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Limnology of two new lakes, Mount St. Helens, WA

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AN ABSTRACT OF THE THESIS OF Valerie Jean Kelly for the
Master of Science in Biology presented November 8, 1991.

Title: Limnology of Two New Lakes, Mount St. Helens WA

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

Richard R. Petersen, Chairman

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Coldwater Lake and Castle Lake are two new lakes which
were formed in the aftermath of the volcanic eruption of
Mount St. Helens, WA in May, 1980. This research describes
the limnology of these lakes ten years later, and includes
physical, chemical, and biological parameters. The two
lakes are compared and contrasted. Previous research on the
eruption and its aftermath, as well as earlier studies of

the lakes are described.

A total of 30 field trips occurred during the summer, 1989 and 1990; physical measurements included temperature, dissolved oxygen, light intensity, and the construction of bathymetric maps. Laboratory analysis included major nutrients ($\text{NO}_3\text{-N}$, $\text{PO}_4\text{-P}$, total phosphorus, SiO_2), as well as major ion analysis for selected trips. Biological data include phytoplankton species composition and abundance, as well as biovolume and chlorophyll a. Zooplankton species composition and abundance are also reported. Trophic state indices are compared for the various parameters.

Both lakes are moderately productive, having undergone a decrease in trophic status since their inception as hypereutrophic systems. Coldwater Lake continues to receive high inputs of inorganic ions from the watershed, which the watershed of Castle Lake does not supply. Both lakes develop an oxygen deficit in the deep water, which is moderated by the great volume of the hypolimnion of Coldwater Lake and accentuated by the small volume of Castle Lake. The phytoplankton in Coldwater Lake is dominated by the diatom *Cyclotella*, while phytoplankton in Castle Lake is dominated by chrysophyte flagellates.

LIMNOLOGY OF TWO NEW LAKES,
MOUNT ST. HELENS WA

by
VALERIE JEAN KELLY

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
in
BIOLOGY

Portland State University
1992

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DEDICATION

This thesis is dedicated to my father.

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INTRODUCTION

The catastrophic volcanic eruption of Mount St. Helens, Washington in May, 1980 radically altered the landscape north of the mountain. The eruption blew out the north flank of the volcano, producing an immense avalanche and destroying the forest that had previously covered vast areas of the region. Avalanche debris produced enormous mudflows which streamed across the volcanic deposits and down the valleys of the Toutle and Cowlitz Rivers, causing floods which destroyed roads, bridges, and homes. The drainage valleys of North Coldwater Creek and South Castle Creek, on the northwest flank of the mountain, were dammed by debris-avalanche deposits which were overlaid by the mudflow as it moved down the North Fork Toutle River. Subsequently, streamwaters collected behind these debris dams, filling the impounded drainage valleys and creating two new lakes, Coldwater and Castle, which have remained stable in the ten years since they were established. They provide a unique opportunity for scientific research into the natural process of evolution of lakes following cataclysmic formation.

The purpose of this research included the following objectives: (1) Describe the limnology of two recently

created lakes, Coldwater and Castle; (2) Compare recent limnological data (1989-1990) with data collected in 1980 and 1981, shortly after the lakes were formed, to determine how and to what extent these lakes have evolved over the past decade; (3) Compare and contrast the limnological attributes of Coldwater and Castle lakes; (4) Provide the U.S. Forest Service's Mount St. Helens National Volcanic Monument with reliable baseline limnological data for use as a basis for comparison with future investigations; (5) Determine to what extent each lake has evolved in response to morphometric-edaphic-climatic interactions, that is, to estimate trophic status and identify the factors contributing to these trophic states.

SUMMARY OF EARLIER STUDIES OF MOUNT ST. HELENS

PHYSICAL SETTING

Mount St. Helens is located in southwestern Washington, on the west side of the Cascade Mountain Range, between 46°10' and 46°15' latitude north, and 122°10' and 122°15' longitude west. Prior to the explosive eruption of May 18, 1980, which followed a series of eruptive episodes beginning on March 27, 1989, the mountain was a symmetrical composite volcano or stratovolcano rising to a height of 2960 meters above sea level (cf. Janda et al. 1985). The hillslopes of the upper Toutle River Valley, on the northwest flank of the volcano, are relatively steep, with an average gradient of 45% (Collins and Dunne 1988). The area is underlain by Tertiary volcanic and metavolcanic rocks, which had weathered to a loamy and well-aggregated colluvium soil with a correspondingly high infiltration capacity (Collins and Dunne 1988). Despite the recent history of volcanic activity by Mount St. Helens, only 137 years having passed since the last previous eruptive incident, a dense coniferous forest had developed on the mountain, dominated by Douglas fir (*Pseudotsuga menziesii*), Western hemlock (*Tsuga heterophylla*), and Western redcedar (*Thuja plicata*)

up to about 900 meters, and at higher elevations by true firs (*Abies* sp.) (Franklin and Dyrness 1973).

Precipitation in the area typically follows a strong WNW to ESE orographic gradient and varies from 165 to 305 cm yr⁻¹ (USDA SCS and US Weather Bureau 1975). The winter rainy season generally begins in October and persists until spring with a peak in December or January; about 75% of the annual total precipitation falls during this period, and is most often associated with low intensity storms, rather than heavy rains (Collins and Dunne 1988). Freezing level throughout the winter sometimes reaches to sea level and may be as high as 1000m; the snow line is usually between 750 and 1200 m at midwinter, and snow accumulation, which can be as much as 7.6 m at higher elevations, is an important factor in the hydrology of the system (Meyer and Dodge 1988). When warm spring rain falls on the dense snow, snow melt is added to the runoff from rainfall, causing the highest flows of the year during this period, essentially the month of April.

Eruption Events

On May 18, 1980, following the development for nearly two months of a massive bulge on the north slope of Mount St. Helens, a magnitude 5.2 earthquake caused the north flank of the mountain to collapse, one of the largest gravitational slides of historic time (Janda et al. 1985). This debris avalanche deposited 2.8 km³ of unconsolidated

and poorly sorted material over an area of 60 km², advancing 23 km down the North Fork Toutle River Valley. The thickness of the deposit averaged 45 m and attained a maximum height of 195 m about 2.5 km west of the old Spirit Lake Lodge (Voight et al. 1981). The flow of the avalanche was guided by the strongly dissected nature of the topography of the region, causing the formation of several avalanche lobes; one of these descended into Spirit Lake, raising the level of the lake about 60 m and blocking the outlet. A part of this sector of the avalanche came up and partially overtopped a saddle of Coldwater Ridge, coming to rest in the valley of South Coldwater Creek. The primary lobe was deflected from its northward course to the west by Coldwater Ridge, effectively damming both North Coldwater Creek and South Castle Creek as it traveled down the valley of the North Fork Toutle River.

The avalanche was accompanied by a release of confining pressure which caused immediate phreatic and magmatic explosions, resulting in the generation of a directed blast that advanced outward in an 180° arc north, hugging the ground, at velocities of about 200 m s⁻¹ (Janda et al. 1985). The intense heat and force of this blast destroyed nearly all the above-ground vegetation within an area of 550 km², uprooting trees and removing them from south-facing hillsides as far as 13 km from the volcano (Collins and Dunne 1988). Those hillslopes nearest the vent were

affected most dramatically, experiencing scouring of the soil at least partially, if not totally, by the hurricane force of the winds associated with the blast cloud. The blast deposited an additional 0.01-1 m of noncohesive material over the area as well, consisting primarily of pieces of rock, soil, and wood fragments, in sizes ranging from fine silt to small pebbles (Janda et al. 1985).

Within minutes of the onset of the eruption, the heat of the pyroclastic debris began to melt snow and ice on the upper regions of the volcano, producing destructive lahars which swiftly travelled down Smith and Pine Creeks and the Muddy River on the eastern flank of the mountain, entering the eastern end of Swift Reservoir before an hour had elapsed (Foxworthy and Hill 1982). Mudflows developed on the western slope of the mountain during the initial hours after the eruption, coursing down the South Fork of the Toutle River. The enormous mudflow that developed hours later in the North Fork of the Toutle River was characterized by a sustained sediment load which carried pebble- and cobble-sized pieces of rock 120 km to the Columbia River, attaining a total volume 10 times that of the other lahars (Janda et al. 1981). The deposits left by these various lahars are similar in composition, being primarily gravels in a highly erodible silt and clay matrix (Janda et al. 1981). The thickness of the mudflow deposits ranges typically from 0.5 to 2 m (Janda et al. 1981), with

3-4 m of fill occurring at some locations on the flood plain of the North Fork Toutle River.

Shortly after the lateral blast had begun, a vertical eruption column developed from the old volcanic summit crater, producing dense clouds of ash, or tephra, of varying textures. This eruption column persisted for 9 hours, releasing 1.1 km³ of uncompacted tephra (Janda et al. 1985). Most of this tephra plume was swept to the east, and deposits were found more than 1500 km away. None of these deposits, however, were thick, even close to the crater. Within the area extending approximately 12 km from the crater, ash deposits reached a maximum of 100 cm at various sites. The surface layer of this tephra deposit formed a silty crust with a low infiltration capacity overlying the other deposits resulting from the eruption.

Hydrologic Impacts

The heavy cloak of sediment which was deposited over the stream channels and hillsides surrounding Mount St. Helens has had a profound effect on the hydrology of the area. Stream discharges were increased, with flood peaks exceeding those normally observed only once in 25 years (cf. Janda et al. 1985). Several factors contributed to the rise in runoff and discharge, including scouring of stream channels by lahar flows, reduced infiltration capacity of the soil, and elevated levels of suspended sediment in stream flows.

Streams in the Mount St. Helens area flowed through dense forest prior to the eruption in May 1980, and were characterized by bed material of cobbles and boulders, often accumulating downed tree trunks and other coarse debris (Janda et al. 1985). The hydraulic roughness of these streams was significantly decreased when the lahars poured down them, removing all vestiges of these large woody and cobblestone elements.

Infiltration capacities of the soil were drastically affected by the deposits which were laid down during the eruption. Immediately after the explosion, and throughout the first summer, the surface crust formed by the airfall tephra caused the soil in the areas north of the volcano to be nearly impervious; infiltration capacities of 1 to 4 mm hr⁻¹ were measured in August 1980, in contrast to values which were typically greater than 50 mm hr⁻¹ and often greater than 100 mm hr⁻¹ before the eruption (cf. Janda et al. 1985). As the winter rainy season proceeded during the first year, sheet erosion by overland flow along the steep slopes, as well as the development of rill and gully systems which eroded into underlying soil, removed 8.0×10^6 m³, or 11% of the tephra deposited by May, 1981 (Collins et al. 1983). Infiltration capacities had increased by August, 1981, to 7 to 9 mm hr⁻¹ in some areas (cf. Collins and Dunne 1986).

The finest material was removed during this initial

period; about one half of this material was sand (0.0625 to 2 mm grain size), and another one third of it was less than 0.0625 mm in size (silt and clay). Thirty percent of all the sediment removed from hillslopes during the first year following the eruption was deposited in the lake systems impounded by the debris avalanche, with the remainder transported into the Toutle River system (Collins et al. 1983). Coldwater Lake had received 2.11×10^6 t of sediment by the end of this period, fully 17% of the total sediment eroded from the area; Castle Lake received 0.23×10^6 t of sediment during this same interval, less by a factor of ten.

During the second year, the extent of rill and sheet erosion was decreased to 16% of the total for the first year; this reduction was largely due to the exposure of the underlying soil with its profuse root mat, as well as the stability of the rill drainage systems (Collins and Dunne 1986). By 1983, hillslope erosion had been replaced by stream-bank erosion as the major source of sediment discharge to the primary drainage systems of the area. These stable gully systems provided a suitable substrate for the reestablishment of vegetation cover in the area devastated by the eruption, as well. Stabilization of the soil was assisted thereby, and losses from erosive processes were further decreased (Frenzen and Chrisafulli 1990).

A sediment trap analysis performed in the summer of 1982 and 1983 indicated that sediment yield into Coldwater Lake

continued to surpass, by two orders of magnitude, the typical values observed for lakes of comparable drainage basins which are covered with vegetation (Anderson et al. 1985). Erosion in the South Coldwater Creek drainage was severe due to the proximity of the area to the crater, and the large quantity of non-cohesive deposit material which was deposited there (Larson and Glass 1987). As the stream reached the lower reaches of the drainage, the declining slope of the valley allowed the deposition of sand and gravel, forming a delta at the point where South Coldwater Creek entered Coldwater Lake. The remaining sediment load was largely deposited in the quiet waters of the lake, so that the water leaving via the manmade outlet channel was relatively clear (Larson and Glass 1987).

Sediment discharge into Coldwater Lake was increased further by the construction of the tunnel outlet for Spirit Lake into South Coldwater Creek, which became operational in May, 1985, and discharged 20 percent of the volume of the lake within six months of initial release. Significant erosion of blast deposits from the upper and middle reaches of the South Coldwater Creek drainage resulted from the increase in stream flow, removing approximately 900,000 m³ of material between May and October, 1985. Most of this material was deposited in the lower depositional area of the drainage and considerably enlarged the delta into Coldwater Lake (Larson and Glass 1987).

Water quality of South Coldwater Creek was observed during the summer, 1986, to be essentially identical to that of the tunnel outflow from Spirit Lake, with the exception of turbidity, which was several orders of magnitude greater. Evidence from that summer suggested that mixing of waters from South Coldwater Creek in Coldwater Lake was incomplete, as waters in the lake outflow showed water chemistry intermediate between the inflow and the body of the lake (Larson and Glass 1987). The close proximity of the inflow of South Coldwater Creek and outlet channels in the lake is likely to be a factor preventing complete mixing.

LIMNOLOGICAL BACKGROUND

Initial studies of the lakes on Mount St. Helens were begun late in June, 1980, and assessed the impact of the eruption by comparison of lakes located within the blast zone, defined as the area contained within a radius of 16-28 km north of the crater, to lakes outside of the blast zone, considered to have been unaffected by the eruption (Wissmar et al. 1982a). Both Coldwater Lake and Castle Lake (referred to as North Coldwater Lake and West Castle Lake in the above paper) are located within the blast zone. No samples were analyzed from North Coldwater Lake on this date; data are presented for South Coldwater Lake, however, a transitory lake which formed temporarily behind obstruction of South Coldwater Creek. All the lakes in the

blast zone shared similar characteristics, according to this report; it seems reasonable to assume, therefore, that the characteristics of North Coldwater Lake were likely to have been comparable for this date.

Further analysis of chemical and biological characteristics was made the following spring, 1981, for both Coldwater Lake and Castle Lake (Dahm et al. 1981). Later studies were made in August, 1982 (Smith and White 1985), and intermittently throughout the next two years (D. Larson unpublished data). Chemical data available for Coldwater and Castle Lake in June, 1980, April, 1981, August, 1982, and September, 1984, are presented in Table I.

Major Ions

In terms of cations, concentrations of calcium, magnesium, and sodium were increased in all blast-zone lakes up to forty times the levels found in the lakes unaffected by the blast (Wissmar et al. 1982a); potassium was elevated as well, although most markedly in Castle Lake. Levels of manganese and iron were also increased, generally by one to two orders of magnitude, although iron in Castle Lake was increased an additional order of magnitude higher than in the other two blast zone lakes for which data is available. Major anions in these lakes were bicarbonate, sulfate, and chloride, as is typical. But levels were again several orders of magnitude higher than those in the unaffected lakes. Wissmar et al. (1982a) suggest that hydrothermal

processes and chemical weathering of blast deposits proceeded quickly in the heat of the pyroclastic flows, aided by the small size of the particles, with their corresponding large surface area and high reactivity.

TABLE I

MAJOR ION DATA FROM 1980-1984
COLDWATER LAKE AND CASTLE LAKE

		Concentration (meq/l)		
<u>South Coldwater</u>		<u>Coldwater Lake</u>		
	30 June 1980	30 April 1981	August, 1982	Sept 1984
Ca ⁺⁺	4.54	1.54	0.93	0.89
Mg ⁺⁺	1.21	0.56	0.57	0.36
Na ⁺	3.83	1.06	0.27	0.49
K ⁺	0.44	0.10	0.08	0.04
Cl ⁻	3.24	N.D.	N.D.	N.D.
SO ₄ ⁼	6.50	1.13	N.D.	N.D.
Alk	1.52	1.17	N.D.	0.64
Fe (mg/l)	0.18	0.05	0.10	July 1983 0.05
		<u>Castle Lake</u>		
	30 June 1980	30 April 1981	August 1982	Sept 1984
Ca ⁺⁺	4.71	1.13	0.64	0.49
Mg ⁺⁺	1.74	0.42	0.19	0.15
Na ⁺	4.87	0.66	0.11	0.16
K ⁺	1.02	0.08	0.06	0.02
Cl ⁻	4.01	N.D.	N.D.	N.D.
SO ₄ ⁼	2.50	0.27	N.D.	N.D.
Alk	4.5	1.38	N.D.	July 1983 0.48
Fe (mg/l)	15.70	1.51	0.10	0.03

During the winter and spring of 1981, dilution of both Coldwater Lake and Castle Lake was considerable due to the heavy accumulation of snow and precipitation characteristic of the region. The volumes of both lakes increased significantly; Coldwater Lake swelled from $1.3 \times 10^7 \text{ m}^3$ in the autumn of 1980, to $8.0 \times 10^7 \text{ m}^3$ in the spring, 1981, and Castle Lake increased proportionally even more, from $1.3 \times 10^6 \text{ m}^3$ to $1.8 \times 10^7 \text{ m}^3$ during the same period (cf. McKnight et al. 1984).

Dilution of major ions was also substantial over the course of the initial winter following the eruption, although values remain elevated compared to those observed in lakes outside the blast zone. Data are not available for comparison for Coldwater Lake from the first summer; however, analysis of cations from that lake in April, 1981 reflect values three to six times those in the unaffected lakes. On the same date, measurements from Castle Lake indicates that dilution was not proportional in that lake for all ions. Calcium and magnesium, in particular, are increased in relation to others, being lowered to 1/4 the initial concentrations by the 13-fold increase in lake volume, from 94.30 mg/l and 21.19 mg/l to 22.1 mg/l and 5.01 mg/l, respectively. Concentrations of potassium declined consistently by a factor of 13, while sodium decreased relatively somewhat less, by a factor of seven (Wissmar et al. 1982a, Dahm et al. 1981b). This asymmetry suggests

watershed or sediment characteristics may have been influencing the influx of these ions into Castle Lake.

Dissolved Organic Carbon

In addition to dissolved mineral input, a second consequence of the eruption was the enormous influx of dissolved organic carbon (DOC) as a result of dissolution of pyrolyzed forest and soil particulates entrained in the blast deposits, as well as the leaching of plant material and volcanic ash, coated with pyrolyzed organic material, which blanketed the lake watersheds (McKnight et al. 1988, Pereira et al. 1980). In June, 1980, measurements of DOC in Castle Lake were 148.65 mg/liter (Wissmar et al. 1982b); in comparison, DOC concentrations in lakes outside the blast zone ranged from 0.65 to 2.28 mg/liter. By August or September, 1980, DOC in Coldwater Lake exceeded 100 mg/l and Castle Lake levels were greater than 200 mg/l (Baross et al. 1982). Characterization of the dissolved organic material, four months after the eruption, described it as primarily yellow organic acids, with relatively high molecular weight, resembling aquatic fulvic acids (McKnight et al. 1984).

Over the winter following the eruption, concentrations of DOC were correspondingly diluted as well, although values remained elevated six to ten times those observed in Spirit Lake prior to the eruption (McKnight et al. 1984). In Castle Lake, DOC decreased from 135 mg C/liter in late summer 1980, to 10.2 mg C/liter in the spring 1981 (McKnight

et al. 1988). Dilution of DOC in Coldwater Lake reduced concentrations from 114 mg C/liter to near 6 mg C/liter (Dahm et al. 1981a). One possible explanation suggested for the disparity between the 6-fold increase in lake volume and the 19-fold dilution of DOC is an increased rate of water renewal for this period in Coldwater, for which an outlet had been created at this time, compared to Castle, still a closed system (Wissmar et al. 1988, McKnight et al. 1984).

Temperature/Dissolved Oxygen

Lake temperatures were increased, although moderately, by the immense heat of the lateral blast (200-350° C); Spirit Lake was found to have a surface temperature of 32.7° C the day after the eruption, while a representative surface temperature for a Cascade lake in May is typically less than 10° C (Dahm et al. 1981b). By the end of June, 1980, the temperature had decreased somewhat to 22° C, still atypically high (Wissmar et al. 1982b). This increased temperature, in concert with the excess quantities of organic carbon and inorganic nutrients, provided the environment for the development of dense heterotrophic bacterial communities. Oxygen supplies in the water column were rapidly depleted as a consequence of intense microbial oxidation of organic carbon, as well as the decreased solubility of dissolved oxygen at higher temperature. Completely anaerobic conditions were reported for both Coldwater Lake and Castle Lake by August 1980. Under these

conditions, the bacterial community was converted to obligately or facultatively anaerobic organisms (Dahm et al. 1981b).

The abundant inflow of oxygenated waters as snow melt and runoff from rain through the winter resulted in near-normal levels of oxygen in both lakes by early spring, 1981; dissolved oxygen levels of 7.5 to 8.0 mg/l were observed on April 30, 1981, at the surface of Castle and Coldwater Lakes, respectively, before the onset of thermal stratification (Dahm et al. 1981b). There was no decrease with depth in Coldwater Lake on this date, although the deeper waters of Castle Lake were already showing an oxygen deficit. By the end of June, the lakes were well stratified and the bottom waters of Castle Lake were nearly anoxic; anaerobic conditions were maintained below 15 m throughout the summer. In contrast, although oxygen levels were beginning to be depleted in the deeper waters of Coldwater Lake in June, oxygen persisted at all depths until the end of August, when the D.O. level reached zero below 25 m (Dahm et al. 1981a).

Alkalinity

In the aftermath of the eruption, carbon dioxide was released by the degradation of the elevated levels of DOC, saturating the water. Total alkalinities were greatly increased, measuring 2.54 meq/liter in Coldwater Lake by the end of the summer, 1980, and 4.50 meq/liter in Castle Lake,

compared to 0.15 meq/liter in the unaffected lakes (Dahm et al. 1981b). Although the carbonic acid system contributed significantly to the buffering capacity in these lakes, the high concentrations of minerals and buffering by dissociation of humic substances also played a part (Wissmar et al. 1990). As a result, pH was not markedly acidic in any of the lakes in the blast zone when sampling was initiated at the end of June, although the value reported at that time for Castle Lake was 6.17, the lowest observed for lakes in the area (Wissmar et al., 1982a).

Light Extinction

The enormous input of blast deposits greatly increased the concentrations of suspended particulate matter (SPM), with a corresponding effect on light extinction coefficients, in the waters of lakes in the blast zone. The SPM in South Coldwater Lake was recorded at 89.58 mg/liter on June 30, 1980, reflecting the steepness of the Coldwater Creek drainage area; Castle Lake SPM was lower at 46.36 mg/liter, and the corresponding light coefficient extinction was 12.43, (Wissmar et al., 1982b).

By the summer of 1981 in Coldwater Lake, where suspended particle load remained high, the depth of 1% surface light intensity was 1.3 m on June 29. Light measurements were not taken at Castle Lake in 1981, although levels of suspended particulate matter were less, implying light attenuation might not be as pronounced. Another

factor to consider, however, is the much greater concentration of DOC in Castle Lake, which would have had a staining effect on the water, and be expected to increase the light attenuation despite the lower levels of particulate material in the lake.

Biological Processes

Measurements of adenosine triphosphate (ATP) were taken in June 1980 as an indication of biotic activity in the blast zone lakes (Wissmar et al. 1982b), and were greatly increased. These increases were presumed to be primarily associated with bacterial growth, as chlorophyll a concentrations were extremely low or undetectable. Despite the intense competition for nutrients with the high numbers of bacteria present, the extreme light attenuation was assumed to be the primary limiting factor controlling algal growth. It is also possible that phytoplankton growth was inhibited by exposure to volcanic ash, as suggested by algal bioassay analysis (cf. Wissmar et al. 1982).

Algal surveys conducted during August and September, 1980, reported very low densities of phytoplankton in lakes directly affected by the eruption. For Castle Lake, a value of 5×10^2 total cells/liter was observed in August, 1980; total phytoplankton counts increased to 2.8×10^5 cells/liter by June, 1981 (Ward et al. 1983). Species observed included primarily diatom fragments the first year, and shifted to predominantly cryptomonad microflagellates in

1981. Extremely low values for chlorophyll, in addition, were observed in April, 1981, for Castle Lake and suggest phytoplankton activity continued to be inconsequential (Dahm et al. 1981a). Persisting high levels of metals and organic matter could be factors related to the inhibition of phytoplankton growth (Wissmar et al. 1988).

Microbial communities were reported as exceeding 10^8 cells per ml for both Coldwater Lake and Castle during the summer, 1980, with manganese/sulfur oxidizing bacteria comprising the bulk of the bacteria present (Baross et al. 1982). Iron, manganese, and sulfur were solubilized from the sediment layers and suspended particulate matter via a complex of bacterial reduction reactions as anoxic conditions developed throughout the water columns of these blast-zone lakes. Active methanogenesis and sulfate reduction was suggested by reports of waters darkly stained with sulphides and persistent bubbling of CH_4 and CO_2 with trace amounts of H_2 , CO and N_2O , on the surface of Coldwater Lake during the summer and fall of 1980 (Baross et al. 1982). In the absence of oxygen, nitrate is presumed to have been the alternative electron acceptor facilitating the growth of the metal oxidizing bacterial communities, which were not confined to the sediments but were found distributed throughout the anoxic waters (Dahm et al. 1981a).

Bacterial numbers continued to be recorded in the range

of 10^7 to 10^8 cells/ml for both Coldwater and Castle Lakes during the summer of 1981 (Dahm et al. 1981b). Measurements for manganese/sulfur oxidizing bacteria indicated they were still an important segment of the bacterial community in both lakes, similar to observations for the initial months following the eruption (Dahm et al. 1981a). Carbon fixation rates in the plankton were low (24-48 mg C/m³/day); significantly, fixation rates in the dark were roughly equal to those in the light (Dahm et al. 1981a). It is assumed, therefore, that chemolithotrophic organisms dominated the autotrophic planktonic communities; phytoplankton, as noted, are presumed to have constituted a negligible fragment.

Nutrient Cycling

Lakewaters were greatly enriched with carbon, both in dissolved organic form (DOC) and as inorganic CO₂, derived from the massive quantities of forest debris deposited in the lakes. It is significant that nitrogen is present to a lesser degree in conifer wood tissue when compared to typical microbial biomass (Hooper et al. 1980). In samples taken during August and September, 1980, DOC/DON ratios were extremely high (>160) for both Coldwater and Castle Lakes, compared to a C:N ratio of around 6 for bacterial tissue (Dahm et al. 1981a).

Phosphorous was also plentiful, especially when compared to nitrogen, being a leachable component of the avalanche deposits as well as the volcanic ash; leaching

experiments demonstrated the release of 3 p.p.m. soluble PO_4 from an aqueous suspension of Mount St. Helens ash under aerobic conditions (Hoope;r et al. 1980). In contrast, very little nitrogen was contained in the ash (cf. Baross et al. 1982). The ratio of inorganic nitrogen (NH_4^+ , NO_2^- , and NO_3^-) to inorganic phosphorous (PO_4^{-3}) was 2:1 or less in water samples taken August and September, 1980 (Dahm et al. 1981a), which suggested nitrogen as the limiting nutrient for the biota, as a N:P of 7:1 is considered typical of most bacterial or algal tissue.

Due to the limiting concentrations of nitrogen in these environments heavily fortified with other nutrients, nitrogen cycle processes are believed to have dominated the cycling of carbon, sulfur, and reduced metals in all the blast-zone lakes by the end of the summer, 1980 (Dahm et al. 1981a, Wissmar et al. 1988). Denitrification was occurring, presumably throughout the anoxic water column, coupled with the anaerobic oxidation of reduced compounds by chemolithotrophic bacteria. Significant rates of nitrification were limited to oxygenated waters (i.e. the littoral and surface waters of Ryan Lake, another blast-zone lake); unusually high rates were observed in the surface stream which feeds into Coldwater Lake, presumably the origin of nitrate in the lake (Baross et al. 1982). New nitrogen was introduced to the lake systems via extremely high rates of nitrogen fixation.

As has been previously discussed, iron and manganese levels were elevated immediately following the eruption >350 times concentrations reported for lakes outside the blast zone (Wissmar et al. 1982a). Consistent with the dilution of lake waters over the first winter, concentrations were lowered considerably. Levels of iron decreased in Coldwater Lake from 6.27 mg/l at the surface in late summer, 1980, to <1 mg/l in April, 1981, but still more than twice the levels associated with unaffected waters (Dahm et al. 1981a, Wissmar et al. 1982a). However, iron levels of around 1.5 mg/l remained fairly constant in Castle Lake during this same period, more than 37 times the levels observed outside the blast zone, implying continuous influx of that element (Dahm et al. 1981a, Wissmar et al. 1982a). As the summer of 1981 progressed, ferrous iron was increasingly generated in the anoxic waters of Castle Lake, with a concentration of nearly 3 mg/l reported in the hypolimnion by late August. Similar build up of reduced metals was not reported for Coldwater Lake, presumably as a consequence of the more widespread oxygenated condition in that lake (Dahm et al. 1981b).

Nitrogen cycle processes continued to be significant components of the biological activity in both lakes during the second year after the eruption, particularly in Castle Lake. Nitrification was active, as indicated by increased concentrations of nitrate at the surface relative to those

in the deep water. Increased levels of ammonia, as well as DOC in the anoxic waters, coincident with sulfate reduction in the sediments as suggested by the release of H_2S , indicated intense bacterial metabolism of the high organic content in the sediment layer. Denitrification in the anaerobic hypolimnion was suggested by the decrease in N_2O gas with depth. These observations are supported by the high rates of nitrifying and denitrifying activity reported for Castle Lake during the summer, 1981 (Wissmar et al. 1988). In Coldwater Lake, however, the pattern differed somewhat, as levels of all species of inorganic nitrogen were substantially less, and rates for nitrification and denitrification were also decreased. Again, an explanation suggested for the difference between the two lakes is a consequence of the greater volume in Coldwater Lake and the existence of an outflow, which allowed greater dilution and water loss (Wissmar et al. 1988).

Both Castle Lake and Coldwater Lake apparently shifted by the summer, 1981, from a nitrogen-limited system to a phosphorus-limited one, as evidenced by much higher concentrations of inorganic nitrogen species in contrast with very low levels of inorganic phosphate. In June, 1981, for example, N/P ratios in Castle Lake ranged from 45 to 59, and Coldwater Lake was similar, while Spirit Lake continued to reflect characteristics of nitrogen limitation (N/P of <1) (Dahm et al., 1981b). In addition, no evidence of

nitrogen fixation was observed in either lake during the summer, 1981 (Wissmar et al. 1988). A possible explanation is offered for the change to a phosphorus limited system (Dahm et al. 1981b) which considers the avalanche deposits as a source for phosphorus in these lakes. Since both Castle Lake and Coldwater Lake were formed behind the avalanche deposit, which is enriched in phosphorus, while Spirit Lake received a considerable deposit load directly, the content of volcanic material is likely to be much less in the newly formed lakes, with a consequent reduced supply of leachable phosphorus to the system. A second possibility suggested, scavenging of phosphate by insoluble iron phosphates, is unlikely as no buildup of phosphate was noted in the anaerobic hypolimnion of Castle Lake as the summer progressed, while concentrations of reduced iron increased considerably under those conditions (Wissmar et al. 1988).

METHODS

FIELD SAMPLING

Coldwater Lake was visited nine times in 1989 and eight times in 1990. Castle Lake, less accessible because of early summer snowfall, was visited six times in 1989 and six times in 1990. Data is reported from one station per lake, although sampling was conducted routinely at two stations, with most of the work done at station 1 (Figure 2 and 3). Sampling stations were marked with a buoy for consistency; the primary stations for which data are reported were located over the deepest part of each lake.

During each trip, transparency was measured using a 30 cm diameter Secchi disk. Temperature measurements were made with a thermister (Montedoro-Whitney Corp., model TC-5C) at intervals of one meter between the lake surface and 20 meters, and at five meter intervals between 20 m and 50 m. Samples for dissolved oxygen (D.O.) were collected at various depths; samples were immediately fixed, as described below, and stored in the dark until laboratory analysis could be completed, within 24 hours.

One liter samples were taken, using a 2.5 liter Van Dorn bottle, for nutrient and chlorophyll a analysis; five depths were sampled, two replicates at each depth. Samples

were transferred to acid-washed, dark amber polyethylene bottles which were placed on ice within one hour. Filtering was done in the field for dissolved $\text{PO}_4\text{-P}$ analysis, using Whatman GF/C glass microfiber filters; samples were stored on ice in acid-washed, dark amber polyethylene bottles. Within 24 hours, laboratory analysis was completed, as outlined below.

Samples for identification and enumeration of phytoplankton were collected at intervals of 5 m from the lake surface to 20 m and were stored in 250 ml dark amber polyethylene bottles, preserved in a 1% Lugols solution. Plankton tows for the identification and enumeration of zooplankton were performed at various depth intervals, generally sampling the epilimnion, thermocline, and hypolimnion regions of the water column. The plankton net used a pore-mesh size of 130 μm , with a 50 cm mouth and a 5:1 scope ratio. Identification and enumeration was performed by Allan Vogel.

On three occasions at each lake in 1989, water samples were taken for major ion analysis; analytical data were provided by the Cooperative Chemical Analytical Laboratory established by Memorandum of Understanding No. PNW-82-187 between USDA Forest Service and the Department of Forest Science, Oregon State University. The sample depths were surface, approximate mid-lake, and bottom for both lakes. Samples were filtered in the field, using pre-washed and

oven dried Whatman GF-C glass fiber filters; samples were placed immediately on ice. Analysis was performed for the following ionic constituents (reported in mg/l): Na, K, Ca, Mg, Fe, Cl, $\text{SO}_4\text{-S}$, dissolved solids, and hardness as CaCO_3 .

Transects of depth soundings were performed during the summer, 1990, using a Morrow recording depth sounder, and were used to construct bathymetric maps.

LABORATORY ANALYSIS

Nanopure distilled water (Barnstead Nanopure II dionizer) was used exclusively in the preparation of all reagents. Washing consisted of six rinses with Nanopure distilled water, followed by soaking in 4% HCl for a minimum of four hours, generally overnight, before rinsing again six times and air drying.

A complete description of the laboratory methods, including the preparation of reagents, can be found in Appendix A.

Nitrate-Nitrogen

Nitrate analysis was by reduction with cadmium, according to Jones (1984). The method detects the combined concentrations of nitrate and nitrite. It was assumed that very little nitrite was present under the conditions in Coldwater and Castle Lakes.

Dissolved ortho-Phosphate and Total Phosphorous

Procedures for dissolved ortho-phosphate and total phosphate analysis were according to Wetzel and Likens (1979); persulfate digestion of total phosphorous was according to Standard Methods (1976).

Dissolved Silica

Reagents and procedure for silica analysis are according to Wetzel and Likens (1979). Preparation of the silica standard was according to Dennis Barnum (personal communication).

Chlorophyll a

Chlorophyll a analysis is according to the method of Golterman (1971).

Winkler Method for Dissolved Oxygen

The Winkler method is described in Wetzel and Likens (1979).

Phytoplankton Identification and Enumeration

Phytoplankton identification for Castle Lake was according to the inverted microscope method outlined in Wetzel and Likens (1979). Preparation of microscope slides for phytoplankton identification for Coldwater Lake was according to Jim Sweet (personal communication).

RESULTS

MORPHOMETRY

Bathymetry of Coldwater Lake

Coldwater Lake lies in a basin featuring steeply sloping sides which deepen to form a narrow canyon at the bottom in the upper regions of North Coldwater Creek (Figures 1 and 2). The reduced slope of the downstream region of the creek suggests that a prior eruption of Mount St. Helens had previously deposited material in the Toutle River Valley, leveling the land gradient at the confluence of South and North Coldwater Creeks with the North Fork Toutle River. The massive debris avalanche which preceded the explosive eruption of Mount St. Helens in 1980 was laid on top of these older deposits, forming the dam behind which North Coldwater Creek became Coldwater Lake.

Coldwater Lake is long, narrow, and relatively deep (Table II). In contrast with the prior topography, the bottom as shown in Figure 2 is very flat in both the transverse and the longitudinal profile, indicating the considerable input of sediment which the lake has received. The flattened gradient at the downstream end of the lake has been preserved, and has contributed to the formation of the large, arcuate delta where South Coldwater Creek enters the

Figure 1. Topographic map, Coldwater Creek and Castle Creek, 1957, prior to 1980 eruption of Mount St. Helens.

Figure 2. Bathymetric map, Coldwater Lake, summer 1990.

TABLE II

PHYSICAL CHARACTERISTICS FOR COLDWATER LAKE AND CASTLE LAKE
SUMMER 1990

	<u>Coldwater Lake</u>	<u>Castle Lake</u>
Coordinates	46°18'04"N/122°15'06"W	46°15'29"N/122°16'32"W
Elevation (m)	762	796
Maximum Length (m)	5.11 x 10 ³	2.37 x 10 ³
Maximum Breadth (m)	9.85 x 10 ²	7.44 x 10 ²
Area (km ²)	3.10	1.07
Volume (m ³)	8.38 x 10 ⁷	2.16 x 10 ⁷
Maximum Depth (m)	62	32
Mean Depth (m)	27	20
Relative Depth (%)	3.1	2.8
Shoal Area (% <3m)	9.5	5.8
Shore Line (m)	1.41 x 10 ⁴	6.24 x 10 ³
Shoreline Development	2.26	1.70
Volume Development	1.31	1.88
Watershed Area (km ²)	49.45	8.67
Retention Time (yr)	1.7	2.5

lake. Because of the lake's southwesterly exposure, and the fetch of more than 5 km, the wind has contributed to the erosion of the upper reaches of the lake basin, forming an extensive littoral shelf. The ratio of mean depth to maximum depth (0.44) is additionally indicative of a lake in which shore processes have been considerable (Hutchinson 1957). However, due to the depth and size of the lake, the

shoal area (depth less than 3 m) is less than 10%.

Consequently, although littoral communities would be likely to develop in these shallow regions, their contribution to the productivity of the lake system as a whole would be expected to be limited, except in a localized sense.

Bathymetry of Castle Lake

The prior eruption of Mount St. Helens which affected the gradient in the lower reaches of Coldwater Creek also affected the South Fork of Castle Creek (Figure 1 and 3). It is likely, in fact, that the drainage was previously blocked, forming an earlier lake in the same basin which now holds the current Castle Lake. At the time of the eruption in 1980, this region was known as Castle Creek Marsh, a flat expanse with essentially the same shape as the bottom of Castle Lake today.

Castle Lake is open to the north, with an elliptical shape. The deepest water in the lake is situated at the north end, slightly below the center, as is typical of lakes formed behind a landslide dam (Hutchinson 1957). The effect of wind and waves upon the lake basin is apparently not pronounced, possibly due to the existence of a previously modified shoreline as well as the relatively short fetch distance and protection from the dominant east-west weather patterns of the area (Table II). Consequently, a conspicuous littoral shelf has not formed in this lake, and the extent of shallow water is limited. The ratio of mean

Figure 3. Bathymetric map, Castle Lake, summer 1990.

to maximum depth (0.63) also reflects the insignificance of erosion processes in shaping the lake basin (Hutchinson 1957). With a shoal area of less than 6%, development of littoral communities is unlikely to have a notable effect on the productivity of the lake as a whole.

Hypsographic Depth-Area and Depth-Volume Curves

Figures 4 and 5 are hypsographic depth-area curves and depth-volume curves for a comparison of both lakes. The depth-area curve illustrates the relationship between the surface area of particular depth stratum in a lake and its depth; the area may be represented in real units or as the percentage of the area at the lake surface. It is assumed that the surface area of a depth stratum is equal to the surface area of the sediment layer beneath that stratum. Although the area of the sediment layer is underestimated by these graphs, they do indicate the extent of contact between the trophogenic and tropholytic zones in a lake system. For purposes of this analysis, 20 m was chosen as the hypothetical depth of the bottom of the thermocline, and represents the potential extent of the trophogenic zone.

Coldwater Lake has a surface area nearly three times that of Castle Lake (Figure 4A). A substantial proportion of bottom surface is exposed at the depth of 20 m and shallower in Coldwater Lake (Figure 4B). However, due to the great depth of the lake, the trophogenic and tropholytic zones seem likely to be fairly evenly divided; approximately

A.

B.

Figure 4. Hypsographic (depth-area) curves, Coldwater Lake and Castle Lake, summer 1990.

A.

B.

Figure 5. Hypsographic (depth-volume) curves, Coldwater Lake and Castle Lake, summer 1990.

50% of the surface area is exposed to the waters <20 m in depth, and 50% to waters >20 m deep.

In Castle Lake, on the other hand, although the area involved is much reduced, the fraction of surface exposed to the upper water layer is greater. More than 60% of the total area of the lake is less than 20 m deep. As a consequence, there is more interaction between the region of primary production in the surface waters and the zone of decomposition in the sediment layer.

Depth-volume hypsographic curves depict the relationship between volume and depth in a lake. They illustrate the potential effect of thermal stratification on processes occurring in a lake by providing a measure of the relative volume present in each layer.

The volume of Coldwater Lake is much greater than that of Castle Lake, nearly four times (Figure 5A). Figure 5B illustrates the percentage of total volume located above each respective depth; from the graph it can be determined that, in Coldwater Lake, the lake volume is divided roughly in half at 20 m. In contrast, slightly more than 80% of the total volume of Castle Lake is 20 m or less in depth, implying that the photosynthetically productive region of the lake could comprise a major fraction of the total volume.

LIGHT AND TEMPERATURE

Water Transparency

Figure 6 (A and B) portrays Secchi depth measurements from the summer 1989 and 1990 for Coldwater Lake and Castle Lake, respectively. Direct measurements of light intensity at successive depths were also made on one occasion during the summer, 1990. Table III contains light extinction coefficient results for Coldwater Lake and Castle Lake which were calculated from a semilogarithmic plot of the light meter data. As a check on these readings, light extinction coefficients are also presented which were determined from the light meter readings for surface light intensity and the Secchi measurements, using the formula:

$$nz = \ln I_0 - \ln I_z$$

where z is the mean Secchi depth observed (7.5 m for Coldwater Lake and 8.0 m for Castle Lake), assumed to be the level of 10% light intensity (Wetzel 1983).

TABLE III

LIGHT EXTINCTION COEFFICIENTS, COLDWATER AND CASTLE LAKE

	<u>Coldwater Lake</u>	<u>Castle Lake</u>
Light Meter	0.30 m ⁻¹	0.34 m ⁻¹
Secchi Depth	0.30 m ⁻¹	0.29 m ⁻¹

There is good agreement in these data for Coldwater Lake, although some discrepancy exists for Castle Lake. The Secchi depth measurements are more useful, given that they

A. Coldwater Lake

B. Castle Lake

Figure 6. Secchi depth, Coldwater Lake and Castle Lake, 1989 and 1990.

are based on readings taken over a period of two summers, where the light meter reading was one time only.

Using the formula described above, it is possible to estimate the depth at which the light intensity in a lake is 1% of the surface intensity. This depth is an estimation of the euphotic zone, as it represents the maximum depth at which photosynthetic production of phytoplankton is generally considered to exceed the demands of respiration, allowing net growth. Using the light extinction coefficients generated from the Secchi readings, the 1% light level is calculated to be 15.4 m in Coldwater Lake and 16 m in Castle Lake. Alternatively, a less precise estimate of the photic zone is obtained by multiplying the mean Secchi depth by three (D. Larson personal communication), which extends it below 20 m in both lakes.

Thermal Stratification

The pattern of thermal stratification for Coldwater Lake during the summers 1989 and 1990 is depicted in Figure 7A and B, and for Castle Lake in Figure 8A and B. Temperature data is reported in full from both lakes in Appendix B.

Coldwater Lake was undergoing an early stage of stratification at the end of May in both 1989 and 1990 (Figure 7). By early summer, the pattern was well developed, and persisted until the end of sampling in October. A similar situation existed in Castle Lake

A. 1989

B. 1990

Figure 7. Depth-time diagrams of isopleths of temperature in Coldwater Lake, summer 1989 and 1990.

A. 1989

B. 1990

Figure 8. Depth-time diagrams of isopleths of temperature in Castle Lake, summer 1989 and 1990.

(Figure 8); the extent of mixing appears to be slightly reduced, possibly as a consequence of the reduced influence of wind on Castle Lake, as previously suggested.

OXYGEN

Dissolved oxygen data from Coldwater Lake and Castle Lake are portrayed graphically in Figures 9 and 10; detailed oxygen data, including percent saturation, are presented in Appendix C. Mean values for relative areal and volume deficits from summer 1989 and 1990, calculated according to Hutchinson (1957), are presented in Table IV.

TABLE IV
RELATIVE HYPOLIMNETIC OXYGEN DEFICITS
COLDWATER LAKE AND CASTLE LAKE
SUMMER 1989 AND 1990

	<u>Coldwater Lake</u>	<u>Castle Lake</u>
Areal Deficit (mg/m ² day)	460	450
Volume Deficit (mg/m ³ day)	18.45	42.46

Oxygen in Coldwater Lake

Oxygen levels are less than saturated in Coldwater Lake throughout the water column and on every sampling date. It is impossible to determine whether oxygen concentrations reached the 100% saturation level at the time of spring turnover, as thermal stratification had begun by the first sampling date, and oxygen levels were already less than

A. 1989

B. 1990

Figure 9. Depth-time diagrams of isopleths of dissolved oxygen in Coldwater Lake, summer 1989 and 1990.

A. 1989

B. 1990

Figure 10. Depth-time diagrams of isopleths of dissolved oxygen in Castle Lake, summer 1989 and 1990.

saturated. Wind mixing is evidenced by the fluctuations in saturation levels at the surface, while concentrations progressively decreased in the hypolimnion, defined as below about 20 m. By the end of the sampling season, oxygen was depleted at the bottom to approximately 5 mg/l, about 38% saturation.

The oxygen deficit data from Table IV reflect an oxygen demand in Coldwater Lake which is moderately high, according to Wetzel (1983).

Oxygen in Castle Lake

Thermal stratification was well underway in Castle Lake by late June, 1989 and 1990; oxygen depletion was also considerable with concentrations of 5-6 mg/l in the deep waters (percent saturation below 50%) for both years (Figure 10). As the summer progressed, oxygen continued to be consumed in the hypolimnion, and the concentration consistently approached nondetectable limits on the bottom by the last date sampled. The extent of the oxygen deprivation at the season's end is illustrated by the percent saturation values of 32-35% at 15 m, presumed to be the bottom of the thermocline.

The areal oxygen deficit for Castle Lake (Table IV), is nearly identical to that calculated for Coldwater Lake. The volume oxygen deficit in Castle Lake, on the other hand, is more than twice the volume deficit in Coldwater Lake.

SALINITY

Salinity is generally expressed as milligrams per liter, or milliequivalents per liter, and calculated as the sum of the eight major cations and anions, assuming no other ions are present in significant proportions. Another measure of ionic concentration is electrical conductivity, which increases with increasing salinity.

Data is presented in Table V for major ion analysis of Coldwater Lake and Castle Lake, summer 1989. Values are reported in milligrams per liter, with milliequivalents per liter in parenthesis. These data are summarized in Figure 11. In addition, for purposes of comparison, data are reported in Table VI for mean equivalent proportions of major ions characteristic of drainage waters from igneous rock, as described by Hutchinson (1957), and from the Western Lakes Survey, Pacific Northwest region (Eilers et al. 1988). Data from Coldwater Lake and Castle Lake are reported also in this table, in equivalent proportions, as mean values averaged over all dates and depths sampled.

Major Ions in Coldwater Lake

In terms of total salinity values, the values observed for Coldwater Lake (mean, 15 August 1989: 184.6 mg/l) were considerably higher than would be expected for a typical lake situated in a volcanic drainage system. These high salinities were reflected also in the conductivity

TABLE V
CONCENTRATIONS OF MAJOR IONS IN COLDWATER LAKE AND CASTLE LAKE, 1989

Location/Date	Concentration, mg/l (meq/l)							HCO ₃	FeII Salinity (umhos/cm)
	Ca	Mg	Na	K	Cl	SO ₄			
Coldwater Lake 26 May, 1989 ¹ surface	23.10 (1.15)	4.97 (0.41)	31.20 (1.36)	2.72 (0.07)	21.40 (0.60)	76.70 (1.60)			0.08
55 m	19.60 (0.98)	4.08 (0.34)	23.60 (1.03)	2.22 (0.06)	16.5 (0.47)	65.01 (1.35)			0.15
15 Aug, 1989 surface	17.80 (0.89)	3.78 (0.31)	25.80 (1.12)	2.34 (0.06)	17.00 (0.48)	65.91 (1.37)	39.32 (0.64)	0.04	171.95 (264.27)
20 m	20.10 (1.00)	4.39 (0.36)	30.80 (1.34)	2.75 (0.07)	20.90 (0.59)	62.62 (1.30)	46.53 (0.76)	0.00	188.01 (295.68)
59 m	20.90 (1.04)	4.53 (0.37)	31.20 (1.36)	2.83 (0.07)	21.20 (0.60)	63.52 (1.32)	49.52 (0.81)	0.00	193.70 (312.11)
4 Oct, 1989 surface	18.22 (0.91)	3.98 (0.33)	25.60 (1.11)	2.29 (0.06)	17.00 (0.48)	66.21 (1.38)		0.14	
20 m	20.20 (1.01)	4.42 (0.36)	30.80 (1.34)	2.63 (0.07)	20.90 (0.59)	74.60 (1.55)		0.04	
59 m	20.80 (1.04)	4.64 (0.38)	31.60 (1.37)	2.69 (0.07)	21.30 (0.60)	75.80 (1.58)		0.03	

TABLE V

CONCENTRATIONS OF MAJOR IONS IN COLDWATER LAKE AND CASTLE LAKE, 1989
(continued)

Location/Date	Concentration, mg/l (meq/l)							FeII Salinity (umhos/cm)
	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃	
Castle Lake								
24 June, 1989								
surface	7.82 (0.39)	1.31 (0.11)	2.31 (0.10)	0.37 (0.01)	1.59 (0.04)	8.54 (0.18)	29.11 (0.48)	0.08 (73.53)
10 m	7.89 (0.39)	1.34 (0.11)	2.36 (0.10)	0.40 (0.01)	1.59 (0.05)	8.60 (0.18)	28.87 (0.47)	0.07 (71.02)
29 m	8.01 (0.40)	1.41 (0.12)	2.50 (0.11)	0.46 (0.01)	1.95 (0.06)	8.90 (0.19)	30.98 (0.51)	0.29 (81.17)
8 Aug, 1989								
surface	7.97 (0.40)	1.37 (0.11)	2.34 (0.10)	0.40 (0.01)	1.57 (0.04)	8.21 (0.17)		0.07
29 m	8.70 (0.43)	1.48 (0.12)	2.55 (0.11)	0.50 (0.01)	2.02 (2.02)	8.36 (0.17)		0.48
14 Oct, 1989								
surface	8.58 (0.43)	1.41 (0.12)	2.50 (0.11)	0.42 (0.01)	1.68 (0.05)	2.73 (0.17)		0.12

! Data from this date appears to be in error, surface reversed with deep water.

A. Coldwater Lake

B. Castle Lake

Figure 11. Major ions in Coldwater Lake and Castle Lake, August 15, 1989.

TABLE VI
COMPARISON DATA FOR MAJOR ION ANALYSIS
MEAN EQUIVALENT PROPORTIONS

	Igneous Rock Drainage	Western Lake Survey	Coldwater Lake	Castle Lake
Ca ⁺⁺	24.2	22.8	18.6	30.2
Mg ⁺⁺	7.1	12.1	6.6	8.4
Na ⁺	15.3	14.5	23.2	7.9
K ⁺	3.5	2.3	1.2	0.8
Cl ⁻	6.3	4.5	10.2	3.7
SO ₄ ⁼	7.1	0.8	26.5	13.0
CO ₃ ⁼	36.7	43.1	13.7	36.0

measurements.

In contrasting the values observed for the individual ions in Coldwater Lake with those reported for typical igneous drainage and lakes in the Pacific Northwest in general, ionic proportions in Coldwater Lake are clearly dominated by sodium and sulfate, while the comparison waters are characterized by higher levels of calcium and carbonates; sulfate concentrations are especially low in these other systems. Chloride is also elevated in Coldwater Lake, compared to the reference lakes.

When comparing the data observed for the summer, 1989, with earlier major ion data (Table I), values reported for cations in Coldwater Lake, September, 1984, are generally consistent with those from 1989, indicating volume and rate

of supply of these ions was reasonably steady over that time frame. One major exception is sodium; sodium levels from the later date are greatly increased over those reported for 1982 and 1984. In fact, values for 1989 are slightly higher than those observed in April, 1981, one year after the eruption. Anion concentrations are not available for the years immediately following the eruption for comparison; alkalinity values, however, are in good agreement with the 1984 data.

Major Ions in Castle Lake

Total salinities in Castle Lake (mean, 24 June 1989: 52.2 mg/l) fall just at the high end of the typical range for soft waters characteristic of igneous rock formations. From Table VI, comparing Castle Lake to typical values for igneous lakes in the region, it can be noted that the ionic proportions are more typical than in Coldwater Lake, although calcium concentrations are unusually high, and sulfate is slightly elevated as well. Sodium, on the other hand, is relatively reduced in Castle Lake, as is chloride.

Comparing 1989 data with data from Table I for Castle Lake, major ion values appear to be steadily decreasing with time, although at a much slower rate than in the initial one to two years following the eruption. Major cation values reported for 1982 and 1984 show a decrease over the two years in nearly every case, and values from 1989 are decreased further.

NUTRIENTS

Although numerous chemical compounds are required by plants for growth, the great bulk of these chemicals exist in natural waters in concentrations far exceeding the levels needed. As a consequence, they are generally considered to exert little control over the development of plant communities. Nitrogen and phosphorus, on the other hand, are recognized as significant in shaping the metabolism of aquatic systems as they are often available in tiny amounts relative to the plant requirements. Phytoplankton growth is usually limited by one of these two nutrients. Silicon can also be important in the regulation of diatom communities, and thereby have an effect on the pattern of phytoplankton succession and productivity. An analysis of the dynamics of these nutrients in a lake system is fundamental to understanding the ecology of that system.

Nitrogen

Nitrogen data from Coldwater Lake and Castle Lake are presented in Table VII and Table VIII. Nutrient data from the second sampling station in Coldwater Lake are presented in Appendix D, data from the bay and South Coldwater Creek inflow are presented in Appendix E, and data from the second station in Castle Lake are presented in Appendix F. Nutrient data from a one-time only sampling of Spirit Lake in September, 1989 is presented in Appendix G.

TABLE VII

NITRATE/NITRITE-NITROGEN IN COLDWATER LAKE, SUMMER 1989 AND 1990

Concentration, ug/l (uM)

Depth (m)	Date, 1989									
	26 May	7 June	17 June	1 July	20 July	15 Aug.	23 Aug.	13 Sept.	4 Oct.	
0	12.15 (0.87)	13.04 (0.93)	12.38 (0.88)	10.84 (0.77)	8.75 (0.63)	4.61 (0.33)	2.17 (0.16)	1.44 (0.10)	5.71 (0.41)	
10	10.95 (0.78)	11.40 (0.81)	11.09 (0.79)	11.05 (0.79)	8.65 (0.62)	5.07 (0.36)	3.43 (0.25)	3.33 (0.24)	4.32 (0.31)	
20	10.25 (0.73)	13.34 (0.95)	12.44 (0.89)	12.16 (0.87)	11.74 (0.84)	11.22 (0.80)	9.59 (0.69)	11.39 (0.81)	13.45 (0.96)	
35	9.55 (0.68)	10.99 (0.79)	12.02 (0.86)	12.09 (0.86)	15.26 (1.09)	11.34 (0.81)	11.00 (0.78)	10.89 (0.78)	13.77 (0.98)	
55	9.60 (0.69)	10.66 (0.76)	11.57 ¹ (0.83)	11.27 ¹ (0.81)	12.63 ¹ (0.90)	11.27 ² (0.81)	10.71 ² (0.77)	9.55 ² (0.68)	12.30 ³ (0.88)	
¹ 58 m ² 59m ³ 60 m										

TABLE VII

NITRATE/NITRITE-NITROGEN IN COLDWATER LAKE, SUMMER 1989 AND 1990
(continued)

Depth (m)	Concentration, ug/l (uM)							
	Date, 1990							
	24 May	14 June	5 July	26 July	14 Aug.	31 Aug.	20 Sept.	11 Oct.
0	9.96 (0.71)	9.19 (0.66)	7.97 (0.57)	5.28 (0.38)	3.94 (0.28)	2.75 (0.20)	1.49 (0.11)	1.03 (0.07)
10	10.44 (0.75)	8.19 (0.59)	10.34 (0.74)	5.32 (0.38)	3.25 (0.23)	3.71 (0.27)	1.76 (0.13)	1.06 (0.08)
20	10.15 (0.73)	9.21 (0.66)	11.52 (0.82)	9.26 (0.66)	11.15 (0.80)	11.82 (0.84)	10.99 (0.79)	9.93 (0.71)
35	N.D.	N.D.	11.15 (0.80)	8.84 (0.63)	10.19 (0.73)	11.49 ⁴ (0.82)	12.09 (0.86)	10.50 (0.75)
60	N.D.	7.58 (0.54)	11.21 ² (0.80)	8.98 (0.64)	9.95 (0.71)	10.10 (0.72)	10.77 ² (0.77)	9.27 (0.66)
¹ 58 m	² 59m	³ 60 m	⁴ 27 m	N.D. No data				

TABLE VIII

NITRATE-NITRITE NITROGEN IN CASTLE LAKE
SUMMER 1989 AND 1990

Concentration ug/l (uM)

Depth (m)	Date, 1989					
	<u>24 June</u>	<u>7 July</u>	<u>8 August</u>	<u>1 Sept.</u>	<u>20 Sept.</u>	<u>14 Oct.</u>
0	2.56 (0.18)	1.55 (0.11)	n.d.	0.10 (0.007)	0.33 (0.02)	0.09 (0.006)
5	2.66 (0.19)	2.51 (0.18)	0.12 (0.009)	n.d.	0.50 (0.04)	0.09 (0.006)
10	5.19 (0.37)	6.90 (0.49)	1.02 (0.07)	0.46 (0.03)	1.29 (0.09)	0.73 (0.05)
20	6.57 (0.47)	8.88 (0.63)	0.46 (0.03)	5.64 (0.40)	5.37 (0.38)	5.56 (0.40)
28	6.18 (0.44)	7.10 ¹ (0.51)	4.43 ¹ (0.32)	4.62 (0.33)	3.63 ¹ (0.26)	3.64 (0.26)
	Date, 1990					
	<u>28 June</u>	<u>19 July</u>	<u>9 August</u>	<u>6 Sept.</u>	<u>2 Oct.</u>	<u>18 Oct.</u>
0	n.d.	n.d.	N.D.	n.d.	n.d.	0.24 (0.02)
5	n.d.	n.d.	n.d.	n.d.	n.d.	0.17 (0.01)
10	0.18 (0.01)	n.d.	11.18 ² (0.80)	n.d.	n.d.	n.d.
20	3.66 (0.26)	4.36 (0.31)	8.47 ² (0.61)	4.58 (0.33)	4.15 (0.30)	3.88 (0.28)
30	3.78 ³ (0.27)	N.D.	6.69 ^{2,4} (0.48)	2.13 (0.15)	n.d.	0.72 (0.05)

¹ 29 m ² Questionable data ³ 24 m ⁴ 28 m
n.d. Not detectable N.D. No data

Nitrogen in Coldwater Lake. Low levels of nitrate were observed in Coldwater Lake, with a distinct tendency for nitrate depletion in the photic zone through the season (Table VII), typical of oligotrophic lakes (Wetzel, 1983). Concentrations decreased from 11 to 12 micrograms nitrate-N/liter in the spring to 4 to 5 micrograms/liter at the end of the sampling season in 1989. In 1990, concentrations were slightly lower in the spring, 9 to 10 micrograms/liter, and decreased to around 1 microgram/liter by the last sampling date.

Nitrate concentrations with depth clearly reflect the thermocline as a barrier to mixing, causing the hypolimnion levels to remain reasonably constant over the course of the season. The elevated measurement at 35 m on 20 July, 1989 was probably the result of contamination.

Data from Appendix D (second station) agree well with data in Table VI, demonstrating a similar pattern of low levels of nitrate which decreased throughout the season. From Appendix E (bay and inflow), it can be seen that nitrate levels in the bay followed the pattern of the other stations in the lake, while the inflow waters from South Coldwater Creek were consistently depleted in nitrate. Data from Spirit Lake, Appendix G, reveal severe nitrogen depletion at all depths in that lake.

Nitrogen in Castle Lake. Nitrate depletion in the epilimnion of Castle Lake was conspicuous and well underway

by the first sampling date in 1989, and virtually complete by the first sampling in 1990 (Table VIII). This pattern of extremely low levels of nitrate in the upper 10 m of the water column was also observed at the second station (Appendix F). Nitrate was also depleted in the deep water late in the summer, especially in 1990. Nitrate concentrations were lower overall in Castle Lake by about one half than in Coldwater Lake.

Phosphorus

Dissolved inorganic orthophosphate data for Coldwater Lake and Castle Lake, 1989 and 1990, are presented in Table IX and Table X. Total phosphorus data from 1990 for both lakes are presented in Table XI and Table XII. Orthophosphate and total phosphorus data from the second station and the bay and inflow stations in Coldwater Lake are presented in Appendix D and Appendix E; similarly, data for the second station in Castle Lake are presented in Appendix F. Appendix G presents phosphorus data from Spirit Lake, August 1989.

Phosphorus in Coldwater Lake. Orthophosphate was consistently low, but detectable, in Coldwater Lake throughout both summers (Table IX). Levels remained less than 5 micrograms/liter, typically 1 to 2 micrograms/liter; similar data is presented for the second station. While data from the bay and inflow stations are unfortunately limited, a pattern is nonetheless suggested. Orthophosphate

TABLE IX

ORTHOPHOSPHATE-PHOSPHORUS IN COLDWATER LAKE, SUMMER 1989 AND 1990

Depth (m)	Concentration, ug/l (uM)									
	Date, 1989									
	26 May	7 June	17 June	1 July	20 July	15 Aug.	23 Aug.	13 Sept.	4 Oct.	
0	2.10 (0.07)	1.70 (0.06)	<5 (<0.16)	1.70 (0.06)	0.62 (0.02)	1.35 (0.04)	2.87 (0.09)	2.13 (0.07)	3.54 (0.11)	
10	2.10 (0.07)	0.85 (0.03)	<5 (<0.16)	2.50 (0.08)	1.24 (0.04)	1.52 (0.05)	2.15 (0.07)	1.81 (0.06)	2.90 (0.09)	
20	2.80 (0.09)	2.60 (0.08)	<5 (<0.16)	3.30 (0.11)	1.09 (0.04)	1.68 (0.05)	2.92 (0.09)	2.30 (0.07)	3.22 (0.10)	
35	2.80 (0.09)	1.70 (0.06)	<5 (<0.16)	3.30 (0.11)	1.55 (0.05)	1.35 (0.04)	2.62 (0.09)	3.28 (0.11)	2.25 (0.07)	
55	1.40 (0.05)	1.70 (0.06)	(¹ <5) (<0.16)	3.30 ¹ (0.11)	2.95 ¹ (0.10)	1.18 ² (0.04)	2.62 ² (0.09)	2.46 ² (0.08)	2.443 (0.08)	
¹ 58 m	² 59 m	³ 60 m	⁴ 27 m	N.D. No data						

TABLE IX

ORTHOPHOSPHATE-PHOSPHORUS IN COLDWATER LAKE, SUMMER 1989 AND 1990
(continued)

Depth (m)	Concentration, ug/l (uM)							
	Date, 1990							
	24 May	14 June	5 July	26 July	14 Aug.	31 Aug.	20 Sept.	11 Oct.
0	1.75 (0.06)	4.65 (0.15)	1.08 (0.04)	2.52 (0.08)	N.D.	1.26 (0.04)	N.D.	1.61 (0.05)
10	3.10 (0.10)	5.27 (0.17)	1.08 (0.04)	3.15 (0.10)	N.D.	1.57 (0.05)	N.D.	1.93 (0.06)
20	3.10 (0.10)	2.17 (0.07)	1.08 (0.04)	3.15 (0.10)	N.D.	1.57 (0.05)	N.D.	1.57 (0.05)
35	N.D.	2.79 (0.09)	1.44 (0.05)	2.84 (0.09)	N.D.	2.52 ⁴ (0.08)	N.D.	2.25 (0.07)
60	N.D.	3.10 (0.10)	1.44 (0.05)	3.47 (0.11)	N.D.	1.89 (0.06)	N.D.	2.58 (0.08)
¹ 58 m	² 59 m	³ 60 m	⁴ 27 m	N.D. No data				

TABLE X

ORTHOPHOSPHATE-PHOSPHORUS IN CASTLE LAKE
SUMMER 1989 AND 1990

Concentration ug/l (uM)

Depth (m)	Date, 1989					
	<u>24 June</u>	<u>7 July</u>	<u>8 August</u>	<u>1 Sept.</u>	<u>20 Sept.</u>	<u>14 Oct.</u>
0	2.16 (0.07)	N.D.	0.50 (0.02)	1.14 (0.04)	3.68 (0.12)	2.42 (0.08)
5	1.44 (0.05)	N.D.	1.00 (0.03)	2.77 (0.09)	1.34 (0.04)	2.60 (0.08)
10	1.44 (0.05)	N.D.	1.33 (0.04)	5.06 (0.16)	2.51 (0.08)	1.04 (0.03)
20	1.44 (0.05)	N.D.	1.17 (0.04)	1.80 (0.06)	2.18 (0.07)	1.04 (0.03)
28	1.44 0.05)	N.D.	0.17 ¹ (0.006)	2.45 (0.08)	1.84 ¹ (0.06)	1.73 (0.06)
	Date, 1990					
	<u>28 June</u>	<u>19 July</u>	<u>9 August</u>	<u>6 Sept.</u>	<u>2 Oct.</u>	<u>18 Oct.</u>
0	1.83 (0.06)	1.88 (0.06)	2.08 (0.07)	1.56 (0.05)	1.27 (0.04)	0.94 (0.03)
5	0.73 (0.02)	1.57 (0.05)	1.39 (0.05)	1.87 (0.06)	1.90 (0.06)	0.94 (0.03)
10	1.10 (0.04)	2.51 (0.08)	1.74 (0.06)	1.87 (0.06)	1.59 (0.05)	1.26 (0.04)
20	1.83 (0.06)	1.88 (0.06)	1.74 (0.06)	1.87 (0.06)	1.90 (0.06)	1.26 (0.04)
30	2.19 ² (0.07)	1.88 (0.06)	1.39 ³ (0.05)	1.87 (0.06)	2.22 (0.07)	1.26 (0.04)

¹ 29 m ² 24 m ³ 28 m N.D. No data

TABLE XI

TOTAL PHOSPHORUS IN COLDWATER LAKE, SUMMER 1990

Depth (m)	Concentration, ug/l (uM)							
	Date, 1990							
	<u>24 May</u>	<u>14 June</u>	<u>5 July</u>	<u>26 July</u>	<u>14 Aug.</u>	<u>31 Aug.</u>	<u>20 Sept.</u>	<u>11 Oct.</u> ²
0	12.33 (0.40)	14.36 (0.46)	29.35 (0.95)	16.50 (0.53)	6.32 (0.20)	13.92 (0.45)	N.D.	79.36 (2.56)
10	19.05 (0.62)	16.08 (0.52)	28.45 (0.92)	16.49 (0.53)	8.76 (0.28)	43.49 (1.40)	N.D.	81.92 (2.65)
20	32.20 (1.04)	21.54 (0.70)	33.59 (1.09)	22.55 (0.73)	6.52 (0.21)	39.14 (1.26)	N.D.	99.71 (3.22)
35	N.D.	36.53 (1.18)	34.20 (1.10)	23.46 (0.76)	8.96 (0.29)	46.97 ¹ (1.52)	N.D.	116.30 (3.76)
60	N.D.	44.01 (1.42)	43.12 (1.39)	27.15 (0.88)	144.58 (4.67)	40.45 (1.31)	N.D.	114.08 (3.68)

¹ 27 m ² Questionable data N.D. No data

TABLE XII
TOTAL PHOSPHORUS IN CASTLE LAKE
SUMMER, 1990

Concentration ug/l (uM)						
Depth	Date, 1990					
(m)	<u>28 June</u>	<u>19 July</u>	<u>9 August</u>	<u>6 Sept.</u>	<u>2 Oct.</u>	<u>18 Oct.</u>
0	N.D.	22.40 ¹ (0.72)	12.02 (0.39)	4.01 (0.13)	8.94 (0.29)	9.69 (0.31)
5	N.D.	26.29 ¹ (0.85)	6.40 (0.21)	5.10 (0.17)	10.48 (0.34)	12.03 (0.39)
10	N.D.	29.09 ¹ (0.94)	6.40 (0.21)	7.29 (0.24)	16.32 (0.53)	10.69 (0.35)
20	N.D.	40.76 ¹ (1.32)	6.62 (0.21)	6.74 (0.22)	17.52 (0.57)	12.20 (0.39)
30	N.D.	46.52 ¹ (1.50)	8.57 ² (0.28)	15.84 (0.51)	24.40 (0.79)	17.38 (0.56)

¹ Questionable data ² 28 m

concentrations in the bay were generally similar to the main body of the lake, while levels in the inflow station were higher, in the range of 5 to 8 micrograms/liter.

Orthophosphate levels in Spirit Lake, Appendix G, ranged from 2 to 4 micrograms/liter, and are similar to those in Coldwater Lake.

Values for total phosphorus (Table XI) reflect concentrations typically associated with moderately mesotrophic lakes, with concentrations in the range of 12 to 45 micrograms/liters reported for most sampling dates. There was a consistent increase in the deeper waters, sometimes pronounced, reflecting the effect of contact with the sediments. Data from the second station were roughly comparable, although elevated somewhat; the difference was not extreme and was probably a reflection of horizontal patchiness. Total phosphorus in the bay was more markedly increased over the other stations, and concentrations in the inflow waters were higher still.

Ratios of dissolved orthophosphate to other forms of phosphorus were variable, but showed a distinct tendency for a predominance of orthophosphate on certain sampling dates. For example, on 5 July 1990 a ratio of 4% was maintained from surface to bottom in the lake, with a decreased ratio of 2.5% observed for the waters of the bay, and a slightly higher value (7%) for the inflow waters. Later that month, 26 July 1990, ratios in the lake had jumped to a minimum of

14%, ranging up to 24%; values in the bay continued to be lower than the lake water (7%), and the inflow waters maintained the ratio of 8%.

Phosphorus in Castle Lake. Low but detectable levels of orthophosphate were observed in Castle Lake as well (Table X). Data from the second station present a similar pattern. There was no indication of increased phosphate in the bottom waters, in spite of the anoxic conditions which developed as the season progressed. Total phosphorus levels were lower than in Coldwater Lake, in the range of 4 to 20 micrograms/liter typically, which is characteristic of an oligotrophic system. Concentrations of total phosphorus did tend to increase with depth. Ratios of dissolved orthophosphate to the other forms of phosphorus in the water were invariably high, with most values ranging from 20-40%.

Silicon

Silica data for Coldwater Lake and Castle Lake are presented in Tables XIII and XIV, respectively. Additionally, silica data from the second station in Coldwater Lake and the bay and inflow stations are presented in Appendix D and Appendix E; data from the second station in Castle Lake are presented in Appendix F. Silica data from Spirit Lake, August 1989, are presented in Appendix G.

Silica in Coldwater Lake. Depletion of silica in the upper layer of Coldwater Lake did occur progressively throughout the summer season during 1989 and 1990 (Table

TABLE XIII

SILICA (SiO₂) IN COLDWATER LAKE, SUMMER 1989 AND 1990

Concentration, mg/l (uM)

Depth (m)	Date, 1989									
	26 May	7 June	17 June	1 July	20 July	15 Aug.	23 Aug.	13 Sept.	4 Oct.	
0	16.21 (269.79)	15.81 (263.13)	15.51 (258.14)	15.33 (255.14)	15.13 (251.81)	14.66 (243.99)	14.92 (248.32)	14.45 (240.49)	12.78 (212.70)	
10	17.65 (293.75)	17.18 (285.93)	16.31 (271.45)	16.37 (272.45)	15.72 (261.63)	15.15 (252.14)	14.98 (249.31)	14.59 (242.82)	13.01 (216.53)	
20	17.65 (293.75)	17.77 (295.75)	17.18 (285.93)	18.05 (300.41)	17.31 (288.09)	16.55 (275.44)	16.69 (277.78)	16.16 (268.95)	14.94 (248.65)	
35	17.98 (299.24)	17.90 (297.91)	17.24 (286.93)	18.17 (302.41)	17.94 (298.58)	16.95 (282.10)	16.94 (281.94)	16.33 (271.78)	14.30 (238.00)	
55	17.86 (297.25)	17.60 (292.92)	17.38 ¹ (289.26)	18.20 ¹ (302.91)	17.55 ¹ (292.09)	16.95 ² (282.10)	16.88 ² (280.94)	16.50 ² (274.61)	14.71 ³ (244.82)	
¹ 58 m	² 59 m	³ 60 m								

TABLE XIII

SILICA (SiO₂) IN COLDWATER LAKE, SUMMER 1989 AND 1990
(continued)

Depth (m)	Concentration, mg/l (uM)							
	Date, 1990							
	<u>24 May</u>	<u>14 June</u>	<u>5 July</u>	<u>26 July</u>	<u>14 Aug.</u>	<u>31 Aug.</u>	<u>20 Sept.</u>	<u>11 Oct.</u>
0	15.24 (253.64)	13.84 (230.34)	12.93 (214.70)	12.83 (213.53)	14.18 (236.00)	13.42 (223.35)	13.49 (224.52)	13.39 (222.85)
10	14.86 (247.32)	13.95 (232.17)	13.11 (218.19)	12.68 (211.04)	13.97 (232.51)	13.36 (222.35)	13.61 (226.51)	13.36 (222.35)
20	15.96 (265.63)	15.21 (253.14)	14.72 (244.99)	14.01 (233.17)	15.82 (263.30)	15.31 (254.81)	15.20 (252.98)	14.99 (249.48)
35	N.D.	15.47 (257.47)	15.26 (253.97)	15.75 (262.13)	16.14 (268.62)	15.68 ⁴ (260.97)	15.40 (256.30)	15.70 (261.30)
60	N.D.	15.78 (262.63)	15.23 (253.48)	15.58 (259.30)	16.99 (282.77)	15.89 (264.46)	16.00 (266.29)	16.06 (267.29)
¹ 58 m	² 59 m	³ 60 m	⁴ 27 m	N.D. No data				

TABLE XIV

SILICA (SiO₂) IN CASTLE LAKE
SUMMER 1989 AND 1990

Concentration mg/l (uM)

Depth (m)	Date, 1989					
	<u>24 June</u>	<u>7 July</u>	<u>8 August</u>	<u>1 Sept.</u>	<u>20 Sept.</u>	<u>14 Oct.</u>
0	11.54 (192.06)	10.92 (181.74)	10.95 (182.24)	11.43 (190.23)	11.17 (185.90)	11.08 (184.41)
5	10.76 (179.08)	10.81 (179.91)	10.86 (180.75)	11.25 (187.24)	11.08 (184.41)	10.69 (177.92)
10	12.02 (200.05)	10.89 (181.24)	10.75 (178.91)	11.07 (184.24)	11.34 (188.73)	10.97 (182.58)
20	11.85 (197.22)	10.89 (181.24)	10.86 (180.75)	11.37 (189.40)	11.00 (183.08)	10.80 (179.75)
28	11.57 (192.56)	11.15 ¹ (185.57)	11.12 ¹ (185.07)	11.19 (186.24)	11.06 ¹ (184.07)	10.86 (180.75)
	Date, 1990					
	<u>28 June</u>	<u>19 July</u>	<u>9 August</u>	<u>6 Sept.</u>	<u>2 Oct.</u>	<u>18 Oct.</u>
0	10.57 (175.92)	10.38 (172.76)	10.75 (178.91)	11.07 (184.24)	11.47 (190.90)	10.79 (179.58)
5	10.60 (176.42)	10.24 (170.43)	10.67 (177.58)	11.10 (184.74)	11.38 (189.40)	10.79 (179.58)
10	11.04 (183.74)	9.90 (164.77)	10.13 (168.60)	10.98 (182.74)	11.27 (187.57)	10.76 (179.08)
20	12.03 (200.22)	10.36 (174.42)	10.49 (174.59)	11.37 (189.23)	10.96 (182.41)	11.13 (185.24)
30	13.09 ² (217.86)	10.53 (175.25)	10.76 ³ (179.08)	11.40 (189.73)	11.55 (192.23)	11.58 (192.73)
¹ 29 m ² 24 m ³ 28 m						

XIII). Levels of silica remained quite high, however, ranging from a minimum of around 12 milligrams/liter to a maximum of approximately 18 milligrams/liter. Buildup of silica in the bottom waters was not apparent, although there was a suggestion of an increase in silica concentrations in the upper hypolimnetic water. Values for silica were the greatest at 35 meters for four dates in 1989 and two dates in 1990.

Data from the second station in Coldwater Lake was quite comparable, as was data from the bay station. The inflow waters of South Coldwater Creek contained increased concentrations of silica, however, in the range of 21-22 mg/liter. Data from Spirit Lake also reflected elevated levels of silica, similar to the waters of the inflow.

Silica in Castle Lake . Silica levels in Castle Lake were somewhat less than in Coldwater Lake, although still substantial; values averaged around 11-12 milligrams/liter. There was no indication of variation in silica with depth, In fact, concentrations of silica were essentially unchanged throughout the season at all depths. Data from the second station corroborated these results.

PHYTOPLANKTON

Chlorophyll a, as the primary pigment involved in photosynthesis, is an indicator of phytoplankton biomass commonly used in limnological studies. This practice is

slightly problematic, as the concentration of chlorophyll a per cell volume is not consistent for all species; diatoms, in particular, have been observed to contain relatively less chlorophyll a/cell volume than other algal groups (Reynolds 1984). In addition, the content of chlorophyll a can vary as a function of the light environment of the cells. Nevertheless, chlorophyll a levels are widely considered to be useful in assessing the significance of phytoplankton in aquatic systems. Calculations of total algal biovolume from measurements taken during identification can also aid in interpreting phytoplankton data (Sweet 1986).

Phytoplankton species lists, including biovolume estimates, for Coldwater Lake and Castle Lake in 1989 are presented in Appendix H and Appendix I, respectively. Chlorophyll a concentrations are reported for Coldwater Lake in 1989 and 1990 in Table XV; data from the second station and the bay and inflow stations for 1989 and 1990 are reported in Appendix D and E. Chlorophyll a concentrations for Castle Lake in 1989 and 1990 are reported in Table XVI; data from the second station for 1989 and 1990 are reported in Appendix F. Chlorophyll levels from Spirit Lake in August, 1989 are reported in Appendix G. In addition, Table XVII contains a summary of phytoplankton and chlorophyll data from 1989 for both lakes: minimum, maximum, and mean values for phytoplankton density and biovolume, as well as concentrations of chlorophyll a in the photic zone.

TABLE XV

CHLOROPHYLL A IN COLDWATER LAKE, SUMMER 1989 AND 1990

		Concentration, ug/l							
Depth (m)		Date, 1989							
		26 May	7 June	17 June	1 July	20 July	15 Aug.	23 Aug.	13 Sept.
0		<u>1.40</u>	<u>0.60</u>	<u>1.27</u>	<u>1.59</u>	<u>1.53</u>	<u>1.43</u>	<u>1.45</u>	<u>0.58</u>
									<u>1.12</u>
10		2.08	1.10	3.07	2.77	4.74	1.98	2.68	1.97
									0.62
20		2.17	0.45	3.10	2.81	4.07	5.13	1.79	2.32
									1.65
35		0.68	N.D.	0.49	0.45	N.D.	1.48	1.65	1.21
									1.14
Concentration, ug/l (pico fraction)									
		Date, 1990							
		24 May	14 June	5 July	26 July	14 Aug.	31 Aug.	20 Sept.	11 Oct.
		<u>0.84</u>	<u>1.19</u>	<u>1.34</u>	<u>0.99</u> (0.44)	<u>0.93</u> (0.36)	<u>1.29</u> (0.50)	<u>1.41</u> (0.61)	<u>2.30</u> (0.30)
0									
5		0.75	0.93	1.59	0.68 (0.61)	0.63 (0.28)	1.38 (0.74)	1.59 (0.72)	3.09 (0.53)
10		1.03	1.60	2.42	2.74 (0.75)	4.69 (0.48)	2.20 (0.89)	2.57 (0.51)	2.65 (0.53)
15		0.45	1.79	2.72	1.82 (0.60)	3.44 (0.54)	3.88 (0.52)	3.03 (0.52)	3.20 (0.61)
20		0.33	1.09	1.97	1.69 (0.37)	2.82 (0.55)	3.93 (0.58)	4.33 (0.54)	3.88 (0.42)

TABLE XVI
CHLOROPHYLL A IN CASTLE LAKE
SUMMER 1989 AND 1990

Concentration ug/l

Depth (m)	Date, 1989					
	<u>24 June</u>	<u>7 July</u>	<u>8 August</u>	<u>1 Sept.</u>	<u>20 Sept.</u>	<u>14 Oct.</u>
0	2.67	1.73	0.83	1.35	0.76	1.12
5	3.72	2.26	1.44	1.19	0.62	1.04
10	5.39	7.70	3.58	3.33	2.37	1.00
20	1.04	0.78	0.98	0.82	0.64	0.25
28	1.26	N.D.	N.D.	N.D.	N.D.	N.D.

Concentration ug/l (pico fraction)

	Date, 1990					
	<u>28 June</u>	<u>19 July</u>	<u>9 August</u>	<u>6 Sept.</u>	<u>2 Oct.</u>	<u>18 Oct.</u>
0	0.65	1.34	0.55 (0.46)	0.79 (0.41)	2.57 (0.58)	2.20 (0.56)
5	0.65	1.59	0.99 (0.43)	0.61 (0.37)	2.39 (0.87)	2.28 (0.61)
10	4.17	2.42	4.58 (0.61)	5.28 (1.31)	8.41 (1.21)	2.61 (0.66)
15	4.36	2.72	3.51 (0.92)	3.39 (0.59)	4.45 (0.86)	10.02 (0.22)
20	1.95	1.97	1.08 (0.41)	0.78 (0.52)	1.18 (0.41)	0.62 (0.10)

N.D. No data

This research concentrated on the relationship between plankton abundances and lake-trophic status.

TABLE XVII

SUMMARY OF PHYTOPLANKTON AND CHLOROPHYLL DATA
COLDWATER LAKE AND CASTLE LAKE
SUMMER 1989

Coldwater Lake

	<u>Density</u>	<u>Biovolume</u>	<u>Chl a</u>
Minimum	108.0	28022.1	0.45
Maximum	599.3	394316.9	5.13
Mean	317.4	140719.2	2.05
# Samples	45	45	27

Castle Lake

	<u>Density</u>	<u>Biovolume</u>	<u>Chl a</u>
Minimum	174	17310	0.25
Maximum	9524	958905	7.70
Mean	1823.8	141002.4	1.94
# Samples	29	29	24

Density = algal units/ml

Biovolume = $\mu\text{m}^3/\text{ml}$

Chl a = $\mu\text{g/l}$

Phytoplankton in Coldwater Lake

The summarized data (Table XVII) for Coldwater Lake are similar to data reported for lakes in Oregon and Idaho (Sweet 1986) of oligo-mesotrophic productivity; the range between minimum and maximum values is not appreciable for any parameter. Data from Table XV indicates a chlorophyll

maximum generally between 10 and 20 meters, a trend which is observed again in 1990 when sampling for chlorophyll a included the addition of two additional depths, 5 meters and 15 meters. The data for 1989 indicate a chlorophyll peak during the middle of the season, mid-June through August, while the data for 1990 reflect higher values into October. Chlorophyll a levels from the second station and the bay and inflow stations are not markedly different from the primary station.

The species list in Appendix H reflects a system which is clearly dominated by diatoms, especially *Cyclotella*, throughout the season. It should be noted that the species of *Cyclotella* observed in this study was identified as *C. meneghiniana*, although it possessed characteristics which were somewhat reminiscent of *C. stelligera*. It is possible that both species were present and the distinction was not clear between them.

With the exception of *Asterionella formosa*, which exhibited a distinct pattern of growth in the late spring and demise by the end of June, no definite succession of phytoplankton species can be identified in Coldwater Lake for 1989. *Rhodomonas minuta* was present at high densities throughout much of the season; due to the very small size of this alga, however, it never constituted a major fraction of the biovolume. *Cryptomonas erosa* is another member of the Cryptophyta which did assume importance, both in terms of

density and biovolume. These algae, as well as others observed (*Ankistrodesmas falcatus*) have been reported as typically associated with moderately productive systems (Sweet 1986).

Siliceous algae were limited to the diatoms throughout the season in Coldwater Lake; Si:P ratios ranged from approximately 320-450 (utilizing total phosphorus data from 1990). These high values reflect the high concentrations of silica present in the water column.

Phytoplankton in Castle Lake

The summarized data from Castle Lake presented in Table XVII also indicate a lake of moderate productivity, although the minimum and maximum values are more extreme than those reported for Coldwater Lake. In particular, the maximum values for density and biovolume (9524 algal units/ml and 958905 $\mu\text{m}^3/\text{ml}$) are unusually high and are associated with a deep water bloom of *Ochromonas* sp. and *Cryptomonas erosa* which was observed on the last sampling date. These extremely high values for phytoplankton biomass were measured in conjunction with the minimum value reported for chlorophyll a (0.25 $\mu\text{g}/\text{l}$), which was observed in the deep water on the same date.

The pattern for chlorophyll a in Castle Lake reflect a distinct maximum at 10 m on every date except the final one; data from 1990 corroborate this peak at 10-15 m. It is curious to note that the maximum value for chlorophyll a for

1990 (10.02 ug/l) was at 15 m on the last sampling date, while a value close to the minimum (0.62 ug/l) was observed at 20 m on that date.

Again, similar to Coldwater Lake, no pattern of phytoplankton succession in Castle Lake emerges from the data for 1989. The species list from 1989 in Castle Lake is notable for a nearly complete absence of siliceous algae of any group, despite the relatively high levels of silica (11-12 mg/l) which were observed throughout the water column. Ratios of silica:phosphorus ranged from approximately 550-650, when calculated from total phosphorus data from 1990.

The phytoplankton consisted primarily of flagellates, especially *Ochromonas* sp., *Chromulina* sp., *Cryptomonas erosa*, and the dinoflagellate *Glenodinium pulvis*. These algae, with the exception of *Glenodinium*, have been identified as capable of mixotrophic nutrition, i.e. the ingestion of organic material in particulate or dissolved form while maintaining the ability to photosynthesize (Ishida and Kimura 1986, Sanders and Porter 1988, Porter 1988).

ZOOPLANKTON

Zooplankton data from Coldwater Lake from 1989 are presented in Appendix J; data from Castle Lake, 1989 are presented in Appendix K.

Zooplankton in Coldwater Lake

The zooplankton community in Coldwater Lake, 1989, (Appendix J) was dynamic in terms of total densities. *Daphnia pulicaria* dominated the zooplankton with maximum densities tending to occur in the surface waters. Although *D. pulicaria* was the most significant species, the other major zooplankton groups were generally well represented throughout the water column, with *Diaptomus tyrrelli* being the main copepod and several rotifers assuming significant proportions at various times.

A community decline on June 7 was possibly indicated by a decrease in density in the deeper waters, although the data from the surface sample on that date is missing due to a contaminated sample; rotifers, especially *Synchaeta oblonga* and *Polyarthra dolichoptera*, had become the dominant fraction in the surface waters by ten days later and total densities had again reached former levels. The highest total densities were observed to develop by July 1 in the upper 5 m, with the community dominated by *S. oblonga* and *D. pulicaria* at that time.

These high levels were followed by a crash on July 20, when numbers were reduced dramatically. Rebuilding appeared to be slow through the month of August, with the community again dominated by *D. pulicaria*. By the final sampling date on October 4, total densities had regained the levels reported for the beginning of the season, with *D. pulicaria*

continuing as the dominant species and *Asplanchna priodonta* as an important component as well in the surface waters.

Zooplankton in Castle Lake

The zooplankton community in Castle Lake during 1989, was clearly dominated by rotifers during the first two sampling dates, especially *Kellicottia longispina* and *Polyarthra dolichoptera*, with *Daphnia pulicaria* present at very low densities (Appendix K). *Daphnia* assumed more significance as the season progressed, and remained dominant through October 11, with rotifers tending to be more important in the deeper waters. There was no evidence for a major decline in community levels at any point. In addition, members of the Copepoda were rarely observed and appeared to be completely absent from the water column through most of the season.

DISCUSSION

Analysis of a limnological system generally begins with an examination of the physical morphology of the lake basin and the surrounding drainage area. The geomorphology of a lake provides the foundation upon which the metabolism of the system is based, as it governs the volume and nutrient status of the waters entering the lake.

MORPHOLOGY

The physical parameters of Coldwater Lake, a relatively deep lake, suggest a tendency towards an unproductive system (Table II). The mean depth, for example, has an influence on the trophic status of a lake, with shallow mean depths tending to be associated with more productive lake systems. Coldwater Lake has a mean depth of 27 m, suggestive of oligotrophic status. The relative depth of 3.1%, reflective of the relationship between the maximum depth and the surface area, also suggests an unproductive system. Wetzel (1983) observes that the majority of lakes have relative depths of less than 2%; higher values indicate relatively deep lakes with correspondingly smaller surface areas. The area of the watershed is also sometimes a predicator of the lake's trophic status, as a watershed many times larger in area than the area of the lake will tend to

contribute high levels of nutrients causing the lake to be more productive. The watershed area:lake area ratio (15.95) for Coldwater Lake is not large, and may be considered typical for a relatively unproductive system.

The mean depth in Castle Lake is 20 m, which suggests this lake will tend toward oligotrophic conditions, as well. The maximum depth is 32 m; the ratio of mean to maximum depth is high (0.63), reflective of the gently sloping contours of the lake bottom. The relative depth (2.8%) is moderately high, indicating the lake is somewhat deep relative to its surface area, which could encourage the tendency toward oligotrophy. Relative to the size of the lake, the area of the watershed is small, only eight times the surface area of the lake, suggesting again that the lake will tend to be unproductive.

The hypsographic curves describe the much larger surface area and greater depth of Coldwater Lake, compared to Castle Lake (Figure 4 and 5). The trophogenic and tropholytic zones are fairly evenly divided in Coldwater Lake; the processes of production and decomposition could potentially occur in essentially separate and equal partitions of the lake.

In Castle Lake, in contrast, significant contact between the upper productive waters and the sediment layer (Figure 4) is compounded by the lesser total depth, and the gently sloping contours of the bottom of the lake. These

factors suggest that the potential level of biological productivity could be higher in Castle Lake than in Coldwater Lake. In addition, the major fraction of the total volume in Castle Lake is surface water (Figure 5). Thus, the potential for an increased primary productivity which was suggested by the hypsographic curve is supported. The deeper waters, which would be separated from the surface layer after stratification, contain significantly less volume.

Considering the much smaller total volume relative to Coldwater Lake, this decrease in hypolimnion volume in Castle Lake is especially pronounced; comparing Coldwater:Castle, the ratio of lake volumes above the depth of 20 m is 2.6 while the ratio of volumes below 20 m is 8.9. A further contrast is given by the ratio of hypolimnion volume:surface area, which is 6.6 in Castle Lake and 23.8 in Coldwater Lake. These numbers indicate that deep water processes could vary considerably between the two lakes.

LIGHT AND TEMPERATURE

The light data, when compared to the similar data reported from 1986, indicate that water transparency in Coldwater Lake and Castle Lake has essentially stabilized and would not be expected to change significantly in the future (Table III). Transparencies of this order are typically associated with lakes of low to moderate

productivity.

Thermal stratification of a lake system effectively separates the body of a lake into layers based on the density characteristics of water. The depth of the epilimnion is dependent on the degree of mixing of the surface waters, and is an important factor in determining the trophic level which a lake can sustain. As the 1% light level is an estimation of the depth to which net phytoplankton growth will occur, the depth of mixing determines whether the plankton will be carried below this "compensation depth," or maintained under conditions of adequate light.

Epilimnion depths of three to five meters in early summer, extending to ten or eleven meters by the end of the season, were observed in both lakes (Appendix B, Figure 7 and 8). These data, taken with the water transparency data just considered, indicate that mixing would not be sufficient to remove organisms from the photic zone. Light would therefore not be a limiting factor for phytoplankton growth in the epilimnetic region of either lake.

One interesting contrast between these two lakes lies in the elevated temperature readings observed at the surface in Castle Lake. During 1989, a peak of 20.00 °C was recorded for Castle Lake, while the maximum temperature at the surface for Coldwater Lake was 18.51 °C; in 1990, values greater than 20 °C were observed on three dates in Castle

Lake, with a maximum of 22.8 °C, whereas the maximum surface temperature was 18.8 °C in Coldwater Lake. These numbers suggest the possibility that levels of dissolved organic matter in Castle Lake continue to exceed those in Coldwater Lake. High concentrations of DOM in lakes have been reported to selectively absorb infrared wavelengths of light, significantly heating the surface waters (Wetzel, 1983).

OXYGEN

Oxygen is a key element in lakes, because the concentration and distribution of dissolved oxygen plays a central role in the geochemical cycles of many nutrients. The variations in dissolved oxygen concentrations which generally occur with increasing depth in a lake change over the course of a growing season in a characteristic fashion, depending on several factors. These include the morphology of the lake basin, the quantity and quality of organic matter present, and the solubility characteristics of oxygen in water.

In studying the pattern of oxygen concentrations with depth and over time for a particular lake, several analyses can be utilized to quantify the general relationship between the two principal processes which are going on, i.e. primary production and decomposition. One evaluation of the extent of oxygen deprivation for a particular depth stratum is the

ratio of the observed oxygen concentration and the concentration expected at saturation given the temperature, expressed as a percentage. This value is termed the absolute oxygen deficit, or percent saturation. This measurement is problematic since it depends upon the assumption that surface mixing is adequate to completely saturate the water column during overturn. However, it remains useful in a general sense as it is reflective of the level of oxygen demand upon the lake system. Alternatively, analysis of the difference between the measured oxygen concentrations of the water column at the end of spring mixing and in the hypolimnion just prior to fall overturn provides a measure of the relative oxygen deficit. This assessment of oxygen consumption is more accurate as it takes into consideration the volume characteristics of the lake basin.

Oxygen concentrations in both Coldwater and Castle lakes were less than saturated throughout the sampling period in both 1989 and 1990 (Appendix C). A metalimnetic oxygen maximum in Coldwater Lake was indicated by the increase in both total concentration and percent saturation on various dates at depths ranging from 5 to 15 m. This pattern produces a positive heterograde curve and is associated with phytoplankton communities situated in the metalimnion (Appendix H).

The oxygen deficit data from Table IV imply that

Coldwater Lake is mesotrophic to eutrophic, according to Wetzel (1983). These high values clearly reflect the increased load of organic material dating from the eruptive events of 1980, as other indications previously discussed suggest that physical limnology of Coldwater Lake would not support a highly productive system. In spite of the high oxygen demand, the fact that oxygen concentrations were not depleted further is likely the result of the large volume of the hypolimnion, especially with respect to the sediment surface area which is the primary site of oxidative processes. As a consequence, the total amount of oxygen present in the deep water of the lake was relatively large and depleted slowly.

The presence of a metalimnetic oxygen maximum was not pronounced in Castle Lake in 1989, except at 20 m on 8 August. Otherwise, a smooth decrease in oxygen levels was observed with depth throughout the season. In 1990, however, an apparent maximum developed at 10 m through the first half of the season.

The areal oxygen deficit for Castle Lake (Table IV), is nearly identical to that calculated for Coldwater Lake. This value is reflective of the high oxygen demand normally associated with mesotrophic to eutrophic lakes. The volume oxygen deficit in Castle Lake, on the other hand, is more than twice the volume deficit in Coldwater Lake, a consequence of the basin morphology. The morphometry of

Castle Lake delineates a basin which stratifies to create a hypolimnion with a small volume relative to the epilimnion. The result is a decrease in the total amount of oxygen in the deep water, which is rapidly utilized by the decomposition processes occurring there. Additionally, it is possible that Castle Lake may contain higher levels of dissolved organic material due to the previous presence of the marsh upon which the lake was formed. All of these influences are likely to be involved in the increased rate of oxygen consumption in the deep waters of Castle Lake.

SALINITY

As exorheic lakes (open basins with an outlet), the chemical composition of the water in Coldwater Lake and Castle Lake is determined principally by the chemical composition of the inflow. The components which contribute to the character of the waters entering a lake include the precipitation characteristic of the area, the properties of the drainage basin surrounding the lake, and the equilibrium reactions which occur in the soils and sediments associated with the lake waters (Hutchinson 1957).

Precipitation in the Cascade Mountains of the Pacific Northwest is classified as essentially marine in origin (U.S.G.S., 1990), due to the presence of the Pacific Ocean less than 100 miles to the west, and the predominance of air currents out of the west. Chloride concentrations, which

decrease in proportion to the distance from the ocean, can be utilized as a gauge of the influence of precipitation on the chemistry of a lake. Hutchinson (1957) described expected chloride concentrations in rain falling progressively inland; the value for 90 miles (198 km) is approximately 2-3 mg/l.

The high levels of chloride observed in Coldwater Lake (Table V) suggest that precipitation is not a factor in influencing major ion chemistry in Coldwater Lake. Rather, they point to the likelihood of a source of sodium in the drainage basin. As sodium levels in Spirit Lake have also been observed to increase in the years following the eruption (Larson and Glass 1987), it seems possible that sodium-rich inflow from Spirit Lake may be contributing to elevated concentrations of that element in Coldwater Lake.

The concentrations of chloride in Castle Lake, on the other hand, are representative of the levels expected in rain water in the area. These low chloride concentrations, in addition to the more typical major ion concentrations in general, suggest that the influence of the watershed is less pronounced than in Coldwater Lake.

The post-eruption watersheds above Coldwater and Castle lakes were described earlier (Janda et al. 1985, Collins et al. 1983, Collins and Dunne 1986). Both watersheds feature steep topography, extensive volcanic deposits and somewhat stable patterns of surface run-off. Additionally,

vegetative cover is limited and erosion is still considerable. Geothermal seeps continue in the debris avalanche.

Drainage from igneous rock formations is typically dilute, with salinity values generally of less than 50 mg/l (Wetzel 1983). The extremely high values for salinity reported for Coldwater Lake (Table V) suggest that the drainage basin for Coldwater Lake contains easily weathered soils and continues to supply high levels of weatherable sediment particles to the lake waters. This suggestion is supported by the relatively constant concentrations of major ions observed when data from 1989 is compared to earlier data (Table I). This effect is likely to be at least partially associated with significant levels of erosion in the tunnel outlet into South Coldwater Creek. In addition, as previously mentioned, it is possible that the waters from Spirit Lake continue to be chemically enriched due to the excessive volcanic deposits which that lake received, and contribute to the enrichment of Coldwater Lake, in spite of incomplete mixing (Larson and Glass 1987).

The elevated concentrations of sulfate, in particular, in Coldwater Lake are likely influenced by geothermal input. Studies in 1985 and 1986 showed Spirit Lake to be enriched in sulfate due to geothermal seeps which contained average concentrations of sulfate of 1500 mg/l (Larson and Glass 1987). It is possible that Coldwater Lake may be influenced

by Spirit Lake waters or directly influenced by geothermal waters, seeps having been observed during the first summer after the eruption in regions near the lake which are now covered with lake water.

The total salinity values observed in Castle Lake (Table V) suggest that the drainage basin appears to have stabilized in its drainage patterns, with weatherable particles not supplied to the lake in excess of typical lakes of volcanic terrain, in contrast with Coldwater Lake. The elevated levels of calcium may reflect the influence of the old lake bottom, with a correspondingly greater sedimentary influence than might be expected in the region. The decrease in concentrations of major ions over the ten years since the formation of the lake (Table I) corroborate the stabilization of the watershed and lake volume suggested by the values for salinity as a whole in Castle Lake.

NUTRIENTS

Nitrogen

Nitrate concentrations were low and progressively depleted in Coldwater Lakes (Table VII), probably a consequence of phytoplankton uptake. The pattern of depletion in the surface waters suggests that ammonia levels were low as well. Utilization of nitrate would be limited if ammonia was present in sufficient quantity, as ammonia is the preferred form of nitrogen for phytoplankton growth

(Wetzel 1983).

The relative constancy of the nitrate levels in the hypolimnion of Coldwater Lake suggest that ammonia concentrations were low in this layer as well. The lake was oxygenated at all depths throughout the season in 1989 and 1990, although the oxygen concentration was less than saturation and progressively depleted in the deep water. If excess ammonia had been generated from the sediments, it would likely have been oxidized to nitrate in the presence of oxygen, as the lack of light at that depth would preclude assimilation of the ammonia by photosynthetic organisms.

Nitrate data from the bay in Coldwater Lake reflect a similar pattern of low levels which decrease as the summer proceeded (Appendix E). The inflow waters from South Coldwater Creek consistently contained less nitrate than the bay waters, and nitrate concentrations were undetectable in Spirit Lake (Appendix G). These data corroborate suggestions from earlier research (Larson and Glass 1987) that the waters in South Coldwater Creek are essentially overflow waters from Spirit Lake via the tunnel outlet. The fact that the waters of the bay, in close proximity to the inflow waters across the delta, contained levels of nitrate comparable to levels observed in the deeper waters of the lake, also suggest that mixing is minimal between the inflow waters of S. Coldwater Creek and the lake water.

It seems likely that nitrate levels in Coldwater Lake

during 1989 and 1990 were adequate to prevent nitrogen fixation in the water column from becoming a major nitrogen source. However, the terrestrial ecology of the watershed surrounding the lake is dominated by nitrogen fixing organisms (*Alnus* sp., *Trifolium* spp., *Lupinus* sp.). The drainage waters therefore are possibly relatively enriched with nitrate as a result, so that nitrogen fixation is ultimately a significant source. It appears that decomposition of the organic material in the lake sediments, while being sufficient to cause the oxygen deficit observed by season's end, was not releasing significant amounts of nitrogen to the lake. There is little nitrogen associated with the conifer forest remains which were the source of the organic material. The passage of time since the influx of debris undoubtedly has produced compounds more resistant to decay with lower nitrogen content.

Extremely low concentrations of nitrate, depleted in the surface waters, were also observed in Castle Lake (Table VIII). Ammonia levels were probably quite low in the surface waters, similar to Coldwater Lake, as it is unlikely that ammonia would be abundant under the oxygenated conditions.

Concentrations of nitrate in Castle Lake were approximately half those in Coldwater Lake. It is tempting to point out that these reduced concentrations exactly mirror the difference in watershed area:lake area between

the two lakes, which is nearly 16 units for Coldwater Lake and 8 for Castle Lake. It is possible that the depletion in nitrate in Castle Lake was a consequence solely of these lower initial concentrations.

The profile of nitrate concentrations in the hypolimnion of Castle Lake suggest the likelihood of denitrification occurring in the sediments. Nitrate gradually decreased in the deepest stratum of the lake, a phenomenon which was quite pronounced in October, 1990. As Castle Lake consistently developed anoxia in the bottom waters as the season progressed, most profoundly in 1990, it is plausible that nitrate would have been utilized as an alternate oxidizing agent in the decomposition of organic matter in the anaerobic sediments, leading to a decrease in concentrations of fixed nitrogen near the sediment.

The existence of nitrogen fixation is not indicated by the nitrate data, in spite of the near absence of nitrate in the photic zone for a large portion of the growing season. Nitrogen fixation occurs only if microbial communities utilizing nitrogen gas as the source for nitrogen are present. Accordingly, in the absence of definitive tests for the presence of the enzymes required for nitrogen fixation, the nature of the plankton communities serve as an indication of the presence or absence of nitrogen fixation. Nitrogen fixers were not observed in the phytoplankton, and the small fraction of chlorophyll a represented by

picoplankton in 1990 suggest that nitrogen fixers were not present.

Phosphorus

The forms of phosphorus in fresh waters can be considered in two phases: particulate and dissolved. The particulate phase consists of phosphorus contained in organisms, as well as that associated with inorganic complexes of mineral origin, and adsorbed onto dead organic particulates. The dissolved forms of phosphorus include inorganic orthophosphate, which is ecologically significant as the form of phosphorus most readily assimilated by phytoplankton. Because of the rapidity with which soluble inorganic phosphate is taken up by algae and bacteria, concentrations in surface waters are generally quite low, constituting a small fraction of the total phosphorus present.

The dynamics of exchange between the particulate and dissolved phases of phosphorus in the surface waters are crucial in determining the availability of phosphorus to the phytoplankton communities; the concentration of inorganic orthophosphate in the water at any one time is of relatively less significance. Especially when phosphate levels are reduced in the productive regions of a lake, phosphorus which is rapidly recycled from the waste products of herbivorous zooplankton provides a significant portion of the phytoplankton requirement. Another factor is the

ability of phytoplankton to assimilate phosphorus in excess of immediate requirements and sequester it within the cells; this "luxury" phosphorus is utilized by the cells for growth when external concentrations become depleted.

Concentrations of total phosphorus are useful as general indicators of the trophic level of an aquatic system; higher levels are commonly associated with increased levels of productivity. According to Wetzel (1983), oligotrophic lakes are normally characterized by total phosphorus concentrations averaging 8 micrograms $\text{PO}_4\text{-P}$ /liter, with an upward limit of about 18 micrograms/liter. Mesotrophic lakes have a broader range of total phosphorus concentrations, averaging about 27 micrograms/liter, with a upper limit close to 100 micrograms/liter.

Inorganic phosphate concentrations in Coldwater Lake were relatively constant, consistently less than 5 ug/l (Table IX), with values generally similar among the lake stations and higher in the inflow waters (Appendix D and E). Values for total phosphorus (Table XI) were moderately high and tended to be more variable, with concentrations highest in the bay and inflow waters. The proportion of total phosphorus observed as soluble orthophosphate ranged from 4% up to 24%, relatively large compared to most other lakes (Wetzel, 1983). These data suggest two things: 1. The elevated concentrations of total phosphorus in Coldwater Lake are possibly associated with the excess load of

suspended material supplied to the lake by South Coldwater Creek, rather than directly related to high levels of primary productivity. 2. As the sediment is deposited in the quiet waters of the bay, which is relatively shallow compared to the rest of the lake, it may provide a significant and continual source of inorganic phosphorus to Coldwater Lake, in spite of the limited mixing of the inflow waters.

The low but detectable pattern of orthophosphate concentrations was also observed in Castle Lake. Total phosphorus concentrations were lower than in Coldwater Lake, indicative a low level of primary productivity. The constancy of the orthophosphate concentrations in the anaerobic hypolimnion also support this view. The oxygen demand was probably due to characteristics of the basin as well as the legacy of organic matter left from the old lake bottom and the influx of material dating from the eruption, as has been discussed. The development of anoxia in the hypolimnion, although probably severe enough to break down the oxidized boundary in the sediment layer, did not appear to be contributing to a massive influx of dissolved phosphate from the lake bottom. It is possible that algal cells sedimenting from the trophogenic zone were largely decomposed by the time they reach the bottom, leaving a relatively less phosphorus-rich residue.

Silicon

Silicon is the second-most abundant element in the earth's crust, comprising more than 27% of the total by weight. As such, it is generally present in abundant amounts in fresh waters, in the form of silicon dioxide or silica (SiO_2). The dissolution of silicate minerals provides the major source of silica. Consequently, water in extended contact with volcanic rocks, usually ground water, typically contains the highest concentrations of silica. In a lake, therefore, the input of silica is relatively uniform over time; the conspicuous variations in silica concentration which commonly occur in many lakes have their origin in biological utilization of silicon by diatoms. As silica is assimilated, concentrations in the trophogenic zone decrease; sedimentation of diatom frustules results in the loss of silica from the epilimnion, and the concomitant transfer of silica to the deep waters and the sediments.

A typical seasonal pattern for silica generally begins with the development of diatom populations in the late winter and early spring, which causes a depletion of silica in the surface waters of the lake. If silica levels are reduced to below approximately 0.5 milligrams/liter, a decline in the diatom community follows, and other phytoplankton generally assume a more important role at that point. In eutrophic lakes, silica levels may approach zero in the epilimnion; the depletion of silica in oligotrophic

lakes, although often noticeable, is generally not sufficient to prevent continued diatom production, which may persevere relatively unabated through the season.

Silica concentrations were quite high in Coldwater Lake (Table XIII). The progressive depletion which was observed in the surface waters reflected assimilation by diatoms, which dominated the phytoplankton throughout the summer of 1989 and 1990. The extremely high levels of silica preclude the limitation of diatom populations at any time in Coldwater Lake.

The increase in silica concentrations at 35 m in Coldwater Lake were possibly a consequence of basin morphology. An increase in silica at this depth could have been a consequence of a greater degree of water movement in the waters overlying the shallower sediments than in the waters associated with the deepest stratum. As the sediment layer between 20 m and 35 m comprises about 50% of the total surface area of the lake, accumulation and dissolution of diatom debris in the sediments at that depth interval would result in a positive heterograde curve for silica.

The higher concentrations observed in the inflow waters from South Coldwater Creek (Appendix E), also reported for Spirit Lake (Appendix G), were likely a consequence of the excess of volcanic material which was deposited on the watershed as well as directly into Spirit Lake. The relative decrease in silica in Coldwater Lake, then, could

be a reflection simply of the slight protection afforded the lake by its location behind Coldwater Ridge. In any case, the great similarity between silica levels observed in the bay and the other two stations provide additional evidence for the minimal impact of mixing of inflow waters of S. Coldwater Creek with the body of the lake.

The impact of the volcanic deposits is apparent also in the relatively high levels of silica reported for Castle Lake (Table XIV). The variation in silica concentrations between Coldwater Lake and Castle Lake was possibly a consequence of their differing location with respect to the crater, with a corresponding effect on the relative quantity of deposit material. The absence of silica depletion with depth in Castle Lake reflects the lack of siliceous phytoplankton, diatoms or otherwise, in that lake.

TROPHIC STATUS

Integration of the physical, chemical, and biological dimensions associated with limnological systems provides an assessment of the productivity level or trophic status of that system, defined by Hutchinson (1971) as a dynamic component of the system. The physical characteristics of a lake, including aspects of basin morphometry and water transparency, provide the foundation for the interaction of the other factors in the evolution of the system, as previously discussed. In turn, the chemistry of the water

and the surrounding watershed define the potential limits for the biological communities which can be maintained in the system. The phytoplankton community, which develops as a consequence of the combined influence of these physical and chemical factors, generally provides the most convenient measure of trophic status, often represented by chlorophyll concentrations and/or biovolume levels.

The trophic status of an aquatic system can therefore be defined according to several possible criteria, generally based on the level of nutrients capable of supporting photosynthetic growth, or the supply of organic matter, autochthonous or allochthonous, to the system (Wetzel 1983, Likens 1972). Indices of trophic status have been developed (Carlson 1977, Sweet 1986) in an effort to reduce the complexity inherent in the ecology of aquatic systems to a single measure or series of measures of productivity. The Carlson indices are based on concentrations of chlorophyll *a* (corrected for the presence of phaeopigments) as a gauge of viable algal biomass, and also include indices based on transparency of the water (i.e. Secchi depth) and levels of total phosphorus as indirect evidence of the productivity of the system. An index incorporating phytoplankton biovolume (Sweet 1986) provides additional perspective on algal biomass.

The concept of "trophic equilibrium" was postulated by Hutchinson (1971) to describe the situation which develops

as a lake proceeds through the maturation of its trophic potential, at which point the lake and the surrounding watershed are considered to have reached a condition of relative stability. Long-term lake studies (Hutchinson 1970) indicate that lake systems can be essentially constant over centuries, as long as the relevant conditions are not significantly altered. However, when significant changes occur in the factors controlling a lake system, a corresponding change in trophic status follows (Wetzel 1983).

The classic progression, described by Wetzel (1983), in the development of a lake basin is from oligotrophy to eutrophy and eventual filling in of the basin. However, the opposite trend also occurs. The initial conditions in Coldwater Lake and Castle Lake have been previously described as highly eutrophic as a consequence of the excessive load of inorganic and organic nutrients which they received during their formation. These systems were essentially heterotrophic during the first summer as the transparency of the water was so low that photosynthetic production was minimal. During the ten years which have elapsed between the formation of the lakes and this study, a dramatic change in conditions has transpired. These lakes provide an opportunity to observe the process by which highly productive aquatic systems, in conjunction with the profound changes occurring in the surrounding watershed,

proceed in the establishment of a relatively stable trophic condition.

Trophic Status of Coldwater Lake

The various factors which cooperate to determine the trophic status of an aquatic system were somewhat contradictory in the case of Coldwater Lake, according to the data collected in 1989 and 1990. The physical morphology of Coldwater Lake, a relatively deep lake with the surface area reduced in comparison (as indicated by the mean depth of 27 m and relative depth of 3.1%), suggests a tendency toward low productivity. The large volume of the hypolimnion, roughly equal in size to the epilimnion, indicates that nutrient recycling from the sediments may not be significant, and is generally associated with oligotrophy. The light characteristics as well, reflected in a mean Secchi depth of around 7 m, are also characteristic of low to moderate productivity ($TSI = 31.9$). However, the unusual nature of the watershed, due to the influence of the massive volcanic deposits which are susceptible to rapid weathering and the relatively limited vegetation of the watershed provides a rich source of nutrients and other inorganic ions. Consequently, salinity values in Coldwater Lake remain extremely high (mean 184.8 mg/l) producing correspondingly high conductivities (mean 307.5 umhos/cm). These salinities are typical of eutrophic lakes.

The mean total phosphorus concentration in Coldwater Lake for the summer season in 1990 was 21.15 ug/l, and the corresponding TSI value was 48.18 (Carlson, 1977). Comparing this value with the TSI calculated for the mean chlorophyll concentration for 1990 (2.03 ug/l; TSI=37.52) suggests that phosphorus was not limiting the production of chlorophyll.

TSI values for phytoplankton biomass throughout the summer, 1989, are in the range typical for mesotrophic lakes (TSI=35-50). The values calculated for chlorophyll a concentrations tend to be lower, although still in the mesotrophic range (TSI=25-35). This discrepancy is possibly due to the dominance of diatoms in the phytoplankton, with proportionately less chlorophyll/cell volume. The greatest differences between these two indices throughout the summer was consistently in the surface samples, with the chlorophyll index being significantly lower; this divergence was likely a result of the greater light intensity at that depth.

Trophic Status of Castle Lake

The various factors contributing to the trophic status in Castle Lake are similarly not consistent with one another. Although the mean depth (20 m) and the relative depth (2.8%) are suggestive of a slightly more productive status than the values for Coldwater Lake, still they do indicate a tendency toward low productivity. The ratio

between the watershed and the lake area is small, supporting the trend toward oligotrophy. The light characteristics are comparable, with a mean Secchi depth of approximately 8 m (TSI=30.0). In contrast, the values observed for salinity and conductivity (mean, 52.2 mg/l and 67 umhos/cm, respectively), while much lower than those reported for Coldwater Lake, are reflective of moderately productive systems. The morphology of the lake basin, as well, suggests a higher level of productivity as a consequence of the sloping bottom which potentially provides a greater degree of nutrient recycling from the sediment layer.

The much reduced volume of the hypolimnion compared to the epilimnion allowed a significant oxygen deficit to develop in the deep waters during both 1989 and 1990, a condition which is normally associated with eutrophic systems. However, the levels of chlorophyll and phytoplankton biovolume do not reflect high levels of autotrophic production in the water column. The oxygen decrease is more likely a result of continued decomposition of organic material present in the sediments, a legacy of the volcanic debris as well as the marshy nature of the region prior to the eruption.

The levels of total phosphorus reported for 1990 in Castle Lake were considerably less than in Coldwater Lake (mean, 9.53 ug/l). The corresponding TSI value (36.68) is indicative of low mesotrophic status, and correlates well

with the mean chlorophyll concentration (1.94 ug/l, TSI=37.07). It is possible, therefore, that phosphorus concentrations are limiting the phytoplankton biomass and chlorophyll concentration in Castle Lake.

In contrasting TSI values for chlorophyll and phytoplankton biovolume over the range of depths sampled, a similar pattern emerges of decreased chlorophyll values in the surface layer. However, the values in the deeper waters agree closely, with the exception of the deep water sample on October 11, 1989. This situation, considered in light of the hypolimnetic oxygen deficit which was present, may reflect a switch to heterotrophic nutrition by mixotrophic flagellates at the bottom of the thermocline, with a concomitant decrease in chlorophyll.

SUMMARY

The trophic status of Coldwater Lake and Castle Lake during the summer, 1989 and 1990, was observed to be reduced from the highly productive levels which were characteristic of the lakes during the first few years following their formation. Moderately productive levels of chlorophyll a and phytoplankton biomass were observed in both lakes, although the species composition was widely divergent in each lake. A decrease in chlorophyll concentration relative to phytoplankton biovolume was observed in the surface samples, suggesting that surface samples of chlorophyll may underrepresent the levels of phytoplankton present. Major ion data for both lakes indicate that the watershed for Coldwater Lake continues to supply an excess of inorganic ions to the water column, while the watershed for Castle Lake is nearly representative of typical lakes in igneous drainage systems.

Typically, limnology describes the status of new lakes as ultra-oligotrophic systems; however, Coldwater and Castle lakes originated as hypereutrophic lakes and have developed into moderately productive lakes over the course of the first ten years since their inception. The physical morphology of both lake basins suggest that the development of the lake systems will be in the direction of further

reductions in lake trophy, contingent on the continued stabilization of the watersheds as terrestrial recovery proceeds in the aftermath of the volcanic eruption.

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APPENDIX A

METHODS FOR LABORATORY ANALYSIS

DESCRIPTION OF LABORATORY METHODS

Nitrate-NitrogenReagents

Nitrate standard stock solution: Weigh 0.722 g KNO_3 and dilute to 1 liter with distilled water; store in polyethylene bottle.

Experimental standard solutions: Dilute stock solution, 1 ml into 100 ml distilled water (100 ug/l $\text{NO}_3\text{-N}$). Using serial 1:1 dilutions, with distilled water and acid-washed test tubes, make a series of standards from 100 ug/l to 6.25 ug/l.

Analytical Procedure Transfer aliquots of 25 ml from each sample into 50 ml test tubes with lids; add 5 ml NH_4Cl and about 1 g spongy wet cadmium to each tube. Cap tightly and shake the tubes in a horizontal position for 90 minutes. Remove subsamples of 10 ml to clean tubes and add 0.5 ml color reagent B. Leave standing in dim light for at least 10 minutes, but not more than 2 hours; read absorbances at 540 nm using a 1 cm cell. The standards and blanks are treated in the same manner as the samples.

Dissolved ortho-Phosphate and Total PhosphorousReagents

Ammonium molybdate solution: Dissolve 15 g of ammonium paramolybdate $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ in distilled water and dilute to 500 ml. Store in an amber polyethylene bottle.

Sulfuric acid: Add 140 ml of concentrated sulfuric acid to 900 ml of distilled water. Store in a glass stoppered bottle.

Ascorbic acid solution: Dissolve 27 g of *L*-ascorbic acid in 500 ml of distilled water. Make fresh as needed.

Potassium antimonyl-tartrate solution: Dissolve 0.34 g of potassium antimonyl-tartrate $[K(SbO)C_4H_4O_6 \cdot 1/2H_2O]$ in 250 ml of distilled water. Store in a glass bottle.

Composite reagent: Mix together 100 ml ammonium molybdate, 250 ml sulfuric acid, 100 ml ascorbic acid, and 50 ml potassium antimonyl-tartrate solutions. Prepare daily for use.

Phosphate standard solutions: Dissolve 0.2197 g oven-dried (105°C, 24 hr) potassium dihydrogen phosphate (KH_2PO_4) in distilled water and dilute to 1 liter. Store in dark bottle with 1 ml of chloroform. (1.00 ml = 50.0 ug PO_4-P). Dilute with distilled water to make standards.

Analytical Procedure Transfer 100 ml of sample to glass Ehrlenmeyer flasks; add 10.0 ml of composite reagent to each flask. After color develops for 10 minutes, before 2 hours, read absorbances at 880 nm, using a 5 cm cell. Standards and blanks are subjected to the same procedure.

Preliminary Total Phosphorous Digestion

Reagents

Phenolphthalein indicator solution: Dissolve 5 g phenolphthalein disodium salt in distilled water and dilute to 1 liter. If necessary, add 0.02N NaOH by drops until a faint pink color appears.

Sulfuric acid solution: Add 300 ml conc. H_2SO_4 to approximately 600 ml distilled water. Dilute to 1 liter.

Ammonium persulfate, solid.

Sodium hydroxide, NaOH, 1N.

Analytical Procedure Mix 100 ml of sample with 1 g persulfate and 2 ml sulfuric acid; place, covered, in autoclave for 30 minutes, at 1.0 to 1.4 kg/cm² (15 to 20 psig). After cooling, adjust the pH to the phenolphthalein endpoint, using 1N NaOH. Measure volumes, adjusting to 100 ml with distilled water if necessary; add 10.0 ml of composite reagent to each flask and read the absorbance as above. Standards and blanks are prepared and undergo the identical boiling method. Concentrations are calculated using volumes corrected to 100 ml.

Dissolved Silica

Reagents

Hydrochloric acid, 0.25N: Mix 22 ml of concentrated HCl (sp. gr. 1.18) with distilled water and dilute to one liter.

Ammonium molybdate, 5%: Dissolve 52 g $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ in distilled water and dilute to one liter.

Disodium EDTA, 1%: Dissolve 10 g disodium EDTA in distilled water and dilute to one liter.

Sodium sulfite, 17%: Dissolve 170 g Na_2SO_3 in distilled water and dilute to one liter.

Silica standard: Fuse about 1 g NaOH in a nickel crucible over a flame; add 0.100 g SiO_2 (optical grade) and dissolve over the flame for a few minutes. Immerse the crucible in distilled water and allow to dissolve for 30 minutes; dilute to one liter. (1ml = 0.10 mg SiO_2) Prepare standards as follows using the stock solution, making up to 10.0 ml with distilled water:

4.0 ml = 0.4 mg/10 ml = 40 mg/l

2.0 ml = 0.2 mg/10 ml = 20 mg/l

1.0 ml = 0.1 mg/10 ml = 10 mg/l

0.5 ml = 0.05 mg/10 ml = 5 mg/l

0.25 ml = 0.025 mg/10ml = 2.5 mg/l

Analytical Procedure Transfer 10.0 ml sample into polyethylene test tubes. Add to each tube:

5 ml 0.25N HCl

5 ml 5% ammonium molybdate

5 ml 1% disodium EDTA

After 5 min have elapsed following the addition of the molybdate, add 10 ml of 17% sodium sulfite. Vortex, and let color develop for 30 minutes. Read the absorbance at 700

nm, using a 1 cm cell. Standards and blanks are prepared and treated to the same procedure.

Chlorophyll a

Analytical Procedure Filter 25 ml of sample, in dim light, using Whatman GF/A glass microfibre filters (Whatman GF/F filters were also used in 1990 for identification of the picoplankton fraction); two drops of saturated MgCO_3 is added before the filter is dry to stabilize the chlorophyll molecule. The filter is folded with the precipitate inside and ground in 10 ml 90% acetone with a tissue grinding mortar and pestle at 1000 rpm for 30 seconds. The solution is allowed to extract in dim light for 24 hours; fluorescence is measured before and after the addition of 2 drops of 5% HCl, using a Turner design fluorometer calibrated with a spectrophotometer for chlorophyll a.

Calculate the chlorophyll a concentration as follows:
 $\text{ug/l chl a} = (\text{abs}_{\text{before}} - \text{abs}_{\text{after}}) (0.062) (\text{dilution factor}) (1000)$, where 0.062 is the calibration factor for the fluorometer.

Winkler Method for Dissolved Oxygen

Reagents

Manganous sulfate reagent: Dissolve 400 g $\text{MnSO}_4 \cdot 2 \text{H}_2\text{O}$ in one liter distilled water.

Alkaline-iodide-azide reagent: Dissolve 500 g NaOH + 135 g NaI in one liter of distilled water; add 10 g NaN_3 (CAUTION: extremely poisonous), dissolved in 40 ml distilled

water.

Sodium thiosulfate stock solution (0.10 N): Dissolve 24.82 g $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5 \text{H}_2\text{O}$ in one liter of freshly boiled and cooled distilled water. Preserve by adding 5 ml chloroform.

Sodium thiosulfate standard solution (0.025 N): Dilute 25 ml stock thiosulfate solution to 100 ml with distilled water.

Starch solution: Add 5 g soluble starch to 1 liter boiling distilled water with stirring; allow to boil a few minutes and then cool overnight. Use the clear supernate and preserve with 1.25 salicylic acid.

Potassium biniodate solution (0.025N): Dissolve 3.249 g $\text{KH}(\text{IO}_3)_2$ in distilled water and dilute to 1 liter to prepare a 0.100 N stock solution. Dilute 250 ml stock solution to 1 l to prepare 0.025 N solution.

Analytical Procedure In the field, transfer samples from the Van Dorn bottle to the bottom of an upturned 300 ml BOD bottle. Allow the water to flow continuously through the bottle to exclude all trapped bubbles as the bottle is slowly righted. Gently withdraw the delivery tube after the bottle is filled completely; slip on the stopper from the edge of the bottle so as to avoid trapping air.

Add, with the tip of the applicator dropper just below the surface of the water, 2 ml of manganous sulfate reagent and 2 ml of alkaline-iodide-azide reagent. Cap the bottle and mix vigorously by inversion; allow the precipitate to

settle. Cover the bottles with canvas at this point to exclude light and transfer back to the lab.

When the analysis can be completed, within 24 hours, add 2 ml concentrated sulfuric acid, inserting the pipet tip just below the surface of the sample. Stopper the bottle without introducing air and shake the bottle to dissolve all the precipitate. Measure 100 ml of the sample into a glass 250 ml Ehrlenmeyer flask.

Titrate with 0.025N standardized sodium thiosulfate solution until a pale yellow color is obtained; add 2 drops of stabilized starch mixture and continue titrating carefully to a colorless end point. Record the volume of titrant used in ml to two decimal places.

Phytoplankton Identification and Enumeration

Samples from Castle Lake (1989 only) were settled in 50 ml aliquots in sedimentation chambers and soft bodied algae were identified under 100 X using phase-contrast with an inverted microscope (Zeiss Invertoscope-D) to genus; diatoms were identified to species, when possible.

For Coldwater Lake (1989 only), 50 or 75 ml aliquots were filtered onto Millipore HA, 0.45 um pore size, white membrane filters. Labelled microscope slides were prepared and 4 to 5 drops of microscope immersion oil were placed onto each slide. Sections of the filters were placed directly onto the oil; the cover slip was gently lowered onto the filter and sealed with clear nail polish to create

a permanent slide. The slides were examined under 100 X with a Zeiss compound microscope using phase-contrast.

For both lakes, enumeration was along a measured transect until a minimum of 100 algal units were counted. An algal unit was considered as an individual organism, either a unicell or a colony/filament. Converting to number of organisms per milliliter was done, using the area of the transect counted, the total area of the filter, and the volume of the sample filtered, according to the following formula:

$$\text{formula: } D = \frac{n (A_f)}{(V_f) (A_c)}$$

where D = density/ml

n = number counted

A_f = area of filter (mm^2)

V_f = volume filtered (ml)

A_c = area of transect counted (mm^2)

APPENDIX B

TEMPERATURE DATA

TEMPERATURE IN COLDWATER LAKE, SUMMER 1990

Depth (m)	Degrees Celsius						
	24 May	14 June	5 July	26 July	31 Aug.	20 Sept.	11 Oct.
0	8.75	11.70	17.91	18.80	17.09	17.30	13.51
1	8.75	11.50	17.75	18.83	17.31	17.30	13.48
2	8.95	11.00	17.48	18.89	17.30	17.20	13.41
3	9.00	10.89	17.12	18.91	17.30	16.91	13.36
4	8.96	10.69	16.75	18.92	17.30	16.82	13.32
5	8.91	10.45	16.30	18.96	17.29	16.75	13.30
6	8.93	10.32	15.00	17.04	17.28	16.69	13.28
7	8.90	10.10	13.50	15.00	17.28	16.63	13.26
8	8.78	10.01	12.42	13.56	17.13	16.13	13.26
9	8.29	10.00	11.31	12.30	13.90	15.25	13.24
10	7.62	9.71	10.56	11.22	12.08	13.81	13.22
11	7.49	8.50	10.00	10.65	10.70	11.22	13.21
12	6.54	7.96	9.03	10.00	9.70	9.87	11.17
13	5.69	7.31	7.81	8.69	8.60	8.52	9.87
14	5.50	6.99	6.82	7.69	7.61	7.99	8.43
15	5.36	6.39	6.70	7.11	6.91	7.42	7.62
16	5.07	6.02	6.58	6.62	6.52	6.90	7.10
17	5.00	5.92	6.02	6.15	6.25	6.53	6.66
18	5.00	5.81	5.82	5.81	6.05	6.09	6.31
19	4.91	5.63	5.72	5.60	5.82	5.73	5.99
20	4.88	5.48	5.53	5.47	5.52	5.48	5.79
25	4.53	5.00	5.05	5.00	5.00	4.98	5.00
30	4.53 ¹	4.76	4.82	4.65	4.58	4.60	4.79
35		4.63	4.71	4.49	4.39	4.39	4.56
40		4.52	4.61	4.32	4.38	4.31	4.45
45		4.41	4.52	4.24	4.32	4.21	4.36
50		4.35	4.38	4.23	4.29	4.11	4.28

TEMPERATURE IN CASTLE LAKE, SUMMER 1989

Depth (m)	Degrees Celsius					
	<u>24 June</u>	<u>7 July</u>	<u>8 August</u>	<u>1 Sept.</u>	<u>20 Sept.</u>	<u>14 Oct.</u>
0	18.19	16.30	20.00	16.91	17.09	14.29
1	18.11	16.29	19.78	16.95	16.65	14.29
2	16.78	16.09	19.19	17.01	16.49	14.29
3	16.48	15.71	18.05	17.05	16.42	14.31
4	16.05	15.00	17.38	17.02	16.32	14.31
5	14.88	14.25	16.77	17.00	16.28	14.31
6	13.18	12.98	16.47	16.96	16.20	14.30
7	10.30	11.78	15.30	16.35	16.16	14.31
8	9.69	10.39	12.76	12.81	13.71	14.30
9	9.12	9.15	9.78	10.38	10.10	14.00
10	8.27	8.19	8.08	9.11	8.71	9.38
11	7.49	6.86	7.00	7.81	7.68	8.00
12	6.42	6.10	6.39	7.12	7.05	7.20
13	5.71	5.75	5.89	6.46	6.12	6.39
14	5.17	5.09	5.24	5.85	5.81	5.83
15	5.00	5.00	5.01	5.41	5.40	5.39
16	4.93	4.70	4.98	5.03	5.04	5.15
17	4.80	4.59	4.79	5.00	5.00	5.00
18	4.68	4.48	4.62	4.99	4.81	4.98
19	4.56	4.37	4.48	4.88	4.65	4.81
20	4.49	4.32	4.40	4.76	4.55	4.65
25	4.22	4.08	4.19	4.45	4.29	4.39
30	4.17 ¹	4.05	4.12	4.37 ¹	4.21 ¹	4.32 ¹

¹ 29 m

TEMPERATURE IN CASTLE LAKE, SUMMER 1990

Depth (m)	Degrees Celsius					
	<u>28 June</u>	<u>19 July</u>	<u>9 August</u>	<u>6 Sept.</u>	<u>2 Oct.</u>	<u>18 Oct.</u>
0	17.18	22.50	22.82	20.20	16.68	10.35
1	17.04	22.11	22.55	20.00	16.71	10.40
2	17.01	21.62	22.12	19.50	16.74	10.41
3	16.81	21.31	21.91	18.50	16.75	10.42
4	16.81	19.76	21.51	18.00	16.76	10.42
5	12.89	17.45	20.03	17.70	16.75	10.44
6	10.98	15.33	18.02	17.30	16.72	10.45
7	9.92	13.42	14.95	16.20	16.70	10.42
8	9.09	11.61	12.51	13.70	15.88	10.42
9	8.31	9.31	10.83	10.50	12.32	10.42
10	7.49	8.41	9.78	9.00	10.92	10.42
11	6.79	7.20	8.58	7.70	9.29	10.19
12	6.46	6.21	7.49	6.70	8.38	8.31
13	5.76	5.50	6.85	5.85	7.41	7.10
14	5.30	5.09	6.32	5.40	6.75	6.20
15	5.00	5.00	5.78	5.20	6.30	5.87
16	4.90	4.90	5.45	5.00	6.05	5.49
17	4.80	4.73	5.17	4.80	6.00	5.18
18	4.52	4.60	5.00	4.70	5.82	5.02
19	4.42	4.50	5.00	4.60	5.58	5.00
20	4.31	4.41	4.90	4.50	5.31	4.99
25	4.22 ¹	4.12	4.63	4.20	4.51	4.68
30	N.D.	4.04	4.58 ²	4.10	4.35	4.52

¹ 24 m ² 29 m

APPENDIX C

DISSOLVED OXYGEN DATA

DISSOLVED OXYGEN IN COLDWATER LAKE, SUMMER 1989

Depth (m)	Concentration, mg/l (percent saturation)								
	Date, 1989								
	<u>26 May</u>	<u>7 June</u>	<u>17 June</u>	<u>1 July</u>	<u>20 July</u>	<u>15 Aug.</u>	<u>23 Aug.</u>	<u>13 Sept.</u>	<u>4 Oct.</u>
0	N.D.	<u>9.56</u> (98.50)	<u>8.86</u> (86.57)	<u>9.14</u> (88.31)	<u>8.36</u> (86.94)	<u>8.56</u> (90.10)	<u>8.36</u> (86.59)	<u>7.45</u> (79.51)	<u>9.36</u> (91.91)
5	N.D.	N.D.	9.06 (88.52)	8.96 (86.94)	8.86 (91.52)	8.36 (87.74)	8.36 (86.68)	8.26 (85.62)	8.60 (84.34)
10	10.20 (86.13)	9.56 (80.38)	9.83 (83.95)	9.32 (80.22)	9.26 (78.21)	8.96 (79.69)	7.87 (70.55)	7.55 (69.81)	8.90 (85.81)
15	N.D.	N.D.	9.62 (78.02)	N.D.	9.97 (79.50)	8.86 (72.47)	8.36 (67.97)	8.05 (66.84)	7.85 (64.63)
20	11.07 (87.80)	9.66 (75.86)	9.46 (74.80)	9.30 (74.32)	8.86 (69.88)	8.36 (65.95)	8.05 (64.16)	7.75 (62.04)	7.15 (56.75)
35	11.07	9.36 (72.00)	9.16 (70.78)	9.06 (70.72)	8.56 (66.14)	8.05 (62.10)	7.75 (60.10)	7.04 (55.00)	7.25 (56.03)
55	9.87	8.94 (68.33)	8.90 ¹ (68.31)	8.36 ¹ (64.20)	7.85 ¹ (60.50)	6.71 ² (51.67)	6.44 ² (49.64)	5.13 ² (39.84)	4.87 ³ (37.49)

Note: Percent saturation values for depths below 50 m were calculated using the temperature observed for 50 m.

¹ 58 m ² 59m ³ 60 m N.D. No data

DISSOLVED OXYGEN IN COLDWATER LAKE, SUMMER 1990

Depth (m)	Concentration, mg/l (percent saturation)							
	Date, 1990							
	24 May	14 June	5 July	26 July	14 Aug.	31 Aug.	20 Sept.	11 Oct.
0	9.77 (84.01)	9.97 (91.87)	9.06 (95.52)	8.26 (88.68)	7.65	8.57 (88.83)	8.40 (87.45)	9.06 (86.95)
5	9.97 (86.06)	10.06 (90.06)	9.16 (93.39)	8.15 (87.79)	7.91	8.52 (88.68)	8.56 (88.10)	8.70 (82.75)
10	9.46 (79.13)	9.87 (86.83)	9.87 (88.59)	9.77 (89.04)	9.36	9.97 (92.68)	8.40 (81.16)	8.76 (83.54)
15	9.66 (75.41)	9.66 (78.37)	9.36 (76.52)	9.31 (76.90)	9.06	8.66 (71.18)	8.86 (73.74)	8.36 (69.93)
20	9.66 (75.41)	9.77 (77.45)	9.16 (72.71)	8.66 (68.63)	8.36	8.46 (67.13)	8.15 (64.61)	7.81 (62.41)
35	9.36 ¹ (72.40)	8.37 (64.91)	8.96 (69.63)	8.26 (63.82)	7.85	7.65 ³ (59.51)	7.39 (56.95)	6.83 (52.87)
60	N.D.	8.27 (63.67)	7.85 ² (60.48)	7.05 (54.11)	5.54	6.24 (47.97)	5.78 ² (39.99)	5.03 (38.65)

DISSOLVED OXYGEN IN CASTLE LAKE, SUMMER 1989 AND 1990

Depth (m)	Concentration mg/l (percent saturation)					
	Date 1989					
	<u>24 June</u>	<u>7 July</u>	<u>8 August</u>	<u>1 Sept.</u>	<u>20 Sept.</u>	<u>14 Oct.</u>
0	9.46 (100.31)	8.76 (89.31)	8.05 (88.54)	8.46 (87.37)	8.46 (87.69)	8.15 (79.58)
5	9.16 (90.60)	8.66 (84.48)	7.97 (81.55)	8.21 (84.95)	8.26 (84.18)	8.05 (78.63)
10	9.16 (77.85)	8.86 (75.15)	6.85 (57.95)	7.37 (63.92)	7.29 (62.62)	6.10 (53.25)
15	8.36 (65.47)	7.85 (61.47)	6.25 (48.96)	5.44 (43.05)	5.03 (39.79)	4.43 (35.04)
20	7.55 (58.34)	7.24 (55.70)	7.37 (56.81)	4.63 (36.03)	4.73 (36.61)	3.52 (27.31)
28	6.44 (49.39)	5.23 ¹ (39.93)	3.42 ¹ (26.17)	2.17 (16.68)	0.71 ¹ (5.45)	0.11 (0.85)

	Concentration mg/l (percent saturation)					
	Date, 1990					
	<u>28 June</u>	<u>19 July</u>	<u>9 August</u>	<u>6 Sept.</u>	<u>2 Oct.</u>	<u>18 Oct.</u>
0	8.66 (89.93)	8.05 (92.95)	8.01 (93.06)	8.05 (88.89)	8.32 (85.50)	8.84 (78.95)
5	8.86 (83.87)	8.46 (88.35)	8.26 (90.90)	8.36 (87.76)	8.36 (86.04)	8.76 (78.40)
10	10.07 (83.96)	9.87 (84.17)	10.35 (91.21)	9.26 (80.11)	8.82 (79.83)	8.66 (77.47)
15	7.85 (61.47)	7.31 (57.24)	6.75 (53.92)	4.79 (37.70)	3.93 (31.81)	4.03 (32.27)
20	7.25 (55.76)	6.22 (47.96)	5.34 (41.71)	3.83 (29.60)	3.28 (25.89)	2.06 (16.13)
30	5.34 ² (40.97)	3.62 (27.65)	4.33 ³ (33.54)	0.30 (2.29)	0.10 (0.77)	0.05 (0.39)

¹ 29 m ² 27 m ³ 28 m

APPENDIX D

NUTRIENT DATA FROM SECOND STATION, COLDWATER LAKE

NUTRIENT DATA FROM SECOND STATION, COLDWATER LAKE
SUMMER 1989 AND 1990

Concentration (uM)

1 July 1989

Depth (m)	NO ₃ /NO ₂ -N ug/l	PO ₄ -P ug/l	SiO ₂ mg/l	Chl a ug/l
0	11.40 (0.82)	1.7 (0.05)	15.72 (261.63)	1.34
10	10.14 (0.72)	1.7 (0.05)	16.52 (274.95)	2.21
20	10.81 (0.77)	1.7 (0.05)	15.77 (262.46)	2.06

24 August 1989

Depth (m)	NO ₃ /NO ₂ -N ug/l	PO ₄ -P ug/l	SiO ₂ mg/l	Chl a ug/l
0	2.69 (0.19)	3.08 (0.10)	14.67 (244.16)	1.45
10	4.88 (0.35)	1.85 (0.06)	15.26 (253.97)	3.05
20	11.06 (0.79)	3.38 (0.11)	16.32 (271.62)	4.49

4 October 1989

Depth (m)	NO ₃ /NO ₂ -N ug/l	PO ₄ -P ug/l	SiO ₂ mg/l	Chl a ug/l
0	3.83 (0.27)	1.45 (0.05)	12.78 (212.70)	1.44
10	3.82 (0.27)	2.09 (0.07)	12.60 (209.70)	1.26
20	13.92 (0.99)	2.25 (0.07)	14.71 (244.82)	1.61

14 June 1990

Depth (m)	NO ₃ /NO ₂ -N <u>ug/l</u>	PO ₄ -P <u>ug/l</u>	Total P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l</u>
0	8.29 (0.59)	2.48 (0.08)	26.22 (0.85)	14.04 (233.67)	0.78
10	8.25 (0.59)	4.34 (0.14)	31.53 (1.02)	14.13 (235.17)	1.36
20	8.30 (0.59)	3.10 (0.10)	26.53 (0.86)	15.41 (256.47)	0.82

26 July 1990

Depth (m)	NO ₃ /NO ₂ -N <u>ug/l</u>	PO ₄ -P <u>ug/l</u>	Total P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l(pico)</u>
0	4.72 (0.34)	2.52 (0.08)	27.55 (0.89)	13.51 (224.85)	1.27 (0.22)
10	6.02 (0.43)	2.21 (0.07)	26.97 (0.87)	14.22 (236.67)	2.85 (0.43)
20	9.12 (0.65)	4.42 (0.14)	32.20 (1.04)	17.71 (294.75)	1.77 (0.40)

20 September 1990

Depth (m)	NO ₃ /NO ₂ -N <u>ug/l</u>	PO ₄ -P <u>ug/l</u>	Total P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l(pico)</u>
0	0.91 (0.06)	N.D.	N.D.	13.43 (223.52)	N.D.
10	2.26 (0.16)	N.D.	N.D.	13.03 (216.86)	N.D.
20	10.36 (0.74)	N.D.	N.D.	14.86 (247.32)	N.D.

11 October 1990

Depth (m)	NO ₃ /NO ₂ -N <u>ug/l</u>	PO ₄ -P <u>ug/l</u>	Total P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l(pico)</u>
0	1.10 (0.08)	2.25 (0.07)	N.D.	13.18 (219.36)	2.13 (0.51)
10	0.87 (0.06)	2.58 (0.08)	N.D.	13.12 (218.36)	3.09 (0.63)
20	9.54 (0.68)	2.25 (0.07)	N.D.	14.78 (245.99)	3.55 (0.36)

N.D. No data

APPENDIX E

NUTRIENT DATA FROM BAY AND INFLOW, COLDWATER LAKE

NUTRIENT DATA FROM BAY AND INFLOW, COLDWATER LAKE
SUMMER 1990

Concentration (uM)

14 June 1990

Sample site	NO ₃ -NO ₂ -N <u>ug/l</u>	PO ₄ <u>ug/l</u>	Total P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l</u>
inflow	0.31 (0.02)	3.41 (0.11)	45.89 (1.48)	20.96 (348.84)	2.95

5 July 1990

Sample site	NO ₃ -NO ₂ -N <u>ug/l</u>	PO ₄ <u>ug/l</u>	Total P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l</u>
bay	7.58 (0.54)	1.08 (0.03)	44.37 (1.43)	12.84 (213.70)	2.00
inflow	n.d.	5.05 (0.16)	73.28 (2.37)	20.78 (345.85)	2.63

26 July 1990

Sample site	NO ₃ -NO ₂ -N <u>ug/l</u>	PO ₄ <u>ug/l</u>	Total P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l(pico)</u>
bay	5.04 (0.36)	3.79 (0.12)	57.56 ¹ (1.86)	13.04 (217.03)	1.10 (0.46)
inflow	0.37 (0.03)	8.52 (0.28)	121.73 ¹ (3.93)	21.71 (361.32)	1.79 (0.59)

14 August 1990

Sample site	NO ₃ -NO ₂ -N <u>ug/l</u>	PO ₄ <u>ug/l</u>	Total P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l(pico)</u>
bay	3.43 (0.25)	N.D.	7.33 (0.24)	13.80 (229.68)	1.12 (0.46)
inflow	1.69 (0.12)	N.D.	22.40 (0.72)	22.12 (368.15)	1.23 (0.49)

NUTRIENT DATA FROM BAY AND INFLOW, COLDWATER LAKE
SUMMER 1990

Concentration (uM)

31 August 1990

Sample <u>site</u>	NO ₃ -NO ₂ -N <u>ug/l</u>	PO ₄ <u>ug/l</u>	Total P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l(pico)</u>
bay	2.35 (0.17)	1.89 (0.06)	45.23 ¹ (1.46)	13.41 (223.19)	1.79 (0.73)
inflow	1.83 (0.13)	4.09 (0.13)	121.78 ¹ (3.93)	21.44 (356.83)	1.41 (0.49)

20 September 1990

Sample <u>site</u>	NO ₃ -NO ₂ -N <u>ug/l</u>	PO ₄ <u>ug/l</u>	Total P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l(pico)</u>
bay	0.96 (0.07)	N.D.	7.58 (0.25)	13.04 (217.03)	1.97 (0.70)
inflow	0.76 (0.05)	N.D.	23.66 (0.76)	21.74 (361.82)	1.56 (0.54)

11 October 1990

Sample <u>site</u>	NO ₃ -NO ₂ -N <u>ug/l</u>	PO ₄ <u>ug/l</u>	Total P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l(pico)</u>
bay	0.64 (0.05)	3.86 (0.13)	N.D.	13.06 (217.36)	N.D.
inflow	0.69 (0.05)	9.34 (0.30)	N.D.	22.68 (377.47)	N.D.

¹ Questionable data N.D. No data

APPENDIX F

NUTRIENT DATA FROM SECOND STATION, CASTLE LAKE

NUTRIENT DATA FROM SECOND STATION, CASTLE LAKE
SUMMER 1989

Concentration (uM)

28 June 1989

Depth (m)	NO ₃ /NO ₂ -N ug/l	PO ₄ -P ug/l	SiO ₂ mg/l	Chl a ug/l
0	0.73 (0.05)	<5 (<0.16)	10.78 (179.41)	1.65
5	0.73 (0.05)	<5 (<0.16)	10.81 (179.91)	3.80
10	3.06 (0.22)	<5 (<0.16)	10.75 (178.91)	5.93

8 August 1989

Depth (m)	NO ₃ /NO ₂ -N ug/l	PO ₄ -P ug/l	SiO ₂ mg/l	Chl a ug/l
0	0.23 (0.02)	n.d.	10.89 (181.24)	0.97
5	0.14 (0.01)	1.17 (0.04)	10.86 (180.75)	1.93
10	0.28 (0.02)	1.16 (0.04)	10.86 (180.75)	1.62

11 October 1989

Depth (m)	NO ₃ /NO ₂ -N ug/l	PO ₄ -P ug/l	SiO ₂ mg/l	Chl a ug/l
0	n.d.	1.04 (0.03)	10.47 (174.25)	1.49
5	n.d.	1.56 (0.05)	10.69 (177.92)	1.29
10	n.d.	0.69 (0.02)	10.58 (176.08)	1.15

n.d. Not detectable

NUTRIENT DATA FROM SECOND STATION, CASTLE LAKE
SUMMER 1990

Concentration (uM)

28 June 1990

Depth (m)	NO ₃ /NO ₂ -N <u>ug/l</u>	PO ₄ -P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l</u>
0	0.03 (0.002)	2.19 (0.07)	11.42 (190.07)	0.72
20	3.86 (0.28)	1.83 (0.06)	11.15 (185.57)	2.60
27	3.16 (0.23)	2.19 (0.07)	10.98 (182.74)	

19 July 1990

Depth (m)	NO ₃ /NO ₂ -N <u>ug/l</u>	PO ₄ -P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l</u>
0	n.d.	1.88 (0.06)	10.27 (170.93)	2.00
10	n.d.	2.20 (0.07)	10.07 (167.60)	2.63
20	4.96 (0.35)	2.20 (0.07)	10.16 (169.09)	

n.d. Not detectable

APPENDIX G

NUTRIENT DATA FROM SPIRIT LAKE

APPENDIX G

NUTRIENT DATA FROM SPIRIT LAKE, 29 SEPTEMBER, 1989

Concentration (uM)

Depth (m)	NO ₃ /NO ₂ -N <u>ug/l</u>	PO ₄ -P <u>ug/l</u>	SiO ₂ <u>mg/l</u>	Chl a <u>ug/l</u>
0	n.d.	4.01 (0.13)	24.60 (409.42)	1.29
4	n.d.	2.84 (0.09)	24.34 (405.09)	1.82
10	0.77 (0.06)	1.17 (0.04)	24.48 (407.42)	2.41
14	n.d.	2.34 (0.08)	23.65 (393.61)	3.74
22	n.d.	3.17 (0.10)	23.88 (397.44)	2.70

Secchi Depth 9 m

Maximum Depth 23 m

APPENDIX H

PHYTOPLANKTON SPECIES COMPOSITION AND RELATIVE ABUNDANCES COLDWATER LAKE, 1989

PHYTOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

May 26, 1989

Percent Density (Percent Biovolume)

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Ankistrodesmas</i> sp.	21 (4)	17 (3)	25 (3)	28 (3)	21 (2)
<i>Chlamydomonas</i> -like	25 (6)	18 (4)	22 (3)	5 (1)	2 (0)
<i>Elakatothrix gelatinosa</i>			3 (1)		
<i>Quadrigula closteriodes</i>		2 (1)			3 (0)
<i>Sphaerocystis schroterii</i>	2 (2)		1 (1)		
Unidentified green alga			3 (0)	3 (0)	1 (0)
Chrysophyte flagellate	2 (1)				3 (0)
<i>Asterionella formosa</i>	2 (22)	1 (9)	1 (6)	3 (17)	4 (22)
<i>Cyclotella meneghiniana</i>	3 (52)	5 (74)	8 (82)	7 (66)	7 (61)
<i>Diatoma tenue</i>				1 (1)	1 (1)
Unidentified pennate					1 (1)
<i>Cryptomas erosa</i>	2 (7)	1 (3)		4 (8)	5 (9)
<i>Rhodomonas minuta</i>	44 (6)	56 (7)	38 (3)	47 (4)	55 (4)
Total Density (algal units/ml)	380	599	517	552	417
Total Biovolume ($\mu\text{m}_3/\text{ml}$)	51893	99214	119548	146845	119192

PHYTOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

June 7, 1989

Percent Density (Percent Biovolume)

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Ankistrodesmas</i> sp.		1 (0)	2 (0)	24 (0)	10 (0)
<i>Chlamydomonas</i> -like			4 (0)	4 (0)	
<i>Elakatothrix gelatinosa</i>	1 (0)				
<i>Oocystis</i> sp.	2 (0)				
<i>Quadrigula closteriodes</i>	6 (0)	4 (0)	5 (0)	5 (0)	3 (0)
Unidentified green alga		1 (0)	2 (0)		1 (0)
Chrysophyte flagellate	4 (0)				
<i>Dinobryon</i> sp.	1 (0)				
<i>Kephyrion</i> sp.			8 (0)	13 (1)	48 (4)
<i>Achnanthes minutissima</i>	6 (0)	1 (0)			
<i>Asterionella formosa</i>	23 (29)	16 (12)	17 (20)	6 (9)	6 (13)
<i>Cyclotella meneghiniana</i>	32 (65)	67 (85)	40 (75)	38 (87)	22 (78)
<i>Cymbella minuta</i>		2 (0)			
<i>Diatoma tenue</i>	3 (1)	2 (0)	7 (2)	2 (0)	
<i>Hannea arcus</i>	1 (1)	2 (2)			
Unidentified pennate	5 (1)	1 (0)	1 (0)		
<i>Cryptomas erosa</i>	4 (2)	2 (1)	4 (2)	4 (2)	6 (4)
<i>Rhodomonas minuta</i>	12 (0)	1 (0)	8 (0)	4 (0)	5 (0)
Total Density (algal units/ml)	108	111	137	113	110
Total Biovolume	132254	219362	182465	123464	77230

PHYTOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

June 17, 1989

Percent Density (Percent Biovolume)

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Ankistrodesmas</i> sp.	1 (0)			3 (0)	
<i>Chlamydomonas</i> -like	10 (1)	13 (1)	13 (1)	17 (1)	4 (0)
<i>Gloeocystis</i> sp.		1 (0)	13 (3)	8 (1)	1 (0)
<i>Quadrigula closteriodes</i>	2 (0)	3 (0)	2 (0)		
Unidentified green alga	2 (0)	3 (0)		1 (0)	
Chrysophyte flagellate	2 (0)		2 (0)	1 (0)	
<i>Achnanthes minutissima</i>		2 (0)	2 (0)		
<i>Asterionella formosa</i>	2 (8)		1 (4)	8 (19)	3 (8)
<i>Cyclotella meneghiniana</i>	13 (80)	13 (87)	14 (84)	19 (73)	19 (85)
<i>Diatoma tenue</i>	2 (2)	6 (5)	1 (1)		3 (2)
<i>Cryptomas erosa</i>	5 (7)	2 (3)	4 (5)	5 (4)	3 (3)
<i>Rhodomonas minuta</i>	61 (3)	7 (3)	49 (2)	36 (1)	68 (3)
Total Density (algal units/ml)	323	246	464	316	273
Total Biovolume ($\mu\text{m}^3/\text{ml}$)	131330	92043	191554	208787	153409

PHYTOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

July 1, 1989

Percent Density (Percent Biovolume)

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Ankistrodesmas</i> sp.		3 (0)			1 (0)
<i>Chlamydomonas</i> -like	4 (0)	6 (0)	4 (0)	7 (0)	13 (1)
<i>Gloeocystis</i> sp.	2 (0)	6 (0)	7 (0)	3 (0)	4 (0)
<i>Quadrigula closteriodes</i>	2 (0)				
Unidentified green alga		2 (0)		2 (0)	2 (0)
Chrysophyte flagellate			2 (0)	1 (0)	7 (0)
<i>Anomoeneis vitrea</i>		1 (0)			
<i>Asterionella formosa</i>		2 (6)		2 (3)	4 (10)
<i>Cyclotella meneghiniana</i>	25 (95)	18 (86)	36 (97)	39 (95)	20 (83)
<i>Diatoma tenue</i>		4 (2)	1 (0)		
Unidentified pennate		2 (1)	1 (0)		
<i>Cryptomas erosa</i>	3 (2)	2 (2)	1 (1)	1 (1)	4 (4)
<i>Rhodomonas minuta</i>	61 (2)	55 (2)	49 (1)	46 (1)	46 (2)
Total Density (algal units/ml)	201	209	323	166	261
Total Biovolume ($\mu\text{m}_3/\text{ml}$)	132300	108659	298009	168794	155291

PHYTOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

July 20, 1989

Percent Density (Percent Biovolume)

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Chlamydomonas</i> -like	23 (1)	14 (1)	2 (0)	13 (1)	9 (0)
<i>Gloeocystis</i> sp.	11 (1)	18 (1)	5 (0)		2 (0)
Unidentified green alga		2 (0)	1 (0)	3 (0)	
Chrysophyte flagellate	2 (0)		3 (0)	5 (0)	1 (0)
<i>Dinobryon</i> sp.	1 (0)				
<i>Achnanthes minutissima</i>	1 (0)		2 (0)		
<i>Anomoeneis vitrea</i>	2 (1)		3 (1)		
<i>Asterionella formosa</i>				1 (1)	1 (0)
<i>Cyclotella meneghiniana</i>	21 (93)	21 (93)	33 (95)	18 (93)	34 (96)
<i>Cymbella minuta</i>	1 (1)				
<i>Diatoma tenue</i>	1 (1)				
Unidentified pennate		1 (0)	1 (0)		
<i>Cryptomas erosa</i>	2 (2)	3 (3)		1 (2)	2 (2)
<i>Cryptomonas ovata</i>			2 (2)	1 (1)	2 (2)
<i>Rhodomonas minuta</i>	34 (1)	41 (2)	48 (1)	49 (2)	49 (1)
<i>Chroococcus</i> sp.				10 (1)	
Total Density (algal units/ml)	325	335	456	326	301
Total Biovolume ($\mu\text{m}^3/\text{ml}$)	184115	184753	394317	155762	267247

PHYTOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

August 15, 1989

Percent Density (Percent Biovolume)

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Ankistrodesmas</i> sp.	6 (0)	5 (1)	5 (0)	1 (0)	6 (0)
<i>Chlamydomonas</i> -like	15 (1)	30 (2)	16 (1)	48 (3)	15 (1)
<i>Gloeocystis</i> sp.	14 (1)	18 (2)	16 (1)	4 (1)	14 (1)
<i>Oocystis</i> sp.		1 (0)	1 (0)	5 (2)	
<i>Quadrigula closteriodes</i>		1 (0)	4 (1)		
Unidentified green alga	3 (0)			2 (0)	3 (0)
Chrysophyte flagellate	10 (1)	11 (1)	13 (1)	2 (0)	10 (1)
<i>Dinobryon</i> sp.	1 (0)				1 (0)
<i>Achnanthes minutissima</i>	3 (0)	2 (0)			3 (0)
<i>Anomoeneis vitrea</i>		1 (1)	2 (1)		
<i>Cyclotella meneghiniana</i>	14 (86)	8 (75)	11 (77)	6 (66)	14 (86)
<i>Cryptomas erosa</i>	6 (8)	8 (16)	11 (16)	6 (26)	6 (8)
<i>Rhodomonas minuta</i>	27 (1)	14 (1)	15 (1)	23 (2)	27 (1)
<i>Chroococcus</i> sp.			4 (0)	4 (0)	1 (0)
Total Density (algal units/ml)	432	585	508	484	664
Total Biovolume ($\mu\text{m}_3/\text{ml}$)	169239	153174	186415	109707	349581

PHYTOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

<u>Species</u>	Aug 23, 1989				
	Percent Density		(Percent Biovolume)		
	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Ankistrodesmas</i> sp.	1 (0)	6 (0)	6 (0)	1 (0)	
<i>Chlamydomonas</i> -like	1 (0)	6 (0)	16 (1)	23 (3)	22 (3)
<i>Gloeocystis</i> sp.		2 (0)	2 (0)	17 (2)	15 (2)
<i>Oocystis</i> sp.		2 (0)	1 (0)		
Unidentified green alga	6 (0)	3 (0)	1 (0)	1 (0)	2 (0)
Chrysophyte flagellate		2 (0)	5 (0)	2 (0)	8 (1)
<i>Kephyrion</i> sp.	52 (6)	35 (4)	9 (2)	4 (1)	6 (1)
<i>Achnanthes minutissima</i>			3 (0)		1 (0)
<i>Anomoeneis vitrea</i>		3 (1)			
<i>Cyclotella meneghiniana</i>	19 (82)	16 (81)	43 (86)	8 (66)	9 (74)
<i>Cymbella minuta</i>		1 (1)		1 (1)	
<i>Diatoma tenue</i>		1 (1)			
<i>Fragilaria crotonensis</i>	1 (1)				
<i>Nitzschia</i> sp.	1 (1)				
<i>Synedra rumpens</i>			1 (0)		
Unidentified pennate				1 (1)	
<i>Cryptomas erosa</i>	10 (9)	10 (11)	12 (9)	14 (24)	10 (17)
<i>Rhodomonas minuta</i>	5 (0)	11 (0)	7 (0)	26 (2)	26 (2)
Total Density (algal units/ml)	139	246	295	189	281
Total Biovolume	81148	1219587	193021	55944	84104

PHYTOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

September 13, 1989

Percent Density (Percent Biovolume)

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Ankistrodesmas</i> sp.	1 (0)		1 (0)		
<i>Chlamydomonas</i> -like	62 (8)	14 (4)	25 (3)	6 (1)	
<i>Gloeocystis</i> sp.				1 (0)	
<i>Sphaerocystis Schroeterii</i>			1 (0)		
Chrysophyte flagellate	14 (3)	22 (6)	6 (1)	14 (1)	2 (0)
<i>Dinobryon</i> sp.	1 (1)				
<i>Achnanthes minutissima</i>	1 (0)				
<i>Cyclotella meneghiniana</i>	4 (66)	4 (72)	10 (78)	12 (82)	12 (88)
<i>Cryptomas erosa</i>	6 (20)	3 (11)	9 (15)	7 (10)	4 (6)
<i>Rhodomonas minuta</i>	7 (1)	56 (8)	47 (3)	59 (3)	80 (5)
Total Density (algal units/ml)	274	519	519	340	327
Total Biovolume ($\mu\text{m}_3/\text{ml}$)	41808	71774	163825	125506	113794

PHYTOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

October 4, 1989

Percent Density (Percent Biovolume)

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Ankistrodesmas</i> sp.	1 (0)	2 (0)		1 (0)	
<i>Chlamydomonas</i> -like	50 (8)	32 (8)	16 (3)	22 (2)	31 (10)
<i>Gloeocystis</i> sp.		1 (0)		3 (0)	2 (1)
<i>Sphaerocystis schroeterii</i>		2 (2)	2 (1)		
Unidentified green alga	4 (1)	5 (1)			
Chrysophyte flagellate	17 (3)	14 (4)	17 (3)	23 (2)	15 (5)
<i>Dinobryon</i> sp.		2 (2)			
<i>Kephyrion</i> sp.		1 (1)			
<i>Achnanthes minutissima</i>	2 (1)		3 (1)		
<i>Anomoeneis vitrea</i>	1 (1)				
<i>Cyclotella meneghiniana</i>	6 (70)	3 (55)	5 (63)	12 (83)	16 (53)
<i>Navicula</i> sp.	1 (1)				
<i>Cryptomas erosa</i>	6 (15)	6 (23)	11 (28)	7 (10)	6 (27)
<i>Rhodomonas minuta</i>	11 (1)	30 (4)	43 (4)	32 (2)	30 (5)
Total Density (algal units/ml)	450	306	181	361	244
Total Biovolume ($\mu\text{m}_3/\text{ml}$)	96736	41957	37534	12971028022	

APPENDIX I

PHYTOPLANKTON SPECIES COMPOSITION AND RELATIVE ABUNDANCES CASTLE LAKE, 1989

PHYTOPLANKTON IN CASTLE LAKE
SUMMER 1989

Percent Density (Percent Biovolume)

June 24, 1989

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Chlamydomonas</i> sp.	5 (1)	4 (1)		7 (1)	
<i>Oocystis parva</i>	5 (9)	6 (11)		14 (27)	2 (3)
Unknown Chlorophyta				2 (1)	
<i>Chromulina</i> sp.	41 (12)	34 (10)		14 (4)	23 (6)
<i>Chrysochromulina</i> sp.	10 (3)	14 (4)		1 (0)	3 (1)
<i>Dinobryon bavaricum</i>				5 (9)	2 (3)
<i>Kephyrion</i> sp.				1 (1)	
<i>Ochromonas</i> sp.	25 (22)	28 (25)		23 (21)	30 (24)
Unknown Chrysophyta	7 (2)	7 (2)		1 (0)	7 (2)
<i>Cryptomonas erosa</i>	2 (15)	3 (23)		1 (6)	4 (27)
<i>Glenodinium pulvis</i>	3 (34)	2 (23)		2 (29)	1 (10)
Total Density (algal units/ml)	1258	1482	N.D.	2324	2494
Total Biovolume ($\mu\text{m}^3/\text{ml}$)	85665	100568	N.D.	154827	187837

PHYTOPLANKTON IN CASTLE LAKE
SUMMER 1989

Percent Density (Percent Biovolume)

July 7, 1989

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Chlamydomonas</i> sp.	8 (2)		6 (2)	1 (0)	
<i>Gloeocystis</i> sp.	4 (1)	6 (1)	4 (1)		5 (1)
<i>Oocystis parva</i>	16 (28)	16 (29)	6 (17)	7 (13)	17 (25)
<i>Chromulina</i> sp.	9 (2)	14 (4)	19 (9)	12 (4)	4 (1)
<i>Chrysochromulina</i> sp.	16 (4)	27 (8)	9 (4)	5 (1)	
<i>Kephyrion</i> sp.					39 (28)
<i>Ochromonas</i> sp.	41 (34)	33 (29)	35 (51)	33 (29)	20 (14)
Unknown Chrysophyta		1 (0)			8 (2)
<i>Cryptomonas erosa</i>	1 (7)	1 (7)	1 (12)	2 (15)	1 (1)
<i>Rhodomonas</i> sp.				2 (3)	
<i>Glenodinium pulvis</i>	2 (21)	2 (22)		1 (12)	
<i>Synechococcus elongatus</i>			18 (1)	31 (1)	2 (0)
<i>Achnanthes</i> sp.			1 (1)		
<i>Anomoeoneis vitrea</i>	1 (2)				
Total Density (algal units/ml)	2381	2125	2907	1433	852
Total Biovolume (μm^3 /ml)	173771	148091	119153	95437	73236

PHYTOPLANKTON IN CASTLE LAKE
SUMMER 1989

Percent Density (Percent Biovolume)

August 8, 1989

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Chlamydomonas</i> sp.		1 (0)			
<i>Chlorella vulgaris</i>		1 (1)	1 (1)	2 (2)	2 (1)
<i>Oocystis parva</i>		1 (1)	1 (1)		1 (1)
<i>Oocystis pusilla</i>	29 (36)	41 (47)	34 (36)	19 (29)	36 (30)
<i>Chromulina</i> sp.	49 (10)	24 (5)	11 (2)	39 (10)	13 (2)
<i>Dinobryon bavaricum</i>	1 (1)	2 (2)			2 (2)
<i>Kephyrion</i> sp.			23 (13)	22 (18)	14 (6)
<i>Ochromonas</i> sp.	14 (9)	15 (9)	13 (7)	10 (8)	20 (8)
<i>Cryptomonas erosa</i>	5 (27)	3 (15)	2 (9)	2 (13)	3 (11)
<i>Rhodomonas</i> sp.					1 (1)
<i>Glenodinium pulvis</i>	2 (16)	2 (15)		2 (20)	7 (38)
<i>Gymnodinium</i> sp.			4 (27)		
<i>Chroococcus varius</i>			8 (4)	1 (0)	
<i>Synechococcus elongatus</i>			1 (0)	1 (0)	
Total Density (algal units/ml)	1307	521	1086	1482	394
Total Biovolume ($\mu\text{m}^3/\text{ml}$)	125104	54378	123361	117073	56236

PHYTOPLANKTON IN CASTLE LAKE
SUMMER 1989

Percent Density (Percent Biovolume)

September 1, 1989

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Chlamydomonas</i> sp.	1 (0)		1 (0)		
<i>Gloeocystis</i> sp.	1 (0)				
<i>Oocystis parva</i>			1 (3)		
<i>Oocystis pusilla</i>	10 (16)	4 (10)	2 (5)	16 (25)	15 (18)
<i>Chromulina</i> sp.	27 (7)	64 (27)	67 (31)	45 (12)	22 (4)
<i>Chrysochromulina</i> sp.	14 (4)	2 (1)	4 (2)	1 (0)	6 (1)
<i>Ochromonas</i> sp.	41 (32)	27 (34)	23 (31)	25 (20)	34 (21)
<i>Cryptomonas erosa</i>		1 (11)	1 (11)	4 (27)	9 (47)
<i>Rhodomonas minuta</i>	2 (2)			1 (1)	8 (5)
<i>Rhodomonas</i> sp.		1 (2)			
<i>Glenodinium pulvis</i>	4 (40)	1 (16)			
<i>Gymnodinium</i> sp.			1 (17)	1 (10)	
<i>Synechococcus elongatus</i>				2 (0)	
<i>Achnanthes</i> sp.					1 (0)
Total Density (algal units/ml)	1515	1550	2476	863	174
Total Biovolume (μm^3 /ml)	117127	74655	109291	64824	17310

PHYTOPLANKTON IN CASTLE LAKE
SUMMER 1989

Percent Density (Percent Biovolume)

September 20, 1989

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Chlamydomonas</i> sp.	2 (0)	1 (0)			
<i>Chlorella vulgaris</i>	10 (9)	8 (6)		2 (2)	2 (2)
<i>Oocystis pusilla</i>	13 (24)	7 (10)	7 (10)	5 (10)	6 (9)
<i>Chromulina</i> sp.	26 (8)	33 (8)	48 (12)	35 (12)	32 (8)
<i>Chrysochromulina</i> sp.	4 (1)	4 (1)	7 (2)	1 (0)	5 (1)
<i>Ochromonas</i> sp.	42 (39)	31 (22)	24 (18)	33 (33)	24 (19)
<i>Cryptomonas erosa</i>	2 (16)	4 (24)	4 (26)	4 (34)	7 (48)
<i>Cryptomonas ovata</i>			1 (21)		
<i>Rhodomonas minuta</i>	1 (1)	3 (2)	2 (1)	3 (3)	14 (11)
<i>Glenodinium pulvis</i>		3 (27)	1 (10)		
<i>Anabaena</i> sp.				1 (2)	
<i>Chroococcus rufescens</i>				2 (2)	
<i>Chroococcus</i> sp.		2 (0)	2 (0)	3 (1)	1 (0)
<i>Synechococcus elongatus</i>			2 (0)	7 (0)	4 (0)
Unknown Cyanophyte			3 (0)	1 (0)	
Total Density (algal units/ml)	1258	1191	1347	464	335
Total Biovolume ($\mu\text{m}^3/\text{ml}$)	80633	102719	108592	27877	26196

PHYTOPLANKTON IN CASTLE LAKE
SUMMER 1989

Percent Density (Percent Biovolume)

October 11, 1989

<u>Species</u>	<u>0 m</u>	<u>5 m</u>	<u>10 m</u>	<u>15 m</u>	<u>20 m</u>
<i>Chlamydomonas</i> sp.			3 (1)	1 (1)	
<i>Gloeocystis</i> sp.	14 (2)	26 (6)	13 (3)	3 (1)	
<i>Oocystis pusilla</i>	4 (5)	5 (9)	14 (26)	11 (16)	5 (6)
<i>Chromulina</i> sp.	38 (8)	22 (7)	31 (10)	12 (3)	16 (3)
<i>Chrysochromulina</i> sp.	4 (1)	2 (1)	3 (1)	5 (1)	2 (0)
<i>Dinobryon bavaricum</i>	1 (1)	2 (4)	1 (2)		2 (2)
<i>Ochromonas</i> sp.	28 (17)	32 (32)	28 (26)	36 (27)	49 (29)
<i>Cryptomonas erosa</i>	4 (22)	1 (8)		7 (45)	10 (52)
<i>Cryptomonas ovata</i>	1 (18)				
<i>Rhodomonas minuta</i>	3 (2)	9 (8)			
<i>Rhodomonas</i> sp.			5 (8)	5 (6)	6 (6)
<i>Glenodinium pulviscula</i>	3 (24)	2 (24)	2 (24)		
<i>Chroococcus dispersus</i>			1 (1)		2 (1)
<i>Synechococcus elongatus</i>				20 (0)	8 (0)
Total Density (algal units/ml)	1247	972	1807	6122	9524
Total Biovolume ($\mu\text{m}^3/\text{ml}$)	119290	59216	115550	492146	958905

APPENDIX J

ZOOPLANKTON SPECIES COMPOSITION AND DENSITIES COLDWATER LAKE, 1989

ZOOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

May 26, 1989
Density (Individuals/m³)

<u>Species</u>	Station 1		
	<u>0-5 m</u>	<u>5-10 m</u>	<u>10-25 m</u>
<i>Daphnia pulicaria</i>	4629	2836	170
<i>Daphnia rosea</i>	945	261	11
<i>Bosmina longirostris</i>	33	16	15
<i>Diaptomus tyrrelli</i>	505	554	120
<i>Diaptomus</i> copepodite	1320	733	46
<i>Cyclops</i> copepodite		16	
Nauplii	750	913	120
<i>Brachionus</i> spp.	163	98	28
<i>Keratella quadrata</i>		16	54
<i>Polyarthra dolichoptera</i>	277	440	61
<i>Synchaeta oblonga</i>	440	733	337
<i>Trichocerca</i> sp.	17		
Total	9078	6617	961

ZOOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

June 7, 1989
Density (Individuals/m³)

<u>Species</u>	Station 1		
	<u>0-5 m¹</u>	<u>5-20 m</u>	<u>20-35 m</u>
<i>Daphnia pulicaria</i>	2	245	36
<i>Daphnia rosea</i>	1	22	5
<i>Bosmina longirostris</i>		22	3
<i>Diaptomus tyrrelli</i>	1	446	76
<i>Diaptomus</i> copepodite	5	750	138
<i>Cyclops</i> copepodite	1	5	2
Nauplii		174	28
<i>Brachionus</i> spp.		5	
<i>Keratella quadrata</i>	7	103	6
<i>Notholca squamula</i>	1	22	
<i>Polyarthra dolichoptera</i>	13	92	17
<i>Synchaeta oblonga</i>	8	467	37
Total	40	2331	348

¹ Bad sample

ZOOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

June 17, 1989
Density (Individuals/m³)

<u>Species</u>	Station 1		
	<u>0-5 m</u>	<u>5-20 m</u>	<u>20-35 m</u>
<i>Daphnia pulicaria</i>	2005	1159	80
<i>Daphnia rosea</i>	212	101	5
<i>Bosmina longirostris</i>	16	58	13
<i>Diaptomus tyrrelli</i>	407	420	174
<i>Diaptomus</i> copepodite	1206	1434	279
<i>Cyclops</i> copepodite		15	3
Nauplii	212	435	49
<i>Brachionus</i> spp.	49	58	
<i>Conochilus unicornis</i>	1271	203	11
<i>Filinia terminalis</i>	33	29	4
<i>Keratella quadrata</i>	130	608	85
<i>Polyarthra dolichoptera</i>	1988	1202	76
<i>Synchaeta oblonga</i>	1695	681	38
Total	9224	6403	214

ZOOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

July 1, 1989
Density (Individuals/m³)

<u>Species</u>	Station 1		Station 2		
	<u>0-5 m</u>	<u>5-20 m</u>	<u>20-35 m</u>	<u>0-5 m</u>	<u>5-20 m</u>
<i>Daphnia pulicaria</i>	4140	744	2369	2781	304
<i>Daphnia rosea</i>	685	76	174	348	44
<i>Bosmina longirostris</i>		22	22	87	4
<i>Diaptomus tyrelli</i>	717	234	630	804	181
<i>Diaptomus</i> copepodite	2901	826	1043	1434	315
<i>Cyclops</i> copepodite	33	11			11
Nauplii	196	71	283	130	51
<i>Asplanchna priodonta</i>	33	5			
<i>Brachionus</i> sp.				44	11
<i>Conochilus</i> sp.	130				
<i>Filinia terminalis</i>		5	44	22	4
<i>Kellicottia longispina</i>	33	11		22	4
<i>Keratella quadrata</i>	293	87	130	87	54
<i>Polyarthra dolichoptera</i>	978	185	652	739	268
<i>Synchaeta oblonga</i>	5769	397	2955	8692	402
Total	15906	2673	8323	15189	1652

ZOOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

July 20, 1989
Density (Individuals/m³)

<u>Species</u>	Station 1		
	<u>0-5 m</u>	<u>5-10 m</u>	<u>10-25 m</u>
<i>Daphnia pulicaria</i>	4		
<i>Daphnia rosea</i>			
<i>Bosmina longirostris</i>	12		
<i>Chydorus sphaericus</i>		2	
<i>Alona rectangula</i>	1		1
<i>Diaptomus coepodite</i>	1		
<i>Asplanchna spp.</i>	2		
<i>Brachionus spp.</i>	3		
<i>Keratella cochlearis</i>	1	1	1
<i>Keratella quadrata</i>	8		
<i>Polyarthra dolichoptera</i>	16		
<i>Synchaeta oblonga</i>	14		
Total	64	4	2

ZOOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

July 20, 1989
Density (Individuals/m³)

<u>Species</u>	Station 1		
	<u>0-5 m</u>	<u>5-10 m</u>	<u>10-25 m</u>
<i>Daphnia pulicaria</i>	4		
<i>Daphnia rosea</i>			
<i>Bosmina longirostris</i>	12		
<i>Chydorus sphaericus</i>		2	
<i>Alona rectangula</i>	1		1
<i>Diaptomus coepodite</i>	1		
<i>Asplanchna</i> spp.	2		
<i>Brachionus</i> spp.	3		
<i>Keratella cochlearis</i>	1	1	1
<i>Keratella quadrata</i>	8		
<i>Polyarthra dolichoptera</i>	16		
<i>Synchaeta oblonga</i>	14		
Total	64	4	2

ZOOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

Aug 23, 1989
Density (Individuals/m³)

<u>Species</u>	Station 1		Station 2		
	<u>0-5 m</u>	<u>5-20 m</u>	<u>20-35 m</u>	<u>0-5 m</u>	<u>5-20 m</u>
<i>Daphnia pulicaria</i>	432	21	12	354	101
<i>Daphnia rosea</i>	128	2	1	19	1
<i>Bosmina longirostris</i>	2	1	1		
<i>Chydorus sphaericus</i>		1	1	3	2
<i>Alona rectangula</i>			2		
<i>Alonella nana</i>		1			
<i>Diaptomus tyrrelli</i>	86	2	3	2	1
<i>Diaptomus coepodite</i>	41	3	5	5	2
<i>Cyclops vernalis</i>				1	
<i>Cyclops coepodite</i>	4	3	6	5	11
<i>Paracyclops fimbriatus</i>				1	
Nauplii	22	17	17	23	58
<i>Asplanchna priodonta</i>	151	2	1	44	3
<i>Filinia terminalis</i>		1	1		
<i>Kellicottia longispina</i>			3	1	1
<i>Keratella cochlearis</i>	2				
<i>Keratella quadrata</i>				3	
<i>Synchaeta oblonga</i>		2			1
Total	870	57	56	462	183

ZOOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

September 13, 1989
Density (Individuals/m³)

<u>Species</u>	Station 1		
	<u>0-5 m</u>	<u>5-20 m</u>	<u>20-35 m</u>
<i>Daphnia pulicaria</i>	357	1365	215
<i>Daphnia rosea</i>	13	116	20
<i>Bosmina longirostris</i>		15	3
<i>Chydorus sphaericus</i>	1		3
<i>Alona rectangula</i>	1		1
<i>Diaptomus tyrrelli</i>	19		8
<i>Diaptomus coepodite</i>	48		4
<i>Cyclops vernalis</i>	2		1
<i>Cyclops coepodite</i>	2		9
Nauplii	7	62	20
<i>Asplanchna priodonta</i>	58	18	7
<i>Keratella cochlearis</i>			5
<i>Polyarthra dolichoptera</i>	3		1
<i>Synchaeta oblonga</i>	39	25	24
Total	550	1601	323

ZOOPLANKTON DATA IN COLDWATER LAKE
SUMMER 1989

<u>Species</u>	October 4, 1989 Density (Individuals/m ³)				
	Station 1		Station 2		
	<u>0-5 m</u>	<u>5-20 m</u>	<u>20-35 m</u>	<u>0-5 m</u>	<u>5-20 m</u>
<i>Daphnia pulicaria</i>	5069	1130	344	4042	937
<i>Daphnia rosea</i>	717	52	10	342	71
<i>Bosmina longirostris</i>	33	14	8		3
<i>Chydorus sphaericus</i>		3	7	16	3
<i>Alona rectangulara</i>		3	1		
<i>Diaptomus tyrrelli</i>	98		3	49	3
<i>Diaptomus copepodite</i>	82	3	1	16	
<i>Cyclops copepodite</i>	33	46	23	82	35
<i>Paracyclops fimbriatus</i>	16				
Nauplii	522	120	34	179	60
<i>Asplanchna priodonta</i>	1451	14	7	1760	3
<i>Conochilus</i> sp.	49	155	19	473	109
<i>Filinia terminalis</i>		3	1		
<i>Kellicottia longispina</i>			1		
<i>Keratella cochlearis</i>		14	30		3
<i>Keratella quadrata</i>	16	5	10		3
<i>Polyarthra dolichoptera</i>		5	1		
<i>Squatinella</i> sp.					3
<i>Synchaeta oblonga</i>	163	16	27	147	5
<i>Trichocerca</i> sp.		3	1		
Total	8247	1584	530	7106	1236

APPENDIX K

ZOOPLANKTON SPECIES COMPOSITION AND DENSITIES CASTLE LAKE

ZOOPLANKTON DATA IN CASTLE LAKE
SUMMER 1989

Density (Individuals/m³)

<u>Species</u>	June 24		July 7		
	<u>0-5 m</u>	<u>5-25 m</u>	<u>0-5 m</u>	^{#1} <u>5-25 m¹</u>	^{#2} <u>0-5 m</u>
<i>Daphnia pulicaria</i>	110	33	38		92
<i>Ceriodaphnia pulchella</i>					
<i>Bosmina longirostris</i>	3	16	5		5
<i>Alona</i> sp.					
<i>Cyclops copepodite</i>					1
Nauplii		16			
<i>Kellicottia longispina</i>	1949	2412	589	51	215
<i>Keratella cochlearis</i>	14	49	30	1	17
<i>Keratella quadrata</i>	20	1891	217	4	48
<i>Polyarthra dolichoptera</i>	968	1434	98		8
<i>Synchaeta lakowitziana</i>	41	505	79		3
Chironomid			3		
Nematode		16			
<i>Chaoborus</i>	4				
Total	3109	6373	1059	56	389

¹ Bad sample

ZOOPLANKTON DATA IN CASTLE LAKE
SUMMER 1989

Density (Individuals/m³)

<u>Species</u>	August 8		September 1		
	0-5 m	#1 5-25 m	#2 0-5 m	0-5 m	5-20 m
<i>Daphnia pulicaria</i>	990	424	2966	2499	905
<i>Ceriodaphnia pulchella</i>	12	4	16		
<i>Bosmina longirostris</i>	110	4	179	837	41
<i>Alona</i> sp.	4				
Nauplii				11	4
<i>Brachionus</i> sp.				11	
<i>Conochilus</i> sp.	481	65	847	1380	436
<i>Filinia terminalis</i>					4
<i>Kellicottia longispina</i>	20	8	8	44	16
<i>Keratella cochlearis</i>	37	33	416	108	25
<i>Keratella quadraia</i>	37	90	25	33	110
<i>Polyarthra dolichoptera</i>	130	1169	1328	848	962
<i>Synchaeta lakowiziana</i>	8	20	122	141	25
<i>Chaoborus</i>				12	
Total	1838	1817	5908	5923	2526

ZOOPLANKTON DATA IN CASTLE LAKE
SUMMER 1989

Density (Individuals/m³)

September 20

<u>Species</u>	<u>0-5 m</u>	<u>5-25 m</u>
<i>Daphnia pulicaria</i>	4485	1361
<i>Ceriodaphnia pulchella</i>		
<i>Bosmina longirostris</i>	522	4
<i>Alona</i> sp.		
<i>Cyclops copepodite</i>		
<i>Tropocyclops prasinus</i>		
<u>Nauplii</u>		16
<i>Brachionus</i> sp.		
<i>Conochilus</i> sp.	222	57
<i>Filinia terminalis</i>	13	29
<i>Kellicottia longispina</i>	39	4
<i>Keratella cochlearis</i>	561	
<i>Keratella quadrata</i>	130	29
<i>Polyarthra dolichoptera</i>	130	342
<i>Synchaeta lakowitziana</i>	117	49
<i>Chaoborus</i>	25	8
Total	6244	1899

ZOOPLANKTON DATA IN CASTLE LAKE
SUMMER 1989

Density (Individuals/m³)

<u>Species</u>	October 11			
	#1		#2	
	<u>0-5 m</u>	<u>5-25 m</u>	<u>0-5 m</u>	<u>5-15 m</u>
<i>Daphnia pulicaria</i>	513	98	204	132
<i>Bosmina longirostris</i>	403	6	111	95
<i>Cyclops copepodite</i>	4	5		
<i>Tropocyclops prasinus</i>		2		
Nauplii		6		1
<i>Conochilus sp.</i>	171	7	10	15
<i>Filinia terminalis</i>	4	11	5	4
<i>Kellicottia longispina</i>	37	6	27	45
<i>Keratella cochlearis</i>	277	13	64	216
<i>Keratella quadrata</i>	20	136	42	46
<i>Polyarthra dolichoptera</i>	130	493	107	164
<i>Synchaeta lakowitziana</i>		2	7	4
<i>Chaoborus</i>	10	6	9	14
Total	1571	792	586	737