
Denver Service Center
P.O. Box 25287
Denver, Colorado 80225-0287

National Technical Information Service (703) 487-4785
U.S. Department of Commerce
5285 Port Royal
Springfield, Virginia 22161

Crater Lake Limnological Studies Final Report
July 1993

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. Oligocheata 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.

Long-term Monitoring Program

The 10-year limnological study of Crater Lake revealed many of the components and processes important to lake clarity and to the dynamics of the lake ecosystem as a whole (Table 1). Although the relative importance of these components was well documented in many instances, many questions were generated which could not be addressed in sufficient detail within the scope of the program. This shortfall poses a problem because several human-related activities were identified which may have negative impacts on the lake (Table 2). Crater Lake is a unique lake from a global perspective, and it is highly valued both nationally and internationally. Responsibility for management of such a system should be a priority. Furthermore, the long-term data set that now exists for the lake has great scientific value for understanding processes that are common to all aquatic systems. Few pristine lakes have received such extensive study. The scientific value of these data will grow immensely if additional data can be added. The National Park Service, the agency charged with maintaining the pristine condition of the lake, must regulate human activities within the context of existing information and regulations, and simultaneously support the collection of additional information. Long-term monitoring of selected features of the lake system coupled with special short-term studies is needed for additional information for management and scientific purposes.

Priorities, Questions, and Hypotheses

A long-term monitoring program at Crater Lake should focus on the collection of meaningful information about the status and trends of the lake. It should provide a

Table 1. A rating of the importance of selected processes or components of the Crater Lake ecosystem in relation to knowledge of lake clarity and the lake system. A rating of the level of knowledge of the processes and components is included.

Component or Process	Relative Importance to Understanding Lake Clarity	Relative Importance to Understanding the Lake System	Level of Knowledge
Lake level	Moderate	Moderate-High	Moderate
Water budget	Moderate	High	Moderate
Depth of surface mixing in winter	High	High	Moderate
Thermal stratification	High	High	Moderate
Depth of surface mixing in fall	High	Moderate	Low
Abiotic particles: mudslides, avalanches, runoff & storm events	High	Low-Moderate	Low
Nutrient budget	Moderate	High	Moderate
Hydrothermal inputs	Low	High	Moderate
Organic detritus			
Water column	Moderate	High	Moderate
Benthic	Low	High	Moderate
Nutrient upwelling from the deep lake	High	High	Moderate
Spring 42 nitrate - N	Low	Low	High
Atmospheric deposition			
Nutrients	Moderate	High	Moderate
Particles	?	Low-Moderate	Low
Particle flux	Moderate	High	Moderate
Boat and automobile Emissions/Petroleum wastes	?	?	Low
Phytoplankton production dynamics	Moderate-High	High	Moderate
Zooplankton production dynamics	Low-Moderate	High	Low-Moderate
Benthic flora (production & nutrient dynamics)	Low	High (?)	Low
Benthic fauna (production dynamics)	Low	Moderate	Low
Fish production dynamics	Low-Moderate	High	Low-Moderate

Table 2. Activities or conditions that may impact Crater Lake and a rating of the level of understanding of the potential impacts.

Issues of Concern	Processes or Components Impacted	Level of Understanding of the Impact
Atmospheric deposition	Nutrients	Moderate
	Particles	Low
Automobile and boat emissions	Carbon particles	Low
	Chemicals	Low
Contamination of Spring 42	Nitrate-N concentration	High
Road and parking lot runoff	Release of petroleum products	Low
Global climate change	Depth of surface mixing	Low
	Amount of deep lake circulation	Low
	Amount of precipitation	Low
	Primary and secondary production	Low
Introduced species:		
Crayfish	Benthic food web	Low
Rainbow trout	Predation on:	
	Benthic macroinvertebrates	Low
	Terrestrial insects	Low
	Amphibians	Low
	Benthic and pelagic food webs	Moderate
Kokanee salmon	Predation on:	
	Benthic macroinvertebrates	Low
	Terrestrial insects	Low
	Daphnia pulicaria	High
	Pelagic food web	Moderate

minimum set of standards by which the health of the system can be evaluated as well as the baseline data needed to support specific investigations into lake processes that we do not understand. Understanding those processes that affect lake clarity is the highest priority of the recommended monitoring program. These processes involve complex interactions with other components and processes in the lake, and the following questions need to be addressed:

1. How much of the variation in lake clarity can be explained by changes in the densities of abiotic and biotic light scattering particles, and how much does each type of particle contribute to changes in lake clarity?
2. Is there a significant relationship between Secchi disk clarity and the clarity of the water column below a depth of 40 m where much of the biological production occurs?
3. What are direct and indirect effects of thermal stratification on lake clarity?
4. Do changes in weather, climatic conditions, and lake level alter clarity by affecting the amount of particles entering the lake from surface runoff, avalanches, mud slides and erosion of the shoreline?
5. How do changes in primary productivity, concentration of chlorophyll, and phytoplankton cell densities relate to variation in lake clarity?
6. Do changes in the abundance and distribution of zooplankton affect lake clarity by affecting cell size and densities of phytoplankton?
7. Does predation by kokanee salmon on zooplankton affect lake clarity through indirect food-chain relationships with phytoplankton populations?

These questions provide a focus for the long-term monitoring program which is described below. Specific hypotheses, which will guide routine monitoring and other scientific studies, emerge from these questions. These hypotheses direct the sampling effort of the long-term monitoring program toward specific components and processes of the lake system. These components and processes are ranked on a relative scale from 1 to 2, with 1 being of highest importance for evaluating changes in lake clarity, and 2 being of least importance (Table 3).

A key aspect of the proposed sampling program (Table 3) is that it is designed to focus on features of the lake system that affect water column clarity and are also sensitive to changing environmental conditions. Thus, the proposed long-term monitoring program is structured to optimize park management's ability to detect and track changes in the lake. The hypotheses of the program are described on the next page.

Table 3. Proposed elements and priorities of the long-term monitoring program.

Monitoring Element	Priority	Monitoring Element	Priority
Weather	1	Lake level	1
Nutrient input	1	Water Temperature	1
Abiotic particles	1	Clarity (water column)	1
Water quality [1]	1	Lake & spring nutrients	1
Chlorophyll	1	Primary production	1
Phytoplankton	1	Zooplankton	1
Fish	2		

[1] Total alkalinity, pH, conductivity, and dissolved oxygen.

1. Lake clarity is controlled more by abiotic light scattering particles from the caldera walls and suspended lake sediments than by phytoplankton.
2. Secchi disk clarity and the clarity of the water column below a depth of 40 m exhibit a significant, positive correlation.
3. Thermal structure of the water column has no direct influence on lake clarity.
4. Changes in climate, local weather conditions, and lake levels alter clarity by affecting the amount of turbidity entering the lake from the caldera walls and by affecting erosion of the lake shore.
5. Changes in primary productivity alter lake clarity by affecting phytoplankton cell densities and the concentration of chlorophyll.
6. Climate change and air pollution significantly affect primary productivity by increasing nutrient input to the lake and by affecting the amount of upwelling of nutrients from the deep lake.
7. Changes in the species composition, cell densities, and vertical distribution of the phytoplankton are significantly correlated with changes in primary productivity.
8. Picoplankton, the portion of the phytoplankton community that is too small to be seen under a light microscope, contribute significantly to changes in lake clarity and primary productivity.
9. Grazing by zooplankton affects lake clarity by affecting densities and cell sizes of phytoplankton assemblages.
10. Nutrient regeneration by zooplankton contributes significantly to changes in primary productivity and lake clarity.
11. Changes in primary productivity have a significant impact on the abundance and species composition of the zooplankton community.

12. Predation by kokanee salmon affects lake clarity indirectly by altering the taxanomic structure of the zooplankton community.

Special Short-Term Studies

Several studies should be included in the long-term program in addition to the routine sampling conducted to examine the hypotheses described above. These special studies are as follows:

Nutrient Budget and Particle Flux. Biological activity around the edges of the lake certainly affects the nutrient budget of the whole lake. This effect should be evident specifically in the nitrogen budget. This hypothesis is supported by several observations. The highest fluxes of lithogenic and biogenic components occur during late spring, and this flux is probably controlled by solar radiation, the degree of thermal stratification, and nutrients introduced into the euphotic zone from deep lake mixing and snow melt runoff. Recent studies indicate that nutrient recycling is closely related to primary productivity. However, there is an inbalance in the internal nitrogen budget of the lake (see Particle Flux Measurements section). This discrepancy may reflect "edge effects" from the lake margins. Additional studies are needed to evaluate the source of this discrepancy.

Nutrient bioassays. Some assemblages of phytoplankton are probably nutrient limited. Nutrient-limitation experiments with phytoplankton should be conducted to assess which nutrients limit primary production in the lake. Such studies would also help to refine the nutrient budget of the lake.

Nutrient regeneration by zooplankton. Nutrient regeneration by zooplankton probably has a significant effect on primary productivity and the concentration of deep-water chlorophyll. Experiments should be conducted that examine this regeneration by experimental manipulation of nutrients and densities of natural zooplankton assemblages.

Nearshore plants and animals. Biological components of the nearshore zone of the lake probably play important roles in the structure and function of the lake, but little is known about the distribution and abundance of these components. In the nearshore zone of the lake, the identity, distribution, and abundance of macrophytes, attached algae, and benthic macro-invertebrates, and the distribution and abundance of introduced crayfish should be described. Permanent sites should be established and sampled at yearly intervals to assess changes in distribution and abundance through time, especially in relation to changes in climate and the surface elevation of the lake.

Deep-water Moss. Preliminary studies of a deep-water moss *(Drepanocladus aduncus)* in Crater Lake indicate that this moss probably has an important impact on lake productivity and nutrient dynamics. In addition, the moss provides a suitable surface for a diverse assemblage of epiphytal algae which may have significant effects on benthic primary productivity and nutrient availability in certain areas of the lake. The distribution, productivity, and nutrient uptake of this moss should be studied in the field and laboratory.

Zooplankton. Copepods and chydorid crustacean zooplankton, which may only inhabit the littoral zone of the lake, may be important members of the zooplankton community of the lake. A survey of the zooplankton populations in the littoral zone is recommended.

Boat and automobile petroleum wastes. Petroleum wastes from boat traffic on the lake and automobile traffic around the lake may pollute the lake. Studies of the effects of automobile and boat engine exhausts, gasoline, and oil on the lake are recommended. These studies should include an assessment of contributions via runoff from roads and parking lots on the caldera rim.

General Methods for Monitoring and Sampling Schedule

An array of variables should be monitored (Table 4) following methods developed during the initial 10-year study and described in various chapters of this report. Water-quality determinations (e.g., pH, total alkalinity, conductivity, and dissolved oxygen) are included in the program because they provide a basis for an understanding of processes associated with deep-lake circulation. Measurements of these water quality variables also are needed for monitoring the productive capacity of Crater Lake. The weight of abiotic particles should be estimated by filtering known volumes of lake water and then analyzing material retained by the filter to determine the total mass and the concentration of aluminium, a tracer for particulate material from the caldera walls. Although concentrations of total coliform, fecal coliform and fecal streptococcus bacteria have been very low in the springs, a continuation of bacterial sampling at selected springs is recommended, at least for several more years to continue to monitor for possible changes following the recent removal of the sewage gallery.

Access to Crater Lake is a major consideration in the design of a monitoring program. The lake can be reached by foot via the Cleetwood trail only during summer and early fall (June through September). In winter and spring, the lake only can be reached by helicopter or by descending and ascending the caldera wall. Accessibility for sampling in winter, spring, and late fall (October - November) is restricted further by frequent periods of poor weather. Recognizing these limitations and the difficulty of

Table 4. Monitoring parameters at Crater Lake and at intra-caldera springs of the lake.

Weather
- Precipitation, wind speed and direction, temperature, humidity and solar radiation

Lake temperature and conductivity
- Conductivity, temperature, and depth probe (CTD) from surface to a depth of 550 m.

Optical properties of the lake
- 20-cm Secchi disk
- Photometer (to 150 m)
- Transmissometer (to 550 m)

Abiotic properties of the lake

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

Biological properties of the lake
- Chlorophyll *a* concentration
  - *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, and 25-m intervals from 200 to 300 m, including contribution from picoplankton collected through differential filtering primary production (C-14 light/dark bottle)
- C-14 primary production at the chlorophyll sampling depths to 180 m, including contribution from picoplankton collected through differential filtering
- Phytoplankton
  - Species, density, and biovolumes at all chlorophyll sampling depths to a maximum depth of 200 m
- Zooplankton
  - Species, density, and biomass in samples obtained by a vertical tow of a .5 m diameter, number 25 closing net
- 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 echo-sounder

Bulk atmospheric deposition to the lake

Springs 20, 38, 39, 42, 48
- Temperature, pH, conductivity, alkalinity, nutrients, trace elements, and bacteria (total coliform, fecal coliform, and fecal streptococcus).

---

working on Wizard Island in winter, the lake should be sampled at monthly intervals between June and September, when the lake is accessible by foot and when boats can be moored on the lake. Researchers also should strive to sample the lake during periods of good weather at other times of the year. Although weather conditions in the park are not predictable from year to year, sampling should be attempted each year in January and April to match the "off-season" sampling conducted during the 10-year program. Off-season data are considered essential to evaluate seasonal changes in the lake ecosystem. January and April samples provide estimates of the amount of deep-water circulation, concentrations of nutrients, primary productivity, and characteristics of the phytoplankton and zooplankton communities. Sampling from June through September provide information on the limnological conditions of the lake during the period of thermal stratification. With few exceptions, samples should be taken at Station 13 to be consistent with the major sampling site used over the last 10 years.

Program Flexibility

Science, including long-term monitoring, is an iterative process. Looking at the history of the 10-year program, concerns for the outstanding clarity of Crater Lake played a strong role in initiating the program. Conceptual models were developed to guide the scientific inquiries that followed. These models generated specific hypotheses to be tested. Results were used to answer questions and generate new hypotheses to direct additional inquiries through the long-term monitoring program and special studies described in this section.

The proposed monitoring program should progress in a similar dynamic fashion. The growing base of knowledge about the lake should regularly be reviewed, models that describe the structure and functioning of the lake should be revised based on this knowledge, and new hypotheses should be generated for future studies relative to this knowledge and relative to management priorities. Knowledge of the lake system has progressed to the point where some hypotheses about the lake should be tested with experimental studies, because data gathered experimentally often enables a more rigorous test of a hypothesis than data gathered through observation alone. In general, a dynamic, iterative monitoring program ensures that long-term monitoring progresses in an orderly fashion, in accordance with human understanding of the lake system, and in accordance with the value of the lake to society. It is important that the lake is protected from human-related impacts. Furthermore, developing an understanding of those components and processes that are common to lake systems will provide a basis for comparing and assessing the status and trends in lakes elsewhere, especially those already impacted by human-related activities. We will find the resources to wisely manage Crater Lake if we are dedicated to protecting this heritage for future generations.