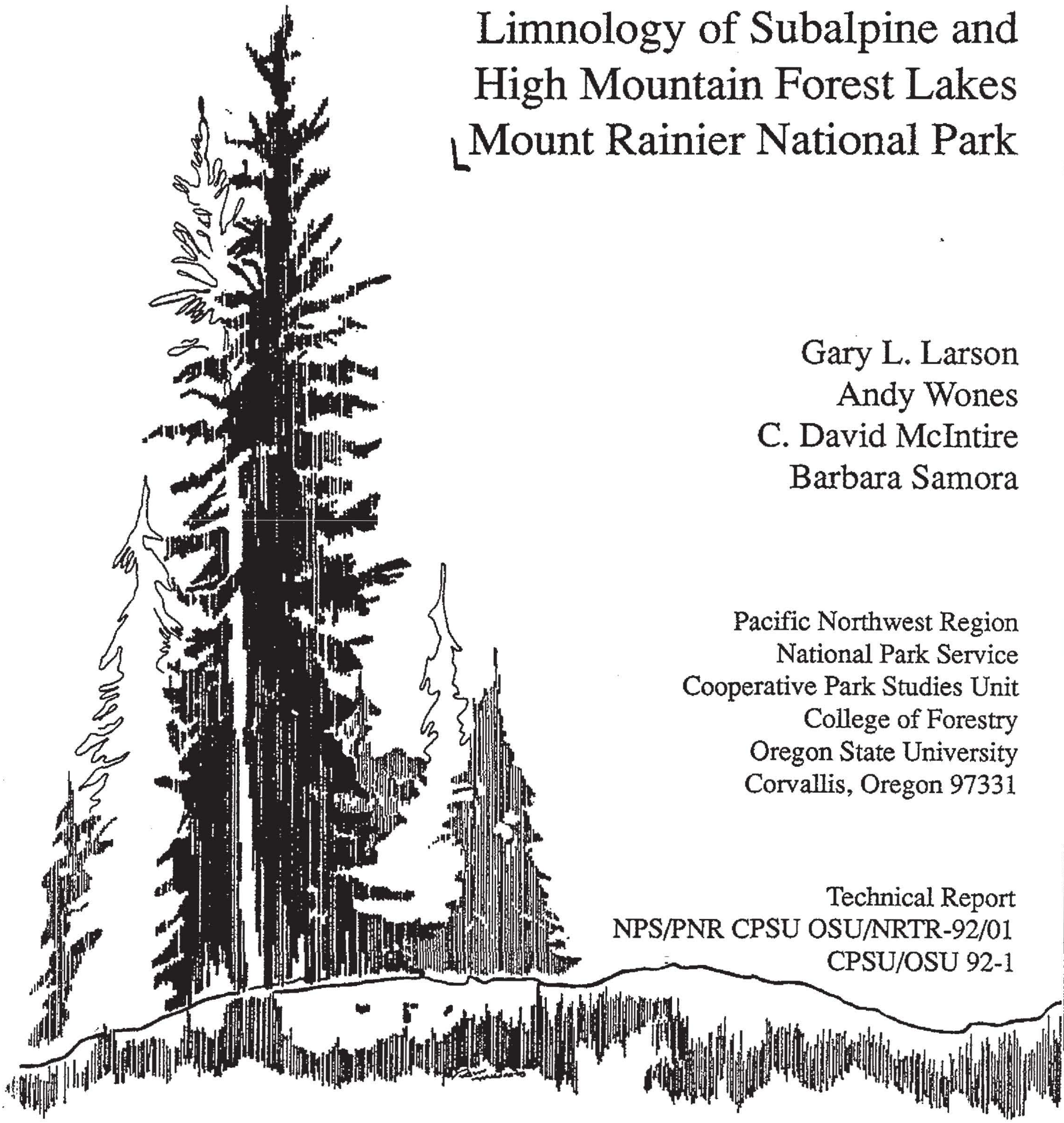
Limnology of Subalpine and High Mountain Forest Lakes Mount Rainier National Park



Gary L. Larson
Andy Wones
C. David McIntire
Barbara Samora

Pacific Northwest Region
National Park Service
Cooperative Park Studies Unit
College of Forestry
Oregon State University
Corvallis, Oregon 97331

Technical Report
NPS/PNR CPSU OSU/NRTR-92/01
CPSU/OSU 92-1

The National Park Service Cooperative Park Studies Unit (CPSU) at Oregon State University was established in 1975. The Unit is located in the College of Forestry. The purposes of the Unit are: (1) to conduct original research on topics of importance to the management of natural and cultural resources; (2) to encourage and facilitate scientific research in national parks of the Pacific Northwest Region; and (3) to disseminate research results within the management system of the National Park Service.

The National Park Service disseminates reports on high priority, current resource management information, with managerial application for managers, through the Natural Resources Report Series. Technologies and resource management methods; "how to" resource management papers; popular articles through the yearly Highlights report; proceedings on resource management workshops or conferences; and natural resources program recommendations and descriptions and resource action plans are also disseminated through this series. Documents in this series usually contain information of a preliminary nature and are prepared primarily for internal use within the National Park Service. This information is not intended for use in open literature.

Copies are available from the following:

Publications Coordinator (FTS) 327-2156 (Commercial) (303) 969-2156
Natural Resources Publication Office
P.O. Box 25287
Denver, CO 80225-0287

Limnology of Subalpine and High Mountain Forest Lakes

Mount Rainier National Park

Gary L. Larson
Andy Wones

National Park Service
Pacific Northwest Region
Cooperative Park Studies Unit
College of Forestry
Oregon State University
Corvallis, Oregon 97331

C. David McIntire
Department of Botany and Plant Pathology
Oregon State University
Corvallis, Oregon 97331

and

Barbara Samora
Mount Rainier National Park
Tahoma Woods, Star Route
Ashford, Washington 98304

Technical Report NPS/PNR CPSU OSU/NRTR-92/01
February 1992

National Park Service
Cooperative Park Studies Report Number 92-1
Cooperative Agreement 9000-8-0006
Subagreement Number 5

Executive Summary

A general conceptual watershed-lake model of the complex interactions among climatic conditions, watershed location and characteristics, lake morphology and fish predation was used to evaluate the limnological characteristics of high mountain lakes. Our main hypothesis was that decreasing elevation in mountainous terrain corresponds to an increase in variability of watershed size and lake area, depth, temperature, nutrient concentrations and productivity. A second hypothesis was that watershed location and aspect relative to climatic gradients within a mountainous terrain influences the limnological characteristics of the lakes. We evaluated these hypotheses by examining watershed location, aspect and size, lake morphology, water quality, and phytoplankton and zooplankton community characteristics among high mountain forest and subalpine lakes in Mount Rainier National Park.

The results revealed patterns which were consistent with our hypothesis that the forest lake group would include more lakes with larger watersheds, larger surface areas, greater depths, higher concentrations of nutrients and higher algal biovolumes than in the group of subalpine lakes. Deep lakes, particularly the forest lake type, exhibited thermal stratification, relatively high Secchi disk clarity, and relatively high concentrations of some of the water quality variables near the lake bottoms. However, the highest near surface water temperatures and phytoplankton densities, and the taxonomic structures of the phytoplankton and zooplankton assemblages were more closely related to geographical location, which corresponded to a west-east climate gradient in the park, than to lake type. Some rotifer taxa, however, were limited in distribution by lake type. Fish predation did not appear to play an important role in the structure of the crustacean zooplankton communities at the genus level with the exception of Mowich Lake where crustacean taxa were absent from the zooplankton community. This was the only lake inhabited by a true zooplanktivourous species of fish.

Introduction

Early studies of high mountain lakes necessarily focused on describing their basic limnological features because little was known about these systems (Pennak, 1955; Pechlaner, 1966; Pechlaner, 1967; Stout, 1969 and Larson, 1973). As more information was gathered, Pechlaner (1971) developed some initial ideas about the primary factors influencing algal production. Other limnologists investigated the variability of water quality and the characteristics of phytoplankton and zooplankton community characteristics among high mountain lakes in specific geographic locations (Anderson, 1974; Stoddard, 1987; Vass et al, 1989; Bahls, 1990; and Larson et al 1991). These studies suggested that water quality and the taxonomic structure of phytoplankton and zooplankton assemblages in high mountain lakes are influenced by watershed characteristics, elevation and lake morphology. Moreover, fish predation was associated with changes in crustacean zooplankton community structure (Stoddard, 1987; Bahls, 1990).

Based on the present knowledge of the ecology of high mountain lakes and other types of lakes (Patalas, 1971; Earle et al, 1986; Arvola, 1986; Kerfoot, 1987; and Pinel-Alloil et al, 1990), we contend that the limnological characteristics of high mountain lakes result from complex interactions related to climatic conditions, watershed characteristics (geographical location, aspect, surface area, elevation, geology, hydrology, soil, and vegetation), lake morphology and fish predation (Fig. 1). Water temperature, soil development, vegetation biomass, nutrient availability, and changes in hydrology increase along a gradient from higher to lower elevations within a watershed and when comparing high elevation and low elevation watersheds (Warren, 1979; Aber and Melillo, 1991). By inference, a decrease in elevation should be associated with an increase in lake productivity and greater variability in watershed area, lake area and lake depth because there are more opportunites for increasing stream order and less confinement of lake basins by precipitous mountain slopes.

In the present study, we surveyed 27 subalpine and high mountain forest lakes located around the base of Mount Rainier in Mount Rainer National Park. Based on

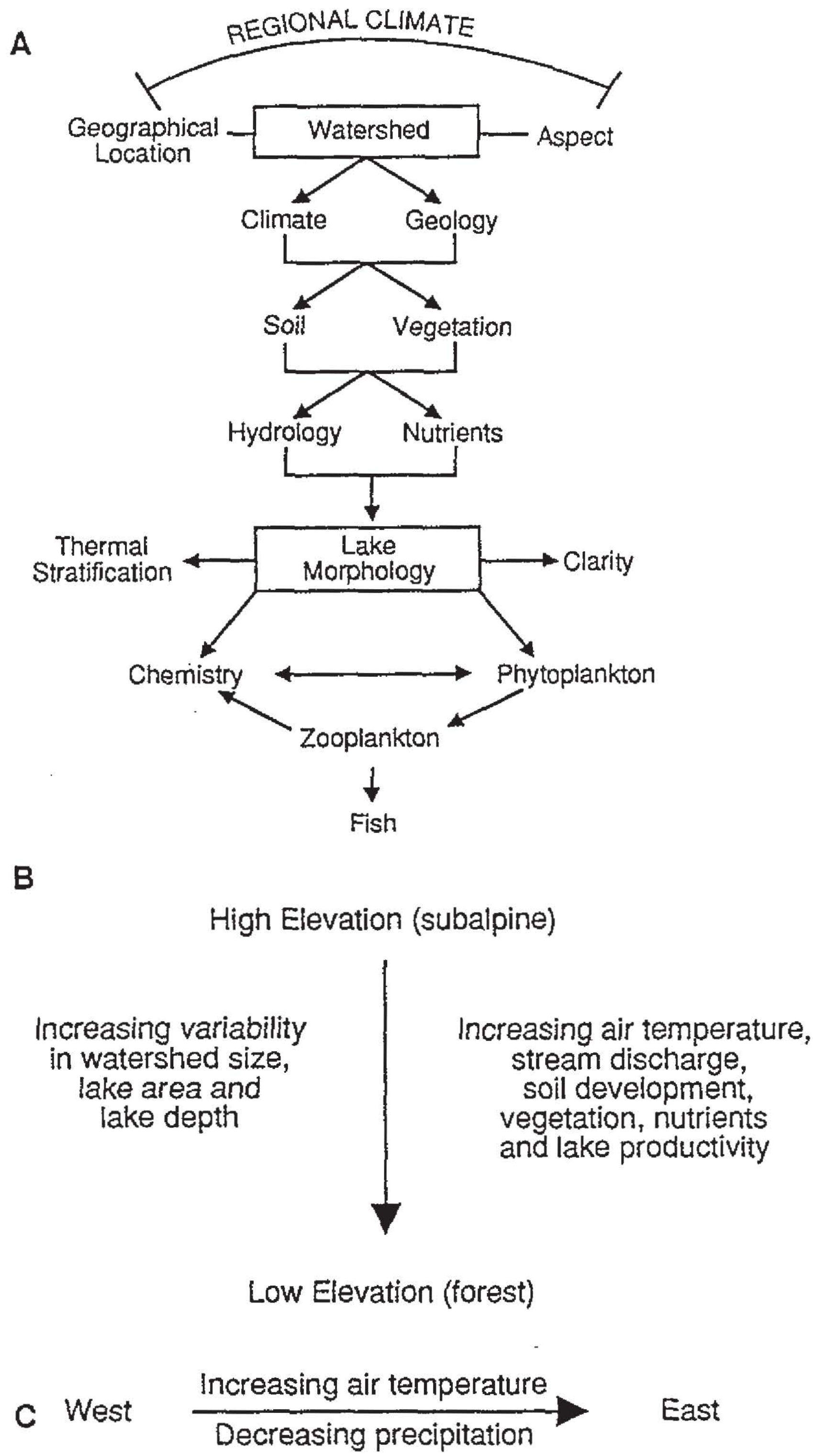


Figure 1. Conceptual watershed-lake model showing (A) the relationships between the environment and selected watershed characteristics relative to lake morphology and fish predation, (B) expected changes in temperature, watershed characteristics, lake morphology and lake productivity with decreasing elevation, and (C) expected changes in climate from the west side to the east side of the park.

the above mentioned conceptual watershed-lake model, our general working hypotheses were that: (1) subalpine systems have fewer lakes with large watersheds, large surface areas, and deep depths, and are lower in temperature, nutrients, phytoplankton cell density and biovolume and zooplankton density in comparison to lakes in the forest systems; (2) the phytoplankton and zooplankton community structures of subalpine and forest lakes are different; (3) lake morphology is closely related to the water quality and biological characteristics of high mountain lakes; (4) a west-east climate gradient created by Mount Rainier is associated with differences in water quality and the distributions of phytoplankton and zooplankton populations (Fig. 1C); and (5) the structures of the zooplankton communities are related to the presence or absence of fish. Within the context of the conceptual model and hypotheses, the objectives of the study were to determine if: (1) differences existed in watershed size, lake morphology, and physical, chemical and biological characteristics between subalpine lakes and forest lakes; (2) the west-east climate gradient influenced the relationships within and between the two lake types; and (3) fish predation had any detectable impacts on the zooplankton communites of both types of lakes.

Study Area

Mount Rainier National Park is located in the south central portion of Washington State on the western slopes of the Cascade Mountains (Fig. 2). The park occupies an area of 969 km2, and Mount Rainier, a dormant volcano with an elevation of 4,393 m, dominates the topography. Four major drainage basins roughly divide the park into four quadrants (Fig. 2). The rugged mountainous area has a diversity of climatic and geologic conditions, soils and vegetation. Warm moist winds from the Pacific Ocean provide an annual precipitation of about 1.52 m at the lower elevations to over 2.45 m at higher elevations. More than 75 percent of the precipitation falls between October and March (Richardson, 1972) and the amount of snowfall is high, especially on the west side of the park. The heavy snowfall has resulted in the development of large glacial systems on all sides of the mountain (Fig. 2). The east side of the park is thought to be typically warmer than the west side in summer months (unpublished park observations). Three main vegetation zones have been identified: lowland forests below 1000 m, subalpine parklands and meadows above 1600 m and alpine areas above 1800 m (Franklin et al, 1988).

The 27 lakes included in the study were distributed in all four quadrants of the park (Fig. 3). The lakes were capped by snow and ice in winter and ice-out between June and July. Based on the vegetation surrounding the lakes, 15 lakes were classified as forest lakes and 12 as subalpine lakes. Although forest and subalpine lakes were studied in each quadrant, many of the subalpine study lakes were in the northeast quadrant. The study lakes ranged from 970.7 to 2049.7 m in elevation, 0.6 to 46.9 ha in surface area, and 0.8 to 58.6 m in depth (Table 1). Watershed areas ranged from 5.8 to 389.5 ha (Table 1). Most of the lake basins were formed by glacial scouring, with the exceptions of Reflection Lake, which was formed by a mud flow, and Frozen Lake, a reservoir constructed in 1930 (unpublished park records). The geological properties of the lake basins reflected the diversity of formations in the park. Based on a cluster analysis of the geological compositions of the watersheds, the 27 basins separated into 7 groups (Table 2).

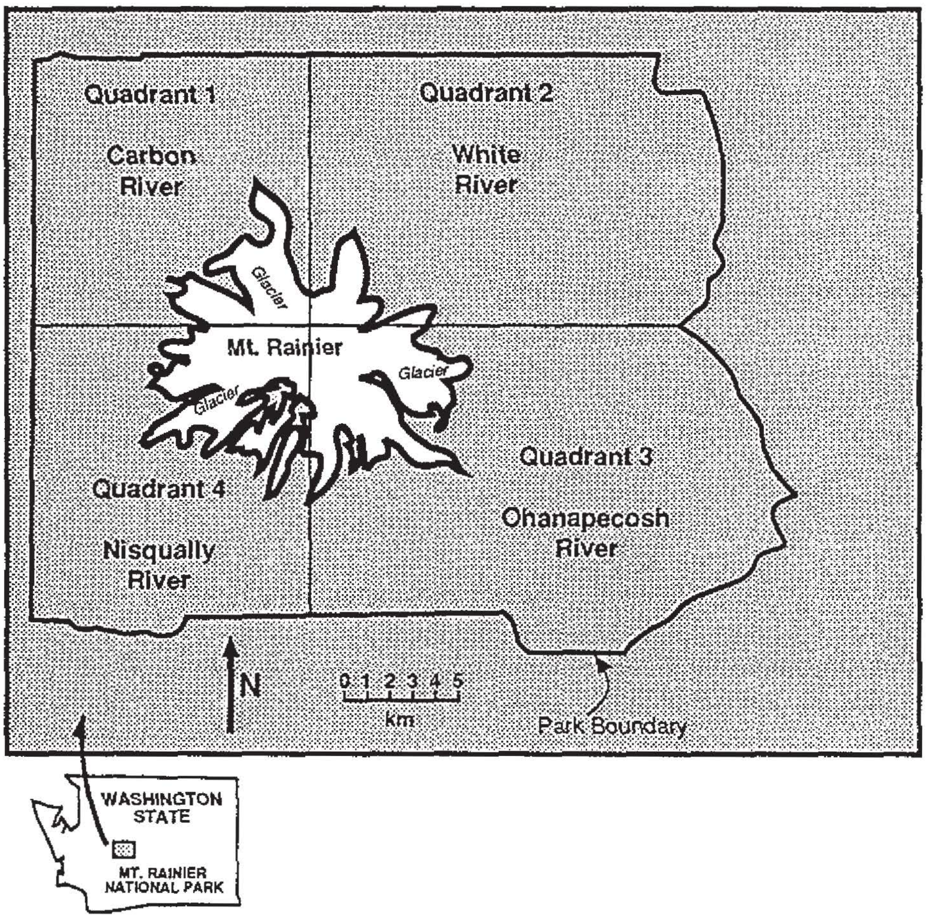


Figure 2. Locations of the four quadrants in Mount Rainier National Park, Washington State.

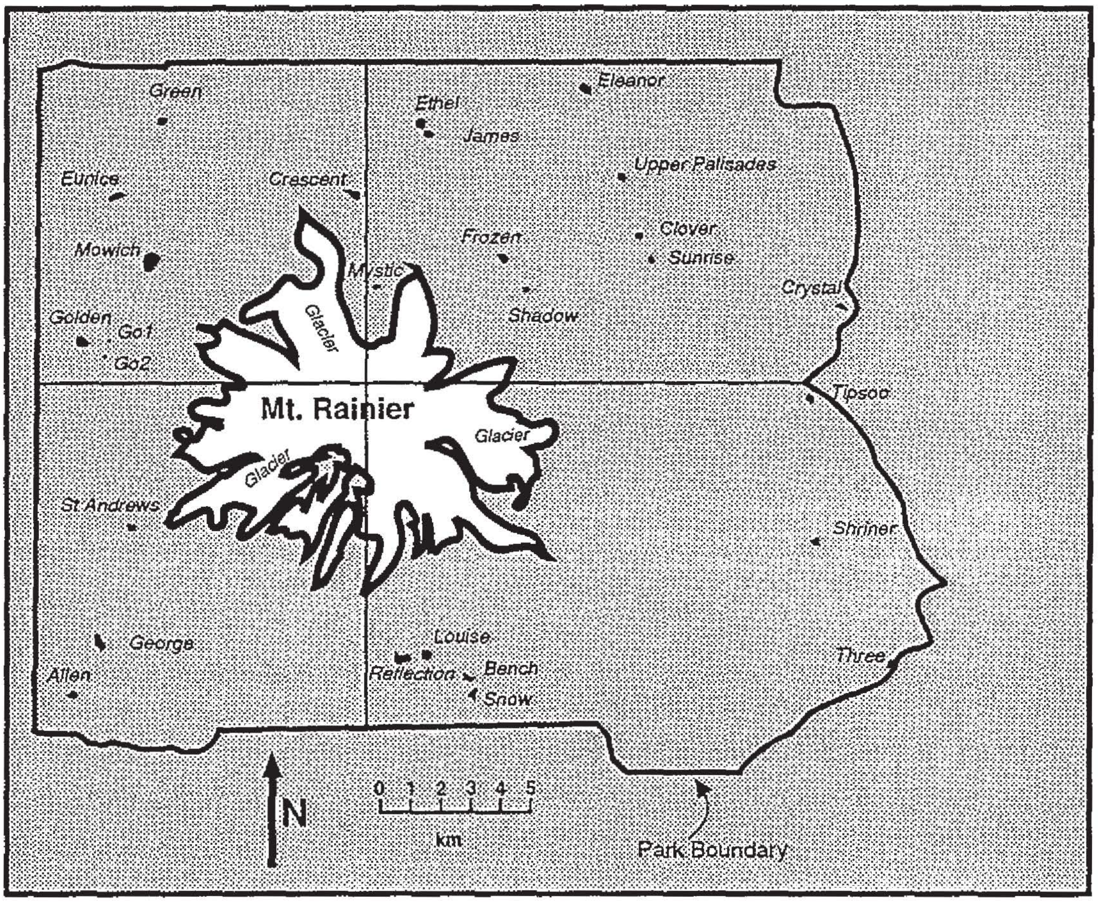


Figure 3. Locations of the study lakes in Mount Rainier National Park.

Table 1. Watershed (WSHED) area and aspect, lake elevation (EL), surface area, depth (Z), vegetation type, quadrant and periods sampled.

Lakes	WSHED (ha)	WSHED Aspect	Lake EL (m)	Lake Area (ha)	Lake Z (m)	Vegetation Type	Quadrant	Periods Sampled**
Allen	20.0	E	1395.0	1.7	6.8	F	4	1,3
Bench	11.9	E	1384.3	2.9	11.0	F***	3	3,4
Clover	64.1	E	1747.0	2.9	13.2	SA	2	2,4
Crescent	51.8	W	1696.1	7.0	27.6	SA	1	1,3
Crystal	13.9	W	1776.2	3.2	9.2	SA	2	1,3,4
Eleanor	63.7	E	1519.3	7.0	14.3	F	2	2,4
Ethel	98.4	E	1306.6	10.2	24.5	F	2	3
Eunice*	29.0	S	1632.1	5.3	11.5	SA	1	3
Frozen	10.0	E/W	2049.7	1.8	6.1	SA****	2	2,4
GO1*	11.6	W	1498.0	0.8	2.5	F	1	3
GO2*	20.4	W	1432.5	0.6	5.5	F	1	3
George	95.1	N	1308.1	13.9	38.3	F	4	1,3
Golden	88.4	W	1368.5	6.4	23.4	F	1	2,4
Green	389.5	N	970.7	5.0	27.5	F	1	2,3
James	292.3	E	1347.2	5.0	22.3	F	2	2,4
Louise	201.7	E	1401.1	7.3	16.0	F	3	1,3,4
Mowich	177.6	W	1502.3	45.9	58.6	F	1	1,3,4
Mystic	42.3	E	1737.3	1.9	3.3	SA	2	2,4
Reflection	122.7	E/W	1479.4	6.8	10.3	F	3	1,3,4
Shadow*	79.6	S	1886.6	0.9	4.5	SA	2	2,4
Shriner	49.6	S	1488.3	1.7	2.9	F***	3	1,3
Snow	166.5	N	1426.1	2.4	10.1	F***	3	1,3,4
St. Andrews*	28.0	W	1792.1	1.5	0.8	SA	4	4
Sunrise	13.4	E	1767.8	1.5	6.7	SA	2	2,4
Three	21.6	S	1478.2	1.7	4.0	F	3	2,4
Tipsoo	45.7	W	1613.5	1.5	1.8	SA	3	1,3
Upper Palisades	5.8	S	1769.3	1.6	10.7	SA	2	2,4

* Fishless lakes
** 1 - July 14-31
2 - August 1-15
3 - August 16-31
4 - September
*** Near the transition between forest and subalpine lake types.
**** Near the transition between subalpine and alpine lake types.

Table 2. Dominant geological formations in the study lake watersheds. Geologic data expressed as the mean percentage of the watershed areas (flat map) for the lakes in each group.

Dominant Geological Formations	$\overline{X}$ Area (%)	Study Lakes
Andesite lava	98.6	Bench, GO1, GO2, Golden, Shadow, Shriner and St. Andrews
Andesite basalt	72.2	Eunice, Green, and Mowich
Ash flow	91.7	Crescent
Silt/sandstone	84.1	Allen, Clover, Crystal, George, Three, and Upper Palisades
Granodiorite	76.7	James, Mystic, Snow, Sunrise, and Tipsoo
Granodiorite Andesite lava	45.1 51.3	Ethel, Frozen, Louise, and Reflection
Silt/sandstone *Surficial deposits*	50.0 50.0	Eleanor

Most lakes in Mount Rainier National Park have been stocked with salmonids. No stocking has occurred since the 1960's, however. Based on field observations made during the study and the stocking records, only 6 of the study lakes were fishless in 1988 (Table 1). Although Eunice Lake and Shadow Lake were fishless in 1988, both had been stocked with fish in years past.

Methods

The study lakes were selected on the basis of accessibility, location within the park and lake type (forest or subalpine). Some lakes were close to roads and required little trail time for each visit while hikes of up to 4 hours were required to reach other lakes. The lakes were sampled from July to September 1988. Three fields crews were involved. The main crew sampled lakes around the park in a counter clockwise direction starting with Reflection Lake. The lakes were sampled for the first time in July (Period 1) or from August 1-15 (Period 2). The lakes were resampled in approximately the same order in the second half of August (Period 3) or in September (Period 4). A few lakes (Reflection Lake, Lake Louise, Snow Lake and Crystal Lake) also were sampled for a third time in September. The second crew focused on Mowich Lake and the third on Three Lake, Sunrise Lake, Upper Palasides Lake, GO1, GO2, and Saint Andrews Lake (see Table 1 for sample periods).

Watershed areas (flat map) were estimated from topographical maps using a compensating polar planimeter. Watershed geology was divided into 6 broad groups as described by Larson et al (1990). Flat map surface areas of the geological groups in each watershed were determined from a geological map (Fiske et al, 1963) using the planimeter. Lake elevations and surface areas were determined from the park Geographic Information System and Wolcott (1961).

Sampling was conducted from an inflatable boat (aluminium row boat at Mowich Lake) near the deepest point of each lake. Maximum depth was determined each time a lake was sampled using a weighted line marked at 10 cm intervals, except at Mowich Lake where a surface bouy was anchored at the deepest point in the lake. Water samples were collected using a 1.5 l PVC Van Dorn style bottle at depths of 1 m below the lake surface (2 m in Mowich Lake) and 1.5 m off the lake bottoms (8.6 m in Mowich

Lake). Water temperature was recorded using a hand thermometer which was inserted into the top of the Van Dorn bottle immediately after retrieval from a selected sampling depth. Water clarity was estimated using a standard black and white Secchi disk, 20 cm in diameter. Readings were reported as the average of descending and ascending values taken as close to 1200 hrs as possible from the shaded side of the boat.

An Orion pH meter (model 81-56) with a Ross combination electrode (model 917001) and an automatic temperature compensation probe (ATC) were used to determine pH and alkalinity. Occasionally an Orion combination electrode (model 91-56) was used when the Ross electrode malfunctioned. Water samples were transferred directly from the Van Dorn bottle to 60 ml syringes fitted with latex tubes on the tips, with the exception of samples from four lakes (Three, Sunrise, Upper Palisades and St. Andrews) which were put directly into collection bottles. The latex tubes were then clamped and the samples kept in the dark on ice or cold packs until processed. Measurements were made in a closed chamber constructed of tygon tubing fitted with silicone stoppers in each end. The bottom stopper was fitted with an entry tube made of glass and the ATC. The top stopper was fitted with the pH electrode and an overflow tube. The sample was injected into the chamber through the entry tube in the bottom stopper until water flowed out of the overflow tube. Readings were recorded every minute until five consecutive readings were obtained. The final value was recorded as the sample pH. Alkalinity was determined following the Gran Titration procedure (Gran, 1952) with 100 ml samples.

Dissolved oxygen was estimated using the Azide modification of the Winkler technique. The reagents (Hach powder pillows) were added to the sample bottles shortly after the samples were taken. The samples were titrated with 0.025 N phenol arsine oxide with the exception of samples from four lakes (Three, Sunrise, Upper Palisades, and St. Andrews) where sodium thiosulfate was used. Percent saturation was calculated following the method described by Wetzel (1975).

Nutrient and trace element samples were collected in acid washed polyethylene bottles. These samples were filtered in the field through prewashed 0.45 μm filters. The filtrate was stored in coolers on ice packs until they could be shipped to Cooperative Chemical Analytical Laboratory (CCAL), Forest Science Laboratory in Corvallis, Oregon, for processing. The samples usually arrived at the laboratory within 48 hours after collection. Unfiltered sample water was collected in 250 ml acid washed polyethylene bottles for analyses of conductivity and total phosphorus. These samples were placed into coolers and shipped to CCAL in the same manner as the filtered samples. Laboratory analytical procedures are listed in Table 3. The water quality data base is presented in Appendix 2.

Phytoplankton samples were collected from a depth of 1 m in each lake except for Mowich Lake where the samples were taken from a depth of 2 m (Larson 1973). Each 1 liter sample was preserved with 10 ml of Lugols solution. The samples were counted (500 cells) using the inverted microscope method (Lund et al, 1958) at 1500 X. Ms. Catherine Nisselson identified and counted the samples. Cell biovolumes were calculated based on the geometric shape of each taxon.

Zooplankton were collected using a new 20 cm diameter net (64 μm mesh) towed vertically at about 0.5 m/sec from 1.5 m off the lake bottoms to the surface. Horizontal tows were taken in two of the shallowest lakes (Tipsoo and Saint Andrews). Net filtration efficiency was assumed to be 100%. Samples were preserved in 4% formalin. The samples were processed using standard methods under a dissecting scope (40 X) by Mr. William Cameron. However, *Keratella hiemalis* was misidentified as *K. quadrata* in Mowich Lake samples (Robert Truitt, personal communication). An inverted scope (40 - 400 X) was used for taxonomic identifications. The presence or absence of fish in each lake was determined from park records, observations and angling. No attempts were made to assess the abundances of fish.

The SYSTAT version of the Kruskal-Wallace non-parametric analysis of variance procedure was used to test for statistical significance between lake types. Correlation analysis (SYSTAT) was used to test relationships among selected variables over all lakes and watersheds. The level of statistical significance was $p < 0.05$. An ordination of phytoplankton community structures was performed using the program DECORANA (Hill and Gauch, 1980). A cluster analysis (McIntire, 1973) was used to group the samples in ordination space, a procedure that provided estimates of mean values for the variables in different regions of the ordination. The SYSTAT program, Kmeans, was used to cluster the geologic formations in the watersheds of the study lakes.

Table 3. Analytical procedures used by the Cooperative Chemistry Analytical Laboratory, Oregon State University.

Variable	Method
Conductivity	Wheatstone Bridge, Yellow Springs model 33; corrected to 25 C
Nitrate-N	Technicon Autoanalyzer, automated cadmium reduction
Kjeldahl-N	Nessler's Reagent finish
Ammonia-N	Technicon Autoanalyzer, colormetric automated phenate
Total phosphorus	Persulfate digestion, ascorbic acid finish
Orthophosphate-P	Reactive phosphate, ascorbic acid finish
Sulfate-S	Technicon Autoanalyzer, method 105-72W
Silica	Technicon Autoanalyzer, method 105-71W/B
Sodium	Flame atomic absorption
Chloride	Flame atomic absorption
Calcium	Flame atomic absorption
Magnesium	Flame atomic absorption
Potassium	Flame atomic absorption

Results

Watershed and Lake Morphology

The average watershed area and lake elevation, surface area and maximum depth for all lakes were 82.0 ha, 1547.2 m, 5.5 ha and 13.8 m, respectively (Table 4). Watershed areas of forest lakes were significantly larger than those of subalpine lakes (Table 5). As expected, subalpine lakes were at significantly higher elevations than were forest lakes, but surface areas and depths did not differ significantly between the two lake types. However, of the lakes with surface areas greater than 5 ha, 9 were forest and only 2 were subalpine (Table 1). Moreover, 11 forest lakes and only 4 subalpine lakes were deeper than 10 m. For all lakes, maximum depth had a significantly positive correlation with surface area (Table 6; Fig. 4).

Secchi Disk

Secchi disk readings were recorded for 10 forest lakes and 3 subalpine lakes; the disk could be seen on the bottoms of the other lakes. Frozen Lake was the shallowest lake (6.1 m) from which a reading was obtained. Secchi disk readings increased as lake depth increased (Table 6; Fig. 5). The deepest reading in a forest lake was 21.9 m (Mowich Lake), whereas the deepest in a subalpine lake was 22.2 m (Crescent Lake). In some lakes from which several readings were taken, the readings were shallowest in July and early August (Fig. 6).

With the exceptions of Mowich Lake, Snow Lake and Frozen Lake, Secchi disk depths decreased as phytoplankton biovolumes increased from 452 to 2433 $\mu m^3/ml \times 10^2$ (Fig. 6). In lakes where the disk was visable on the lake bottoms, phytoplankton biovolumes ranged between 825 and 6825 $\mu m^3/ml \times 10^2$ (Fig. 7).

Water Quality

Near surface water temperatures of most lakes increased quickly after ice-out (Fig. 8). Maximum temperatures of most forest and subalpine lakes occurred in August, although Shriner Lake (forest) and Crystal Lake (subalpine) already were warm in July. Frozen Lake (subalpine) and Snow Lake (forest) remained cold in August, however. Maximum temperatures of forest and subalpine lakes ranged between 18 and 20 C, and

Table 4. Minimum, maximum, and mean watershed areas, lake elevations, surface areas and depths for forest and subalpine lakes and for all lakes.

Variable	Lake type	N	Minimum	Maximum	Mean
Watershed area (ha)*	Forest	16	11.6	389.5	114.4
	Subalpine	11	5.8	79.6	34.9
	All	27			82.0
Lake elevation (m)*	Forest	16	970.7	1519.4	1394.1
	Subalpine	11	1613.5	2049.7	1769.8
	All	27			1547.2
Lake area (ha)	Forest	16	0.6	45.9	7.4
	Subalpine	11	0.9	7.0	2.7
	All	27			5.5
Lake depth (m)	Forest	16	2.5	58.6	17.4
	Subalpine	11	0.8	27.6	8.7
	All	27			13.8

* Statistically significant differences between forest and subalpine lakes (see Table 5).

Table 5. Statistical evaluations of watershed area, lake elevation, surface area, and maximum depth between forest and subalpine lakes.

Dependent Variable	N	Probability
Watershed area	27	0.03
Elevation	27	<0.01
Area	27	0.10
Depth	27	0.10

Table 6. Selected correlations among physical, chemical, and biological variables for the study lakes.

Test Combinations Variable	Variable	Sample Size	r^2	Probability
Depth (m)	Area (ha)	27	0.758	<.01
Secchi disk (m)	Depth (m)	24	0.633	<.01
Secchi disk (m)	Phytoplankton biovolume*	15	0.703	<.01
Conductivity (µmhos/cm)	Sandstone/siltstone (%)	24	0.402	<.01

* Mowich, Frozen, and Snow lakes deleted (see Figure 6).

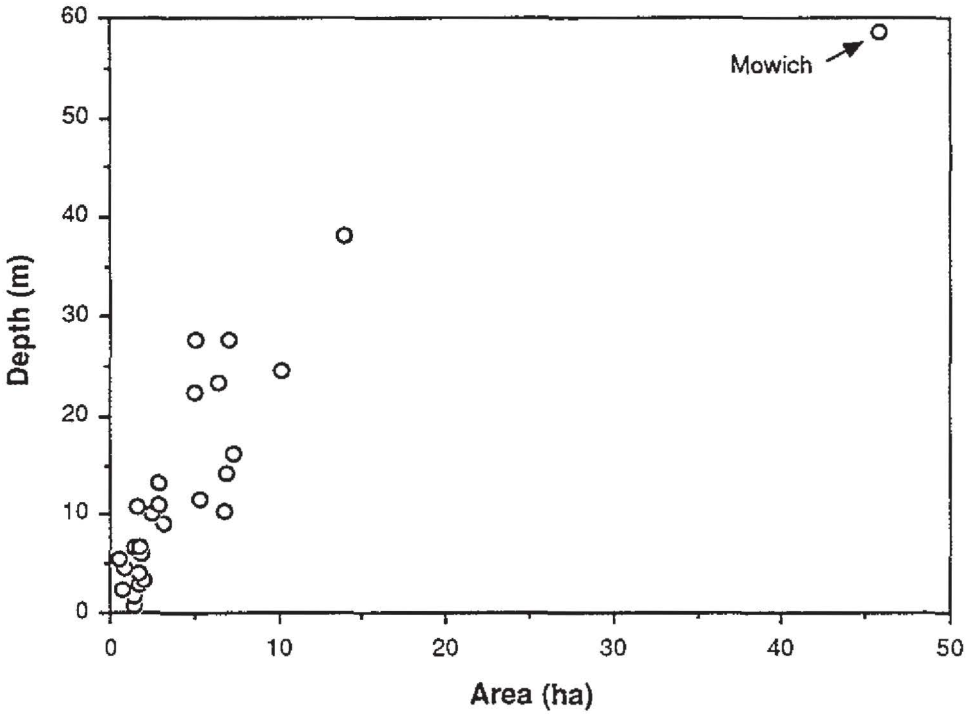


Figure 4. Relationship between maximum lake depth and lake surface area.

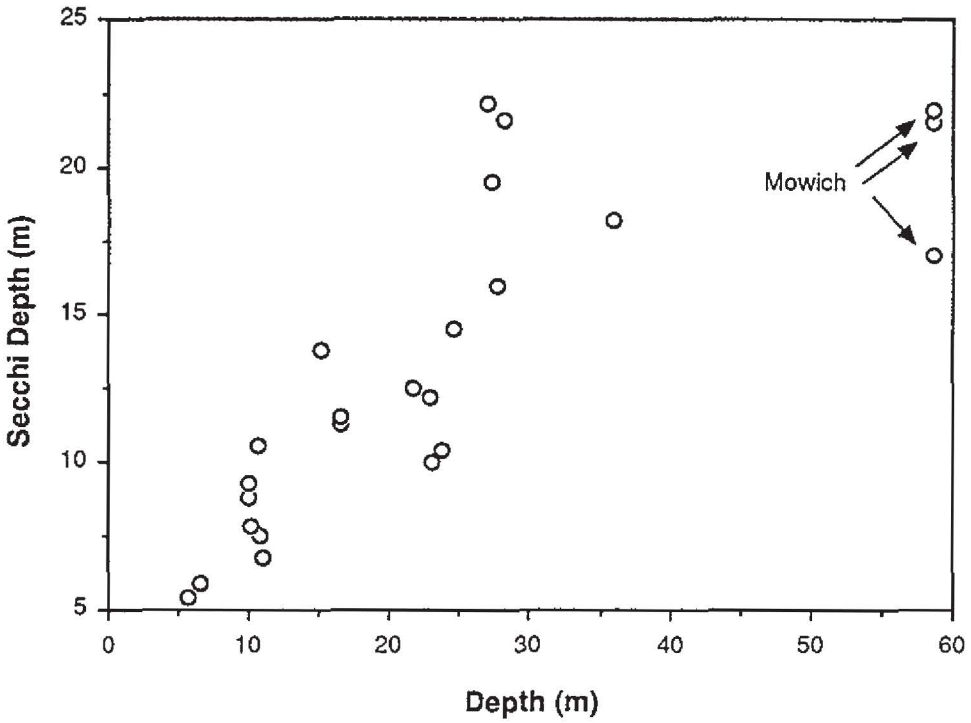


Figure 5. Relationship between Secchi disk clarity and maximum lake depth.

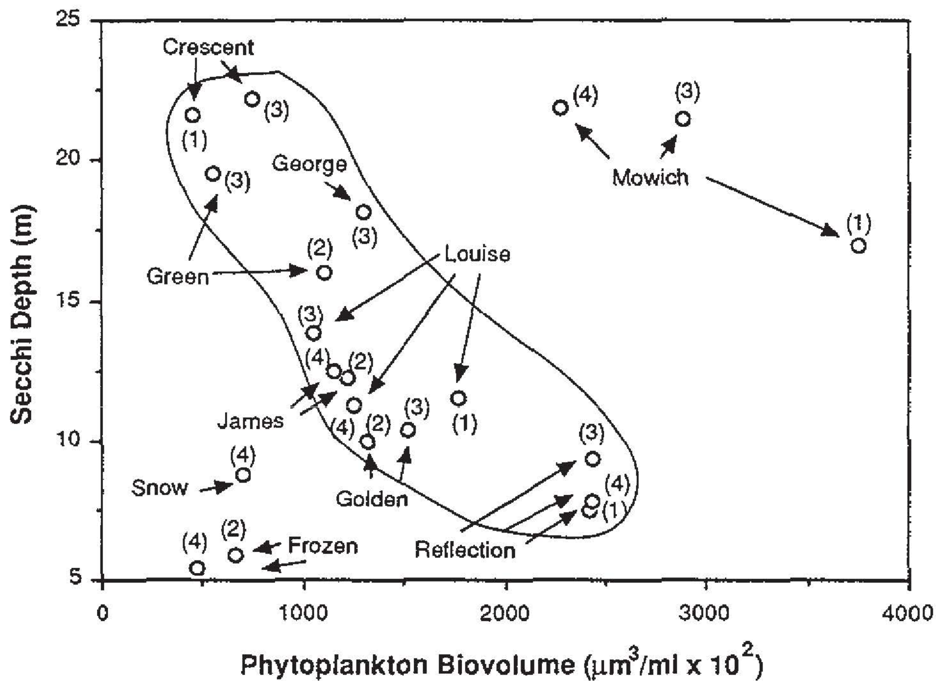


Figure 6. Relationships between Secchi disk clarity and phytoplankton cell biovolume in cases where the disk was not observable on the lake bottoms. Sample periods are indicated in parentheses.

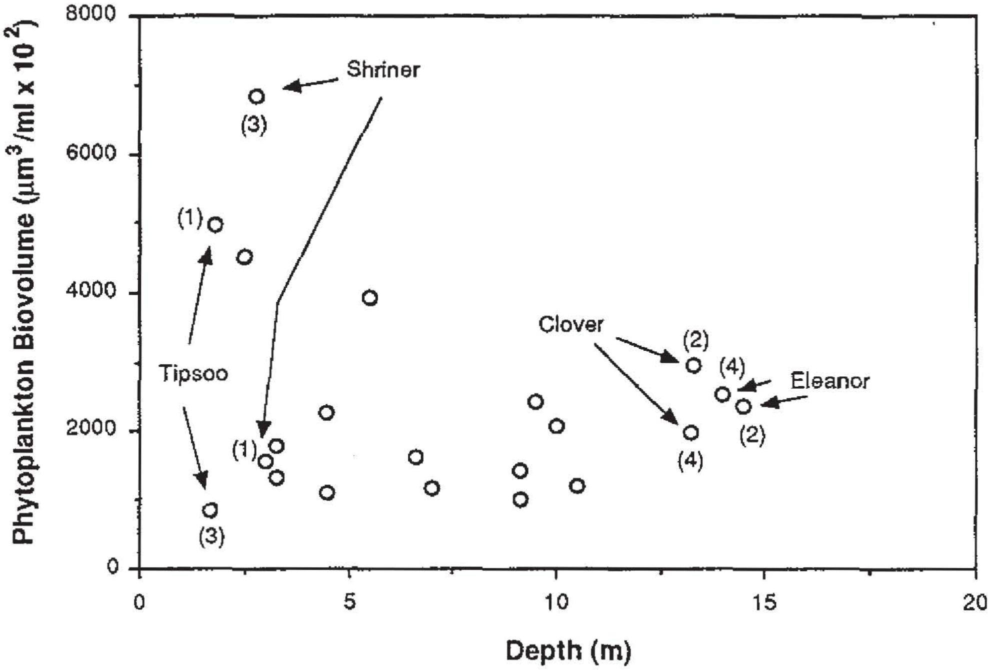


Figure 7. Relationship between phytoplankton cell biovolume and maximum lake depth for lakes in which the disk was observable on the lake bottoms. Sample periods are indicated in the parentheses.

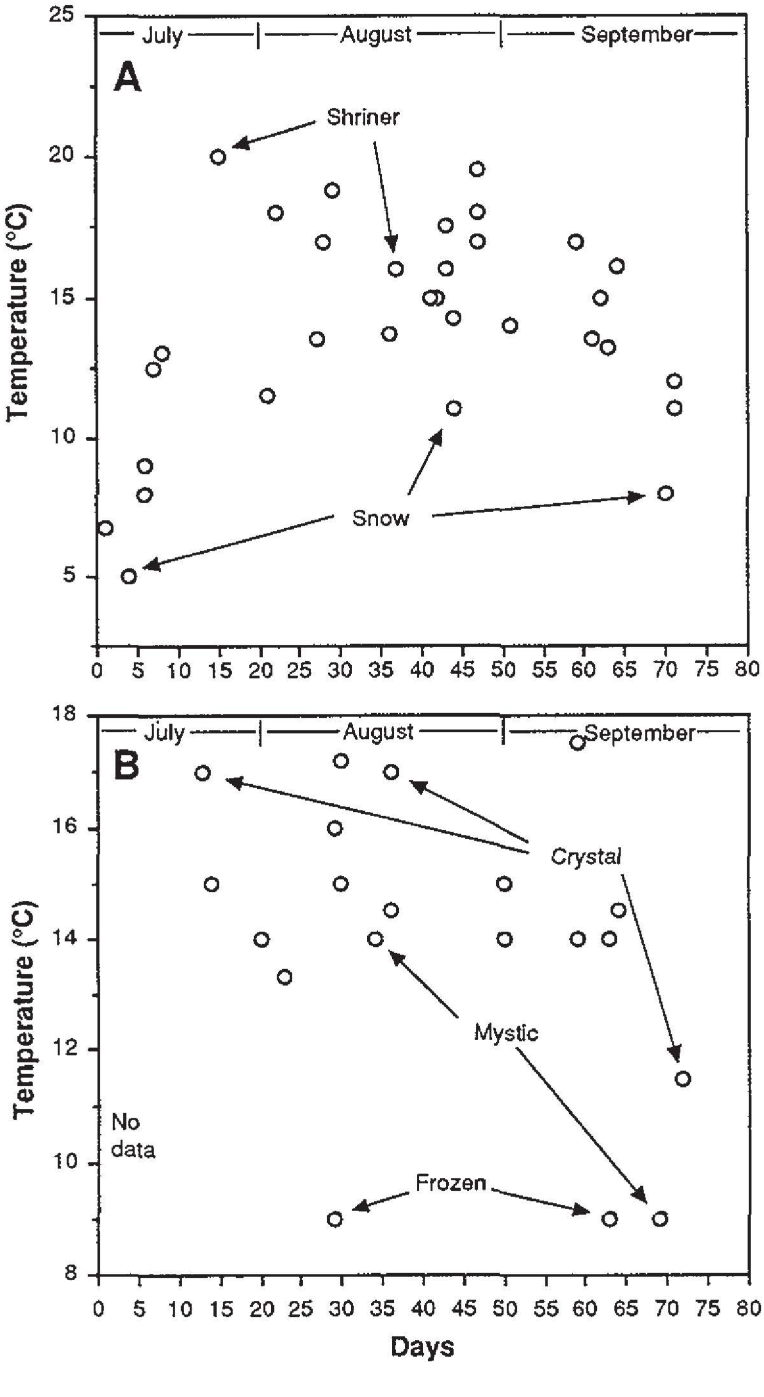


Figure 8. Changes in near surface water temperatures for forest lakes (A) and subalpine lakes (B) during the study. Days refer to the time since the beginning of the field season (day 1). Months are shown at the top of each graph.

15 and 18 C, respectively. However, these differences in temperature were not statistically significant between the two lake types ($p = 0.149$), although nine of the 12 cases with near surface temperatures exceeding 15 C were forest lakes (Fig. 9). Also, 9 of the 12 lakes with near surface temperatures greater than 15°C were located on the east side of the park (Fig. 9). Overall, watershed aspect did not appear to be an important factor in determining near surface temperatures. Surface water temperatures of forest and subalpine lakes generally decreased between August and September (Fig. 8).

Most lakes were too shallow to become thermally stratified. However, the maximum observed differences between near surface and near bottom temperatures increased with increasing lake depth, and maximum temperature differences of between 10 and 15 C were found in the 9 lakes with maximum depths greater than 14 m (Fig. 10). Eight of these were forest lakes. Similarly, there was a negative relationship between near bottom temperatures and lake depth (Fig. 11).

Dissolved oxygen concentrations near the surface of forest and subalpine lakes were near 100% saturation (Table 7). However, the concentrations of dissolved oxygen was lower in near bottom samples from forest lakes than in subalpine lakes (Table 8). In forest lakes, near bottom dissolved oxygen concentrations decreased with increasing lake depth to about 30 m and then increased in the two deepest lakes (Fig. 12). In subalpine lakes, near bottom dissolved oxygen was lowest in Crescent Lake (about 80% saturation) with a maximum depth of 27.6 m.

The study lakes typically were slightly acid and low in alkalinity, conductivity, nitrate-N, ammonia-N, total Kjeldahl nitrogen, orthophosphate-P, total phosphorus, calcium, magnesium and sodium (Tables 7, 8 and 9). In the near surface samples, magnesium was significantly higher in concentration in forest lakes than in subalpine lakes (Table 10). Dissolved oxygen, alkalinity, calcium, magnesium and sodium concentrations were significantly higher in near lake bottom samples from forest lakes than samples from subalpine lakes (Table 10). In general, forest lakes were more acidic and higher in concentrations of most chemical variables than were subalpine lakes, and chemical variables were slightly higher in concentration in near bottom samples than in

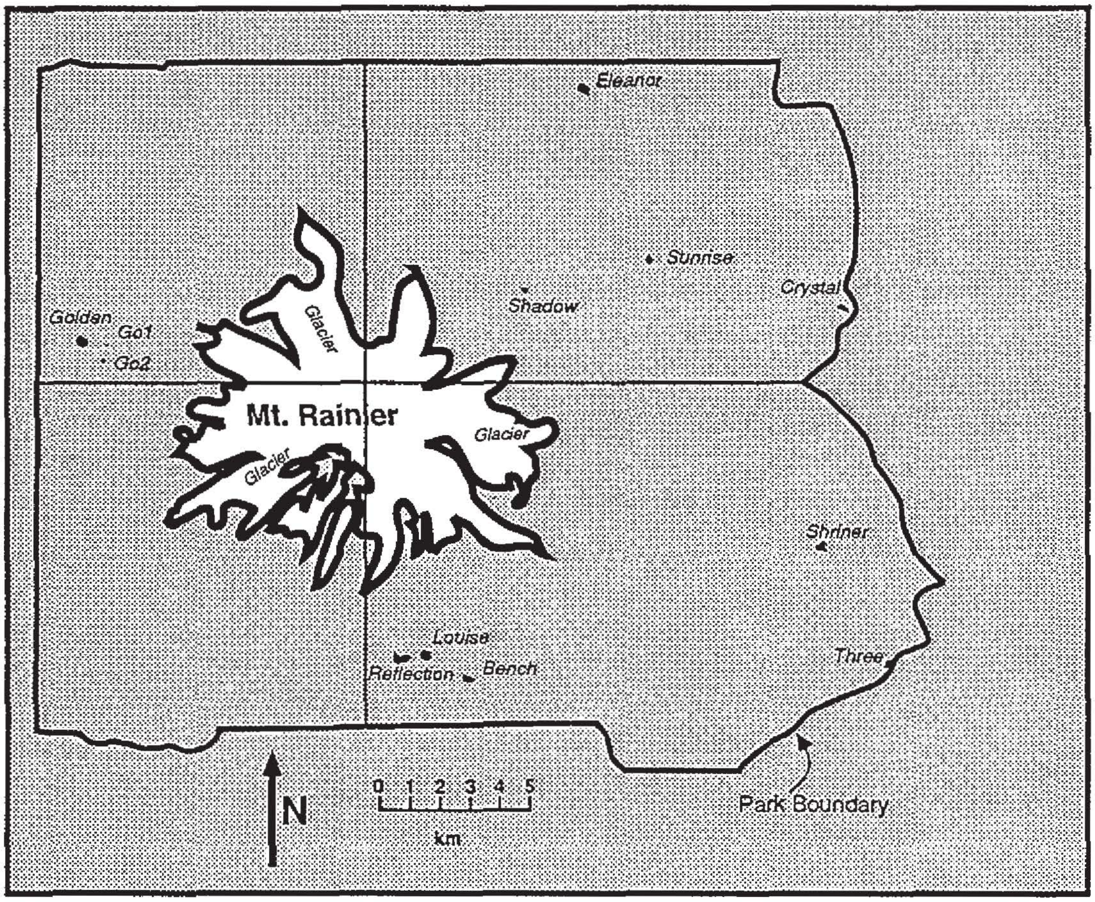


Figure 9. Locations of the lakes with near surface temperatures which exceeded 15°C during the study.

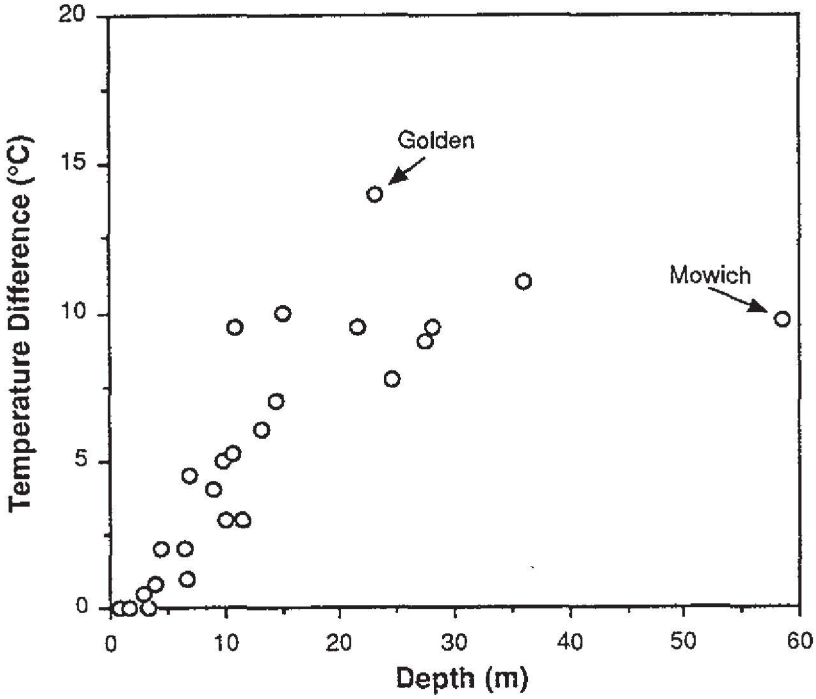


Figure 10. Relationship between the maximum observed differences in water temperature between near surface and near bottom samples and maximum depth for each study lake.

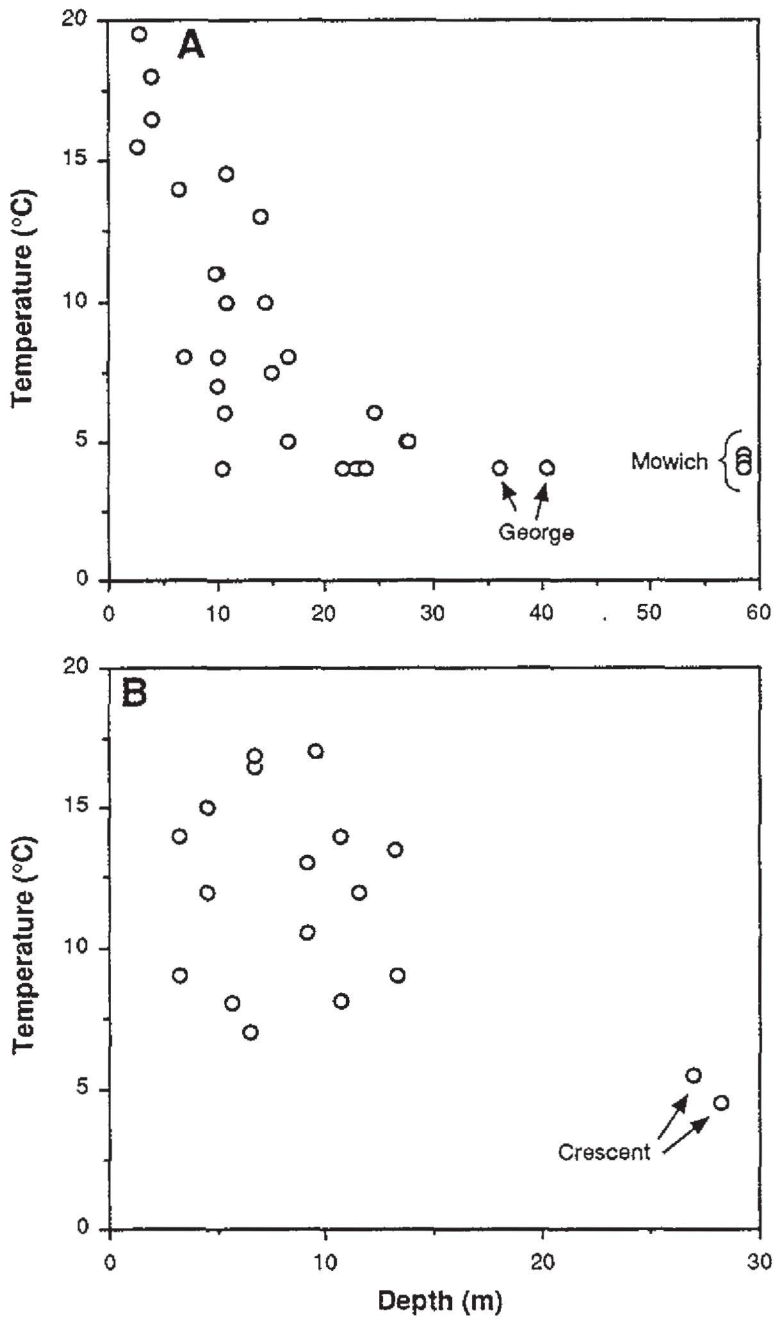


Figure 11. Relationships between near bottom water temperature and maximum lake depth for forest lakes (A) and subalpine lakes (B).

Table 7. Near surface water chemistry for forest and subalpine lakes and all study lakes based on mean values from each lake.

Variable	Lake type	N	Minimum	Maximum	Mean
Dissolved oxygen (% saturation)	Forest	15	90.0	107.0	100.2
	Subalpine	11	96.0	105.0	100.2
	All	26			100.2
pH (standard units)	Forest	16	6.04	7.80	6.64
	Subalpine	11	6.51	7.30	6.93
	All	27			6.74
Alkalinity (mg/l)	Forest	15	0.60	22.92	7.09
	Subalpine	11	0.50	14.50	4.73
	All	26			6.09
Conductivity (μmhos/cm)	Forest	16	4.30	57.93	16.08
	Subalpine	8	4.01	24.97	13.56
	All	24			15.24
Nitrate-N (μg/l)	Forest	16	0	22.0	4.0
	Subalpine	11	0	12.0	2.0
	All	27			3.0
Ammonia-N (μg/l)	Forest	16	0	10.0	4.0
	Subalpine	11	0	6.0	2.0
	All	27			3.0
Total Kjeldahl-N (μg/l)	Forest	16	13.0	181.0	61.0
	Subalpine	11	17.0	91.0	51.0
	All	27			57.0
Orthophosphate-P (μg/l)	Forest	14	1.0	11.0	4.0
	Subalpine	10	2.0	8.0	5.0
	All	24			5.0
Total phosphorus (μg/l)	Forest	14	5.0	47.0	13.0
	Subalpine	11	0	17.0	7.0
	All	25			11.0

Table 8. Near bottom water chemistry for forest and subalpine lakes and all lakes based on mean values from each lake.

Variable	Lake type	N	Minimum	Maximum	Mean
Dissolved oxygen (% saturation)	Forest	15	0	105.0	62.0
	Subalpine	9	84.5	108.0	98.3
	All	24			75.6
pH (standard units)	Forest	14	5.63	7.26	6.296
	Subalpine	9	6.35	6.80	6.709
	All	23			6.416
Alkalinity (mg/l)	Forest	14	2.07	50.07	10.70
	Subalpline	9	1.32	7.68	4.04
	All	23			8.09
Conductivity (µmhos/cm)	Forest	14	5.97	80.26	26.11
	Subalpine	8	4.16	25.00	12.99
	All	22			21.34
Nitrate-N (µg/l)	Forest	14	0	77.0	15.0
	Subalpine	9	0	13.0	3.0
	All	23			10.0
Ammonia-N (µg/l)	Forest	14	1.0	2039.0	158.0
		13*	1.0	62.0	13.0
	Subalpine	9	0	19.0	4.0
	All	23			98.0
		22			9.0
Total Kjeldahl-N (µg/l)	Forest	14	16.0	1925.0	189.0
		13*	16.0	99.0	56.0
	Subalpine	9	11.0	100.0	39.0
	All	23			130.0
		22			49.0
Orthophosphate-P (µg/l)	Forest	14	2.0	17.0	5.0
	Subalpine	9	4.0	8.0	6.0
	All	23			6.0
Total phosphorus (µg/l)	Forest	14	6.0	60.0	16.0
	Subalpine	9	0	17.0	9.0
	All	23			13.0

* Golden Lake deleted.

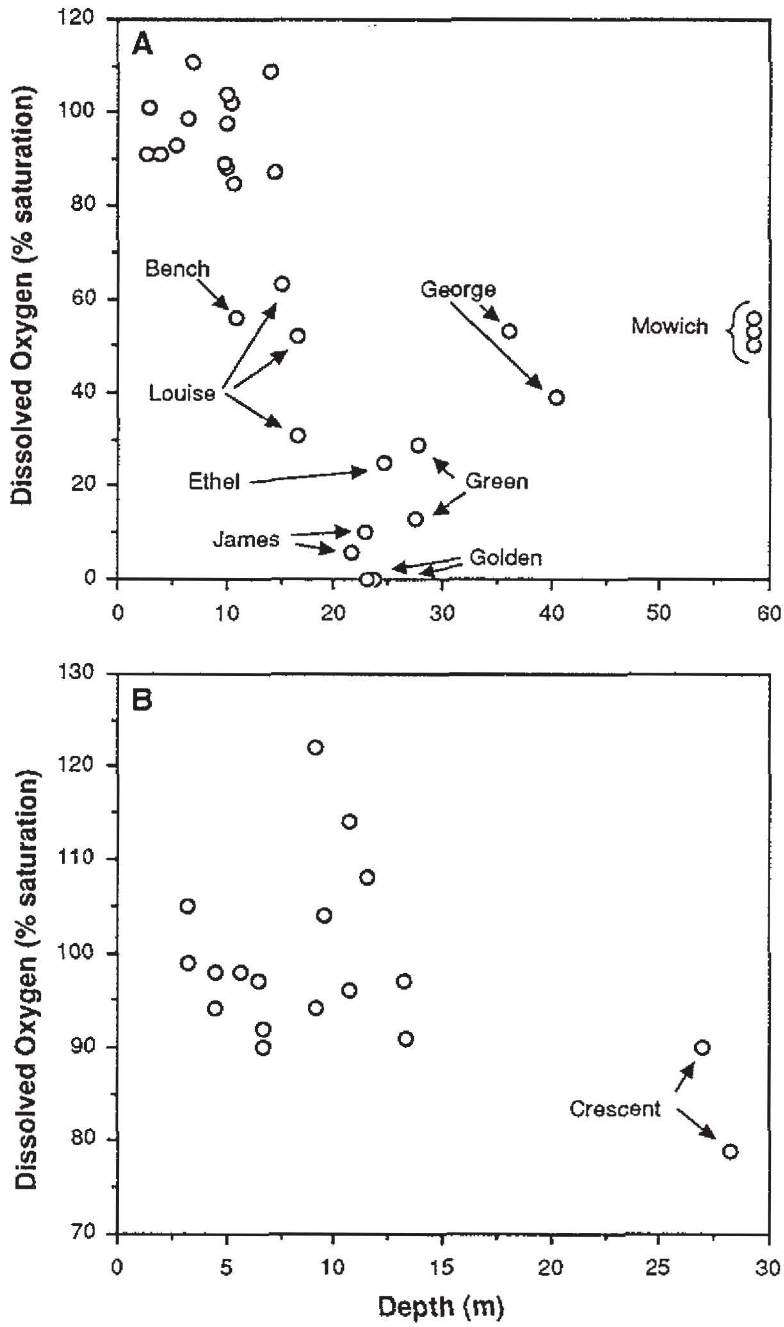


Figure 12. Relationships between dissolved oxygen (% saturation) in near bottom samples and maximum lake depth for forest lakes (A) and subalpine lakes (B).

Table 9. Mean concentrations of trace elements in near surface and near bottom samples from forest and subalpine lakes and all lakes combined.

Variable	N	Forest	N	Subalpine	N	All
			Near Surface Samples (mg/l)			
Calcium	14	2.13	11	1.23	25	1.73
Magnesium	14	0.25	11	0.12	25	0.19
Sodium	14	0.75	11	0.63	25	0.69
Silica	14	1.54	11	1.41	25	1.48
Potassium*	3	0.21	4	0.115	7	0.156
			Near Bottom Samples (mg/l)			
Calcium	14	3.01	9	1.04	23	2.24
Magnesium	14	0.33	9	0.11	23	0.25
Sodium	14	0.94	9	0.64	23	0.82
Silica	14	2.08	9	1.44	23	1.83
Potassium*	3	0.24	3	0.113	6	0.177

* Most samples were below detection limits.

Table 10. Results of statistical tests (Kruskal-Wallace) comparing mean values of selected water quality variables for forest and subalpine lakes.

Dependent Variable	N	Probability
	Near Surface Samples	
Dissolved oxygen	26	0.795
pH	25	0.978
Alkalinity	26	0.169
Conductivity	24	1.000
Total phosphorus	25	0.051
Orthophosphate-P	24	0.139
Total Kjeldahl-N	27	0.786
Nitrate-N	27	0.288
Ammonia-N	27	0.187
Calcium	25	0.090
Magnesium*	25	0.014
Sodium	25	0.090
Silica	25	0.661
	Near Bottom Samples	
Dissolved oxygen*	24	0.010
pH	23	0.186
Alkalinity*	23	0.038
Conductivity	22	0.056
Total phosphorus	23	0.072
Orthophosphate-P	23	0.057
Total Kjeldahl-N	23	0.219
Nitrate-N	23	0.251
Ammonia-N	23	0.062
Calcium*	23	0.020
Magnesium*	23	0.003
Sodium*	23	0.038
Silica	23	0.529

* Statistically significant at the 5% level.

the near surface samples, especially in forest lakes (Tables 7, 8 and 9). Watershed geology was not significantly related to any near surface water quality variable, except for silt/sandstone which had a positive correlation with mean near surface lake conductivity (Table 6).

Phytoplankton

The phytoplankton assemblages in all lakes combined included 203 taxa (Appendix 4). There were no obvious seasonal patterns in the number of taxa per lake, cell density and cell biovolume (Tables 11, 12, 13). Also, there were no significant differences in the mean number of taxa per lake between forest lakes (20.0) and subalpine lakes (18.4) (Table 14). Mean phytoplankton cell densities and biovolumes for all lakes were 2271.8/ml and 208,280 μm^3/ml, respectively (Table 15). Furthermore, there were no significant differences in cell densities and biovolumes between forest and subalpine lakes (Table 14), although the mean cell biovolume was higher in forest lakes (Table 15). Of the 11 lakes with cell densities greater than 2500/ml, 9 occurred on the east side of the park (Table 12). There were no obvious differences, however, in cell biovolumes between the east and west sides of the park, however (Table 13).

Lake ordinations relative to phytoplankton taxonomic composition are illustrated in Figure 13. Regions of this ordination were identified by a cluster analysis (Table 16), and the dominant taxa in samples associated with each cluster were determined (Table 17). Samples in each cluster differed by the dominance and combinations of particular taxonomic groups. Samples in cluster 1 were dominated by chrysophytes, but also included a high percentage of cyanobacteria. This cluster included most of the lakes sampled in July and early August. The only late August (Period 3) and September (Period 4) samples in cluster 1 were from Allen Lake, Snow Lake, Lake George and Eleanor Lake. Cluster 2 samples were dominated by chrysophytes and included lakes in the four quadrants of the park, sampled mostly in August. Most of the lakes in clusters 3, 4, and 5 were sampled in late August and September and occurred on the east side of the park (quadrants 2 and 3). Samples in clusters 3 and 4 were similar in taxonomic structure and included chlorophytes in addition to chrysophytes and cyanobacteria, but the latter cluster had a higher percentage of cyanobacteria. Cluster 5 included only

Table 11. Number of phytoplankton taxa in each lake by sample period.

	Sample Period			
Lake	1	2	3	4
Forest				
Allen	18		22	
Bench			10	
Eleanor		25		15
GO1			16	
GO2			21	
George	23		27	
Golden		25	23	
Green		24	19	
James		22		20
Louise	25		26	24
Mowich	18		18	13
Reflection	31		19	24
Shriner	21		17	
Snow	20		11	17
Subalpine				
Clover		23		23
Crescent	15		17	
Crystal	20		17	28
Frozen		17		11
Mystic		15		23
Shadow		16		19
Typsoo	16		19	

Table 12. Phytoplankton cell densities (cells/ml) by sample period for forest and subalpine lakes.

	Sample Period			
Lake	1	2	3	4
Forest				
Allen	1363		1572	
Bench			1412	
Eleanor		1015		2728
GO1			16698	
GO2			5505	
George	1822		968	
Golden		2243	1929	
Green		1153	941	
James		911		1194
Louise	1440		601	1625
Mowich	1548		1504	893
Reflection	2126		5800	2388
Shriner	1822		7701	
Snow	1559		2338	3546
Subalpine				
Clover		2637		2083
Crescent	721		2105	
Crystal	2972		4947	1045
Frozen		1202		1136
Mystic		2511		1648
Shadow		5566		1898
Tipsoo	3388		1897	

Table 13. Phytoplankton cell biovolumes ($\mu m^3/ml \times 10^2$) by sample period for forest and subalpine lakes.

	Sample Period			
Lake	1	2	3	4
Forest				
Allen	1159		1643	
Bench			2884	
Eleanor		2375		2544
GO1			4518	
GO2			3929	
George	6400		1291	
Golden		1313	1520	
Green		1108	548	
James		1217		1146
Louise	1767		1051	1254
Mowich	3753		2886	2273
Reflection	2424		2433	2432
Shriner	1555		6825	
Snow	1201		2066	699
Subalpine				
Clover		2945		1971
Crescent	452		746	
Crystal	1443		2450	1019
Frozen		670		474
Mystic		1341		1779
Shadow		2289		1111
Typsoo	4977		852	

Table 14. Statistical comparison of the mean number of phytoplankton taxa, cell densities and cell biovolumes between forest and subalpine lakes.

Variable	n	Probability
Number of taxa	21	0.312
Density	21	0.602
Biovolume	21	0.263

Table 15. Minimum, maximum and mean densities and biovolumes of phytoplankton in forest and subalpine lakes and all lakes combined.

Forest Type	Number of Lakes	Minimum	Maximum	Mean
		Phytoplankton Density (cells/ml)		
Forest	14	1047.2	16698.0	3267.0
Forest*	13	1047.2	5504.5	2234.8
Subalpine	7	1168.9	3732.2	2340.5
Combined	21			2958.8
Combined*	20			2271.8
		Phytoplankton Biovolume (μm^3/ml x10^2)		
Forest	14	828.4	4517.6	2480.9
Forest*	13	828.4	4190.1	2324.2
Subalpine	7	571.9	2914.6	1634.6
Combined	21			2198.7
Combined*	20			2082.8

* Lake GO1 deleted.

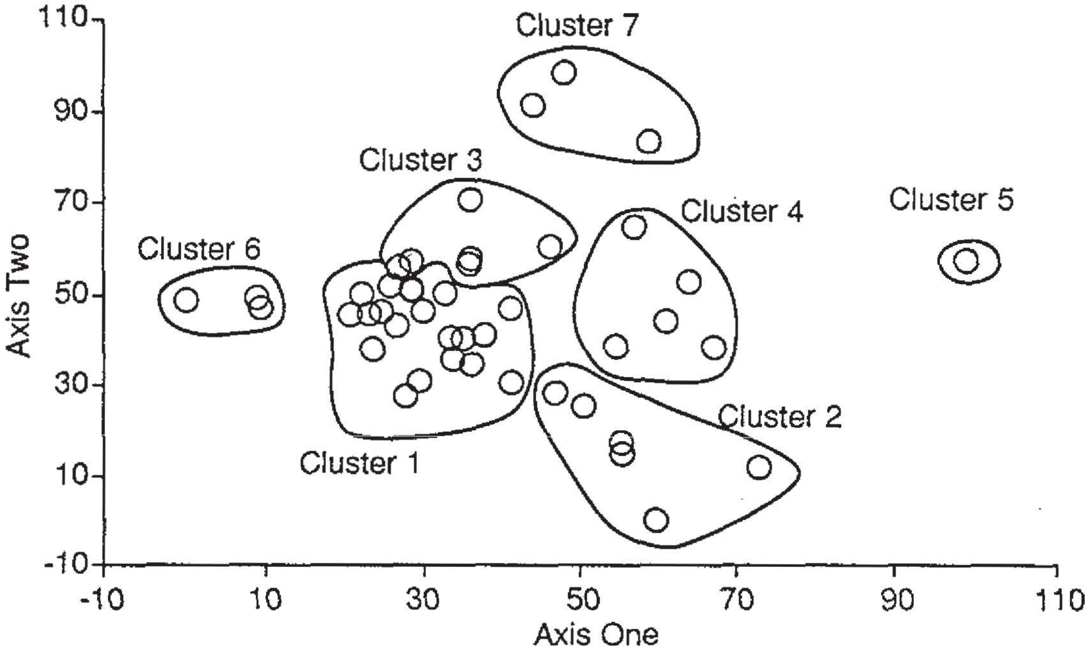


Figure 13. Ordination of the phytoplankton community assemblages by lake and the position of each cluster of lakes.

Table 16. Samples in each cluster of the lake ordination relative to the taxonomic composition of phytoplankton.

Cluster	Lake (sample period)
1	Allen (1,3), Clover (2), Crescent (1), Crystal (3), Eleanor (2,4), Frozen (2), George (1,3), Golden (2,3), Green (2), James (2), Louise (1), Reflection (1), Shriner (1), Snow (1,3), Tipsoo (1)
2	Crystal (1), GO1 (3), Green (3), Louise (3,4), Shadow (2)
3	Clover (4), Crystal (4), Frozen (4), James (4), Mystic (2), Snow (4)
4	Crescent (3), GO2 (3), Mystic (4), Reflection (3), Shadow (4)
5	Bench (3)
6	Mowich (1,3,4)
7	Reflection (4), Shriner (3), Tipsoo (3)

Table 17. Dominant phytoplankton taxa and the distribution (percent) of major taxonomic divisions in the seven lake clusters for taxa with ≥ 5% relative abundance.

Cluster	Chrysophyta	Cyanophyta	Chlorophyta	Pyrrhophyta
1	68.8	31.2	0	0
2	88.0	12.0	0	0
3	32.4	47.8	19.8	0
4	25.5	55.1	19.4	0
5	10.4	89.6	0	0
6	75.2	15.0	0	9.8
7	33.5	9.4	57.1	0

Cluster	Taxa in order of relative abundance
1	*Synechocystis* sp., *Ochromonas silvarum*, *Ochromonas nana*, *Chrysapsis* sp., and *Dinobryon* sp.
2	*Chrysocapsa planctonica*, *Synechocystis* sp., *Dinobryon bavaricum*, *Ochromonas silvarium* and *Ochromonas nana.*
3	*Synechocystis* sp., *Ochromonas nana*, *Chrysapsis* sp./*Oocystis pusilla* and *Sphaerocystis schroeteri.*
4	*Chroococcus dispersus*, *Oocystis pusilla*, *Aphanocapsa delicatissima*, *Chrysocapsa planctonica*, *Ochromonas nana*, and *Merismopedia minima.*
5	*Merismopedia minima* and *Oocystis pusilla.*
6	*Tribonema affine*, *Ochromonas nana*, *Synechocystis* sp, *Ochromonas silvarium*, *Gymnodinium* sp.
7	*Sphaerocystis schroeteri*, *Oocystis pusilla*, *Ochromonas nana* and *Synechocystis* sp.

samples from Bench Lake which was dominated by cyanobacteria. Samples from Mowich Lake (cluster 6) were dominated by chrysophytes and contained a small percentage of dinoflagellates. Samples in cluster 7 were dominated by chlorophytes, and the lakes, sampled in late August or September, were located in quadrant 3.

Zooplankton

Zooplankton assemblages in the study lakes combined included 8 crustacean taxa, 11 rotifer taxa and *Chaoborus* (Table 18). *Diaptomus, Daphnia* and *Holopedium* were the most abundant crustacean taxa, while *Conochilus, Polyarthra, Keratella cochlearis, K. quadrata* and *Kellicottia* were the most abundant rotifer taxa.

Crustacean assemblages were variable among the lakes. In some cases, a taxon dominated an assemblage throughout the sampling season, whereas in other cases dominance changed from one taxon to another. The following combinations of taxa were observed:

Dominant	Subdominant
Diaptomus	None
Diaptomus	*Daphnia*
Diaptomus	*Holopedium* and/or *Bosmina*
Holopedium	None
Holopedium	*Daphnia* and/or *Diaptomus*
Daphnia	*Holopedium* and/or *Bosmina*
Daphnia	*Diaptomus*
Daphnia	*Diaptomus* and *(Holopedium or Bosmina)*
Daphnia and Diaptomus	None

Diaptomus (without a subdominant) was found in the northern portion of the park (quadrants 1 and 2), and in Snow Lake and Allen Lake (Table 19). *Diaptomus-Daphnia* communities were limited to four subalpine lakes and one forest lake, while *Diaptomus-Bosmina/Holopedium* assemblages were found in two subalpine and four forest lakes. *Daphnia and Diaptomus* were dominant in 2 lakes (Eleanor and Green) during late August or September. The *Daphnia-Holopedium* assemblage was found in 3 lakes located on the east side of the park. These lakes were sampled in September.

Table 18. Zooplankton taxa collected from the study lakes and corresponding acronyms in parentheses.

Crustacea	Rotifera
Diaptomus (DIA)	*Conochilus (CON)*
Cyclops (CYC)	*Polyarthra (POA)*
Daphnia (DAP)	*Asplanchna (ASP)*
Bosmina (BOS)	*K. cochlearis (KEC)*
Holopedium (HOL)	*K. quadrata (KEQ)*
Polyphemus (POP)	*K. hiemalis (KEH)*
Chydorinae *(CHY)*	*Kellicottia longispina (KEL)*
Alona (ALO)	*K. taurocephalus (KET)*
	Lecane (LEC)
	Trichotria (TRI)
	Monostyla (MON)

Insecta
Chaoborus (CHA)

Table 19. Crustacean zooplankton community types in each lake by sample period and quadrant. A disk separates dominant and subdominant taxa, whereas equal dominance is indicated by a slash (/). Acronyms: *Daphnia* (DAP), *Holopedium* (HOL), *Bosmina* (BOS), and *Diaptomus* (DIA).

	Sample Period			
Quadrant Lake	1	2	3	4
1 Crescent	DIA		DIA	
1 Eunice			DIA	
1 GO2			DIA-HOL	
1 Golden		DIA		DIA
1 Green		DIA	DAP/DIA	
2 Clover		DIA-HOL		HOL-DAP/DIA
2 Crystal	HOL-DIA		DAP-DIA-HOL	DAP-HOL
2 Eleanor		DAP-DIA		DAP/DIA
2 Ethel			DIA-DAP	
2 Frozen		DIA		DIA
2 James		DIA		DIA-HOL
2 Mystic		DIA-DAP		DIA-DAP
2 Shadow		DIA-DAP		DAP-DIA
2 Sunrise		DAP-DIA		
2 Uppal*				DIA
3 Bench			HOL/DAP-DIA	DAP-HOL
3 Reflection	DIA-HOL		HOL-DAP/DIA	DAP-HOL/DIA
3 Louise	HOL		HOL	HOL
3 Shriner	HOL-DAP/DIA		DAP-DIA-HOL	
3 Snow	DIA		DIA	DIA
3 Three				DAP-DIA
3 Tipsoo	DIA-BOS/HOL		DIA-DAP	
4 Allen	DIA		DAP-DIA	
4 George	DIA-BOS		DAP-DIA/BOS	
4 St. Andrew				DIA-DAP

* Upper Palisades

Daphnia-Diaptomus assemblages, with and without *Holopedium* or *Bosmina*, were found in 9 lakes, 7 of which were located on the east side of the park. *Holopedium* without subordinate taxa was found in Lake Louise throughout the sampling season, whereas *Holopedium-Daphnia/Diaptomus* assemblages were found in 5 lakes on the east side of the park. Mowich Lake was the only lake which did not contain crustacean zooplankton [a single specimen of *Holopedium* was found, but this was probably a result of contamination during sample processing or from the net].

Documenting temporal changes in crustacean zooplankton community structure was difficult because the lakes were not sampled at the same times. However, comparing samples from periods 1 and 2 with those collected in periods 3 and 4 provided some indications of temporal changes. *Diaptomus* was the dominant crustacean in 13 of the 18 lakes sampled in periods 1 and 2 and in 12 of the 24 lakes sampled during periods 3 and 4 (Table 19). In cases where *Diaptomus* was the sole dominant crustacean in periods 1 and 2, it generally maintained dominance in periods 3 and 4 or was in equal abundance with *Daphnia*. In cases where *Diaptomus* was associated with a subdominant cladoceran in periods 1 and 2, it frequently lost its dominance to the cladoceran in periods 3 and 4. When *Holopedium* was dominant to *Diaptomus* in periods 1 and 2, *Daphnia* became dominant in periods 3 and 4. When *Holopedium* was without subdominant taxa early in the season, it maintained its dominance in periods 3 and 4.

Temporal patterns in crustacean zooplankton densities were variable among lakes (Table 20). Nonetheless, densities increased in most lakes sampled between period 1 and period 3. However, zooplankton densities declined in most lakes sampled between periods 3 and 4. There were no significant differences in the densities of each crustacean taxon between forest and subalpine lakes (Table 21).

The *Diaptomus* and *Diaptomus*-cladoceran groups were associated with 3 different dominant rotifer taxa (*Kellicottia, K. cochlearis* and *Conochilus* - see below) in subalpine lakes and 4 rotifer taxa (*Kellicottia, Keratella quadrata, Conochilus,* and *Polyarthra*) in forest lakes (Table 22). In 3 subalpine lakes and 2 forest lakes which were representatives of the *Diaptomus* group, rotifers either occurred in very low densities, including most of the *Kellicottia* cases, or were absent. In contrast, all cladoceran dominated lakes contained rotifers. In subalpine lakes dominated by cladocerans,

Table 20. Densities (NO/m^3) of crustacean zooplankton and Chaoborus by sample period. Abundances in Saint Andrew Lake and Lake Tipsoo are relative abundances expressed as percentages.

Lake	Sample Period	Diaptomus	Cyclops	Daphnia	Holopedium	Bosmina	Polyphemus	Chydorinae	Alona	Chaoborus
Allen	1	2350.8	0.0	30.9	3.5	0.0	0.0	0.0	0.0	3.5
Allen	3	709.9	92.9	7796.3	240.7	0.0	0.0	0.0	24.7	8.0
Bench	3	1114.5	342.9	3460.2	3532.2	0.0	0.0	0.0	0.0	0.0
Bench	4	200.6	106.7	1151.0	343.4	0.0	0.0	0.0	0.0	0.0
Clover	2	3193.4	16.5	141.6	1308.6	0.0	0.0	0.0	0.0	0.0
Clover	4	3228.7	51.0	3236.7	4482.0	0.0	0.0	0.0	0.0	0.0
Crescent	1	1903.7	1.6	0.0	0.0	1.6	0.0	0.0	0.0	0.0
Crescent	3	3621.4	6.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Crystal	1	1983.0	0.0	212.2	5219.9	65.6	0.0	0.0	0.0	0.0
Crystal	3	794.8	18.1	956.8	694.4	0.0	0.0	0.0	0.0	1.3
Crystal	4	111.1	7.7	1304.0	733.0	0.0	0.0	0.0	7.7	1.9
Eleanor	2	2348.1	0.0	5415.5	144.8	52.2	0.0	0.0	0.0	0.0
Eleanor	4	3048.4	26.1	3898.4	170.9	349.0	0.0	0.0	0.0	0.0
Ethel	3	907.1	33.4	515.7	142.7	8.1	0.0	0.0	0.0	0.0
Eunice	3	571.4	0.0	62.7	0.0	0.0	0.0	0.0	0.0	0.3
Frozen	2	2722.2	0.0	6.2	0.0	4.1	0.0	0.0	0.0	0.0
Frozen	4	300.0	2.5	2.5	0.0	0.0	0.0	0.0	0.0	0.0
GO2	3	8277.8	0.0	203.7	1234.6	0.0	0.0	0.0	0.0	203.7
George	1	1129.1	0.0	0.0	16.3	170.2	0.0	0.0	0.0	0.0
George	3	966.1	10.3	4873.7	229.1	914.7	0.0	0.0	0.0	0.0
Golden	2	7006.2	114.6	179.3	154.3	0.0	32.2	0.0	0.0	0.0
Golden	4	3079.4	276.4	116.4	136.1	0.0	3.8	0.0	0.0	0.0
Green	2	6245.3	0.0	801.3	0.0	0.0	0.0	0.0	0.0	0.0
Green	3	4905.6	3.3	4296.8	0.0	0.0	0.0	0.0	0.0	0.0
James	2	1003.1	26.2	21.6	188.3	248.5	0.0	0.0	0.0	0.0
James	4	4214.5	29.3	50.9	1472.2	458.3	0.0	0.0	0.0	0.0
Louise	1	0.0	2.7	0.0	997.9	0.0	0.0	0.0	0.0	0.0
Louise	3	0.0	240.3	0.0	9087.3	11.7	0.0	0.0	0.0	0.0
Louise	4	0.0	189.3	0.0	1740.7	0.0	0.0	0.0	0.0	0.0
Mowich	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mowich	3	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0
Mowich	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mystic	2	3842.6	5.1	1604.9	0.0	0.0	0.0	0.0	0.0	0.0
Mystic	4	4166.7	0.0	787.0	0.0	0.0	0.0	0.0	0.0	0.0
Reflection	1	953.4	16.1	113.2	507.6	0.0	1.1	0.0	0.0	0.0
Reflection	3	2287.1	946.0	1892.0	5527.4	0.0	19.2	0.0	0.0	0.0
Reflection	4	1313.4	48.0	6735.3	1323.7	0.0	0.0	0.0	0.0	0.0
Shadow	2	6948.5	10.3	732.0	0.0	10.3	0.0	0.0	0.0	3.4
Shadow	4	4752.6	13.4	17030.9	0.0	0.0	0.0	0.0	0.0	0.0
Shriner	1	5740.7	108.0	4058.6	7762.4	0.0	0.0	0.0	0.0	0.0
Shriner	3	2818.9	13.8	5864.2	1460.9	0.0	6.8	0.0	0.0	6.8
Snow	1	1433.5	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Snow	3	9441.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 20. (continued)

Lake	Sample Period	Diaptomus	Cyclopoid	Daphnia	Holopedium	Bosmina	Polyphemus	Chydorinae	Alona	Chaoborus
Snow	4	7147.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
St. Andrews	4	91.7	0.0	8.3	0.0	0.0	0.0	0.0	0.0	0.0
Sunrise	2	329.2	13.1	1051.0	57.0	0.0	0.0	0.0	0.0	6.3
Three	4	746.6	0.0	4356.3	0.0	0.0	0.0	3.8	0.0	27.3
Tipsoo	1	46.0	0.0	0.0	27.0	27.0	0.0	0.0	0.0	0.0
Tipsoo	3	77.4	0.7	21.9	0.0	0.0	0.0	0.0	0.0	0.0
Upper Palisades	4	1086.1	0.0	0.0	48.5	0.0	0.0	4.0	0.0	0.0

Table 21. Mean densities (NO/m^3) of each zooplankton taxon in forest lakes, subalpine lakes and all lakes combined.

Taxon	Forest (N=31)*	Subalpine (N=16)*	Combined (N=47)*
Diaptomus	2560.9	2472.2	2530.7
Cyclops	84.9	9.1	59.1
Daphnia	1801.0	1695.5	1765.1
Holopedium	1174.8	784.0	1047.7
Bosmina	71.4	5.1	48.8
Polyphemus	2.0	0	1.3
Chydorinae	0.1	0.3	0.2
Alona	0.8	0.5	0.7
Conochilus	60842.8	749.1**	40385.4
Polyarthra	9959.9	280.6**	6664.8
Asplancha	212.5	71.2	164.4
K. cochlearis	6102.9	14049.4	8808.1
K. hiemalis	147.8	0	97.5
K. quadrata	3695.1	17.7	2443.2
K. taurocephalus	7860.0	0	5184.3
Kellicottia	3430.5	212.6	2335.0
Lecane	0.9	1.3	1.0
Trichotria	0.2	0	0.1
Monostyla	1.0	0.9	1.0
Chaoborus	7.7	0.8	5.3

* Number of samples

** Statistically significant ($p < 0.05$).

Table 22. Dominant rotifer taxa associated with *Diaptomus* and cladocerans.

Dominant crustacean	Dominant Rotifer Taxa	
	Subalpine	Forest
Diaptomus (with or without subdominant cladocerans)	*Kellicottia* *K. cochlearis* *Conochilus* None or very low densities	*Kellicottia* *K. quadrata* *Conochilus* *Polyarthra* None or very low densities
Cladoceran (with or without subdominant *Diaptomus*)	*K. cochlearis*	*K. cochlearis* *Conochilus* *K. taurocephalus* *Polyarthra*

K. cochlearis was the only abundant rotifer (see below), whereas in forest lakes there were 4 different dominant rotifer taxa (*K. cochlearis, K. taurocephalus, Conochilus* and *Polyarthra*).

Rotifer assemblages were divided into the following groups:

Dominant	Subdominant
Conochilus	None
Conochilus	*Kellicottia*
Conochilus	*Asplanchna*
Conochilus	*K. quadrata*
Conochilus	*K. cochlearis*
Conochilus	*Polyarthra*
Conochilus & K. quadrata or K. hiemalis	*Kellicottia*
K. quadrata	*Conochilus, Polyarthra & Kellicottia*
K. hiemalis	*Conochilus*
Polyarthra	*Conochilus* (with or without *K. quadrata)*
Kellicottia	*Conochilus* or *K. cochlearis*
Kellicottia	None
K. taurocephalus	*Conochilus (with or without Polyarthra)*
K. cochlearis	*Polyarthra* (with or without *Conochilus)*
K. cochlearis	None
Very Low Density or absent	None

Thirteen lakes were either dominated by *Conochilus* or *Conochilus* and a subdominant taxon (Table 23). Most of these lakes were located on the west side of the park and western borders of quadrants 2 and 3. The exceptions included Clover Lake (*Conochilus*) and Lake Eleanor (*Conochilus-Kellicottia*) in quadrant 2, and Shriner Lake and Three Lake (*Conochilus-K. Cochlearis*) in quadrant 3. The *K. quadrata - Conochilus, Polyarthra, and Kellicottia* assemblage was found in Lake James, which is located along the west edge of quadrant 2. The *K. hiemalis-Conochilus* assemblage was limited to

Table 23. Rotifer community types in each quadrant by sample period. A dash separates dominant and subdominant taxa, whereas equal dominance is indicated by a slash(/). Acronyms: *Conochilus* (CON), *K. cochlearis* (KEC), *K. quadrata* (KEQ), *Kellicottia* (KEL), *K. taurocephalus* (KET), *Asplanchna* (ASP), *Polyarthra* (POA), and very low density (VLD).

	Sample Period			
Quadrant Lake	1	2	3	4
1 Crescent	KEL		KEL	
1 Eunice			CON	
1 GO2			CON	
1 Golden		CON-KEQ	CON-KEQ	
1 Green		CON	CON	
1 Mowich	KEH/CON		CON/KEH-KEL	CON/KEH-KEL
2 Clover		CON		CON
2 Crystal	KEC		KEC	KEC
2 Eleanor		CON-KEL		CON
2 Ethel				CON
2 Frozen		KEL		VLD
2 James		KEQ-CON/POA-KEL		POA-CON-KEQ
2 Mystic		KEL		none
2 Shadow		KEC		KEC
2 Sunrise		KEC-POA-CON		
2 Upper Palisades				KEC
3 Bench			KET-CON-POA	KET-CON
3 Reflection	CON-ASP		POA-CON	POA-CON
3 Louise	CON		CON-POA	POA-CON
3 Shriner	CON-KEC		KEC-POA	
3 Snow	VLD		none	none
3 Three				CON-KEC
3 Tipsoo	KEC		KEC	
4 Allen	none		CON	
4 George	KEL		KEL-CON	
4 St. Andrews				KEC

Mowich Lake in quadrant 1. The *Polyarthra-Conochilus* assemblage occurred in three lakes which were located along the west edges of quadrants 2 and 3. There were 4 *Kellicottia* lakes. Three of these were subalpine lakes located in the northern portion of the park and the other (Lake George) was in quadrant 4. The *Kellicottia-Conochilus* assemblage was also found in Lake George. *K. taurocephalus* was found in abundance only in Bench Lake, whereas *K. cochlearis* was found mostly in subalpine lakes in quadrant 2. The single case of the *K. Cochlearis-Polyarthra* assemblage was found in Shriner Lake in quadrant 3. Four lakes were without rotifers or the rotifers occurred in very low densities. These included Snow Lake (all samples), September samples of Frozen Lake and Mystic Lake, and the July sample from Allen Lake.

There were very few temporal changes in the species composition of the rotifer assemblages (Table 23). The taxonomic composition in Lake James changed from *K. quadrata-Polyarthra-Kellicottia* assemblage in period 2 to the *Polyarthra-Conochilus* assemblage in period 4. Assemblages in Reflection Lake and Lake Louise changed from a dominance of *Conochilus* in period 1 to dominance of either *Polyarthra-Conochilus* or *Conochilus-Polyarthra*. Shriner Lake changed from a *Conochilus-K. cochlearis* assemblage in period 1 to a *K. cochlearis-Polyarthra* assemblage in period 3.

Seasonal changes in rotifer densities varied among the lakes. In most cases, rotifer densities increased between sample periods 1 and 3 (Table 24). Rotifer densities in some lakes continued to increase in the fall, whereas in other lakes, densities remained the same or decreased. Only *Conochilus* and *Polyarthra* had significantly higher mean densities in forest lakes than in subalpine lakes (Table 21).

Chaoborus was present in 10 samples from 8 lakes (Table 20). Five of the lakes were located on the east side of the park. *Chaoborus* occurred in 3 lakes without fish and 5 lakes with fish (Table 25). The crustacean zooplankton of 6 samples was dominated by *Daphnia*, whereas 4 samples were dominated by *Diaptomus*. Similarly, the rotifer community was dominated by *K. cochlearis* in 5 samples and by *Conochilus* in 4 (Table 25).

Table 24. Densities (NO/m^3) of rotifer taxa by sample period. Abundances in Saint Andrew Lake and Lake Tipsoo are relative abundances expressed as percentages.

Lake	Sample Period	Conochilus	Polyarthra	Asplancha	K. cochlearis	Kellicottia	K. quadrata	K. taurocephalus	K. hiemalis	Lecane	Trichotria	Monostyla
Allen	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Allen	3	37123.5	0.0	8.0	216.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0
Bench	3	14832.0	3456.8	0.0	0.0	27.4	58.3	239197.5	0.0	0.0	0.0	0.0
Bench	4	1679.5	228.9	0.0	0.0	0.0	0.0	4279.8	0.0	0.0	0.0	7.3
Clover	2	3904.5	0.0	0.0	14.3	23.1	4.4	0.0	0.0	0.0	0.0	0.0
Clover	4	41.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.3	0.0	14.2
Crescent	1	0.0	0.0	0.0	142.0	521.0	22.2	0.0	0.0	0.0	0.0	0.0
Crescent	3	0.0	0.0	0.0	0.0	524.1	140.5	0.0	0.0	0.0	0.0	0.0
Crystal	1	0.0	0.0	0.0	4942.5	366.5	0.0	0.0	0.0	0.0	0.0	0.0
Crystal	3	0.0	0.0	0.0	64513.9	12.7	0.0	0.0	0.0	0.0	0.0	0.0
Crystal	4	0.0	0.0	0.0	120563.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Eleanor	2	114290.1	0.0	0.0	0.0	32117.8	125.8	0.0	0.0	0.0	0.0	0.0
Eleanor	4	935161.0	0.0	0.0	0.0	32908.4	0.0	0.0	0.0	0.0	0.0	0.0
Ethel	3	13538.7	0.0	0.0	0.0	737.3	47.6	0.0	0.0	0.0	0.0	0.0
Eunice	3	2221.3	0.0	0.0	146.8	207.6	6.5	0.0	0.0	0.0	0.0	0.0
Frozen	2	0.0	0.0	0.0	0.0	888.9	24.7	0.0	0.0	0.0	0.0	0.0
Frozen	4	0.0	0.0	0.0	0.0	5.2	0.0	0.0	0.0	0.0	0.0	0.0
GO2	3	126030.9	0.0	0.0	1956.8	0.0	259.3	0.0	0.0	0.0	0.0	0.0
George	1	0.0	0.0	0.0	0.0	976.5	7.5	0.0	0.0	0.0	0.0	0.0
George	3	1059.7	0.0	0.0	10.3	13571.8	0.0	0.0	0.0	0.0	0.0	0.0
Golden	2	31687.2	482.1	0.0	25.0	1045.0	5773.1	0.0	0.0	0.0	0.0	0.0
Golden	4	13511.5	569.6	0.0	3.8	545.7	1694.7	0.0	0.0	0.0	0.0	0.0
Green	2	86986.0	0.0	0.0	118.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Green	4	110479.3	0.0	0.0	450.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
James	2	18990.7	15861.1	0.0	0.0	10819.4	58027.8	0.0	0.0	0.0	0.0	0.0
James	4	69444.4	124486.1	2044.8	0.0	6447.2	42438.3	0.0	0.0	0.0	0.0	0.0
Louise	1	6730.5	411.6	0.0	57.6	5.6	318.9	0.0	0.0	0.0	0.0	0.0
Louise	3	29210.8	9433.4	324.1	293.2	599.7	937.0	44.1	0.0	12.6	0.0	24.3
Louise	4	17775.7	56928.0	2631.7	0.0	102.4	2.7	97.9	0.0	9.4	0.0	0.0
Mowich	1	1206.9	0.0	0.0	0.0	109.0	0.0	0.0	1362.1	0.0	0.0	0.0
Mowich	3	3020.0	201.4	0.0	0.0	755.9	0.0	40.7	1609.0	0.0	0.0	0.0
Mowich	4	5856.6	574.5	0.0	0.0	758.6	0.0	0.0	1609.7	0.0	0.0	0.0
Mystic	2	0.0	0.0	0.0	10.3	134.3	5.1	0.0	0.0	0.0	0.0	0.0
Mystic	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reflection	1	1385.5	11.3	737.3	0.0	164.6	253.8	0.0	0.0	0.0	0.0	0.0
Reflection	3	48630.0	69807.9	775.6	0.0	1391.8	0.0	0.0	0.0	4.7	0.0	0.0
Reflection	4	47630.3	22575.5	65.2	0.0	3182.4	9.6	0.0	0.0	0.0	0.0	0.0
Shadow	2	0.0	0.0	0.0	2463.9	329.9	17.5	0.0	0.0	0.0	0.0	0.0
Shadow	4	0.0	0.0	0.0	16628.9	0.0	0.0	0.0	0.0	13.4	0.0	0.0
Shriner	1	134598.8	0.0	0.0	114459.9	41.7	0.0	0.0	0.0	0.0	0.0	0.0
Shriner	3	0.0	2795.4	0.0	67901.2	20.6	0.0	0.0	0.0	0.0	0.0	0.0
Snow	1	0.0	0.0	0.0	0.0	0.0	4.5	0.0	0.0	0.0	4.5	0.0

Table 24. (continued)

Lake	Sample Period	Conochilus	Polyarthra	Asplancha	K. cochlearis	Kellicottia	K. quadrata	K. taurocephalus	K. hiemalis	Lecane	Trichotria	Monostyla
Snow	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Snow	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
St. Andrews	4	0.0	0.0	0.0	93.3	6.7	0.0	0.0	0.0	0.0	0.0	0.0
Sunrise	2	1758.5	4488.8	1139.6	14232.4	387.8	61.7	0.0	0.0	0.0	0.0	0.0
Three	4	15267.5	931.8	0.0	3697.8	15.6	0.0	0.0	0.0	0.0	0.0	0.0
Tipsoo	1	0.7	0.0	0.0	85.2	14.1	0.0	0.0	0.0	0.0	0.0	0.0
Tipsoo	3	7.2	0.0	0.0	92.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Upper Palisades	4	0.0	0.0	0.0	1131.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 25. Study lakes from which *Chaoborus* was collected relative to the presence or absence of fish and the crustacean community types and dominant rotifer taxa.

Lake (Period sampled)	Fishless	Crustacean Community Type	Dominant Rotifer Taxon
Allen (1)	No	*Diaptomus*	None
Allen (3)	No	*Daphnia-Diaptomus*	*Conochilus*
Three (4)	No	*Daphnia-Diaptomus*	*Conochilus*
Shriner (3)	No	*Daphnia-Diaptomus-Holopedium*	*K. cochlearis*
Crystal (3)	No	*Daphnia-Diaptomus-Holopedium*	*K. cochlearis*
Crystal (4)	No	*Daphnia-Holopedium*	*K. cochlearis*
Sunrise (2)	No	*Daphnia-Diaptomus*	*K. cochlearis*
Shadow (2)	Yes	*Diaptomus-Daphnia*	*K. cochlearis*
Eunice (3)	Yes	*Diaptomus*	*Conochilus*
GO2 (3)	Yes	*Diaptomus-Holopedium*	*Conochilus*

Discussion

Several aspects of the results supported our conceptual model and general working hypotheses about expected differences between the limnological characteristics of subalpine and forest lakes, relationships between lake morphology and water quality, and relationships between water quality and the distributions of phytoplankton and zooplankton community types associated with the east-west climatic gradient in the park (Table 26). As expected, watersheds of subalpine lakes were significantly smaller in size than those of forest lakes. Although there were no statistically significant differences in lake area and depth and nutrient concentrations between the two lake types, the forest lake group included more lakes of larger surface area, deeper depth and higher nutrient concentrations than did lakes in the subalpine group. Lake morphology was related to thermal stratification and near bottom concentrations of dissolved oxygen (% saturation) and some nutrients. The highest near surface lake temperatures were associated with park location, not lake type. Although some rotifer taxa were associated with particular lake types, for the lakes as a whole, phytoplankton cell densities and the species compositions of phytoplankton and zooplankton assemblages were more closely related to park location than to lake type.

The negative correlation between watershed area and elevation was consistent with the hypothesis that there is more potential drainage area upstream from lakes at lower elevation than for those at higher elevations in mountainous terrain. Although there were no significant differences in surface area and maximum depth between forest and subalpine lakes, most of the largest and deepest lakes occurred in the forest group. The overall similarity of area and depth between the two groups of lakes was probably related to the distributions of the lakes in the main riverine drainages. Most forest lakes were confined to the upper margins of these drainages owing to the extensive erosion of the valleys by glaciers and streams. Therefore, the potential separation of differences in surface area and depth between forest and subalpine lakes were minimal in Mount Rainier National Park.

For the thirteen lakes from which Secchi disk readings were less than the maximum lake depths, Secchi disk clarity increased with increased lake depth before stabilizing at about 22 m in lakes deeper than 28 m. This nonlinear relationship between

Table 26. Comparisons of watershed area and aspect, lake elevation area and depth between forest and subalpine systems, and temperature, dissolved oxygen, water quality, nutrients and phytoplankton and zooplankton characteristics relative to vegetation type, lake morphology, park location and fish predation. Definitions: Forest (F), Subalpine (SA), * (forest lakes = subalpine lakes) and + (some taxa found mostly in forest lakes, other taxa mostly in subalpine lakes).

Comparison	Statistically significant	Trend	Veg. type	Lake morphology	Park location	Fish predation
Watershed						
Area	Yes	Yes	F>SA			
Aspect	No	No				
Elevation	Yes	Yes	F<SA			
Lake						
Area	No	Yes	F>SA			
Depth	No	Yes	F>SA			
Temperature						
Near surface	No	No				
Stratification	No	Yes		F>SA		
>15°C	No	Yes			*	
Dissolved Oxygen						
Near surface	No	No				
Near bottom	Yes	Yes		F<SA		
Water Quality & Nutrients	Yes/No[1]	Yes	F>SA	F>SA[2]		
Phytoplankton						
Density	No	Yes			*	
Structure	No	Yes			*	
Biovolume	No	Yes	F>SA			
Zooplankton						
Crustacean						
Density	No	No				
Composition	No	Yes			*	*[3]
Rotifer						
Density	No	No				
Composition	No	Yes	+		*	
Chaoborus						
Density	No	No				

1 Yes for alkalinity, calcium, magnesium, and sodium in near lake bottom samples, and magnesium in near surface lake samples.

2 Near bottom samples.

3 Mowich Lake.

Secchi disk and lake depth was expected because of the negative curvilinear relationship between Secchi disk readings and the density of the particles which scatter sunlight in the lakes and affect the readings (Fig. 14). This relationship suggests that Secchi disk clarity in deep clear lakes will be more sensitive to small changes in the densities of light scattering particles than in shallow lakes. Although particle density was not determined in this study, phytoplankton biovolume was negatively correlated with Secchi disk clarity, except for Mowich Lake, Frozen Lake and the September sample from Snow Lake (Fig. 6). Secchi readings in Mowich Lake were much greater than expected, and those in Frozen Lake and Snow Lake were less than expected based on the phytoplankton biovolumes. Similarly, phytoplankton biovolumes in the deepest lakes in which the disk could be seen on the lake bottoms were in the range observed in lakes greater than 5 m deep from which Secchi disk readings were obtained. These results suggest that while phytoplankton biovolume may have contributed to the turbidity, other sources of turbidity were necessary to generate the readings obtained in the 13 lakes. This was especially true for Frozen Lake, considering the low phytoplankton cell biovolumes in this shallow lake.

Lake temperatures increased rapidly after ice-out because of the high level of solar radiation (Larson, 1973). Most lakes reached their maximum temperatures in late August. The highest temperatures were recorded in lakes on the east side of the park where air temperatures are thought to be highest (unpublished park observations). Relatively warm July temperatures on some lakes (Crystal and Shriner) indicated that they probably iced-out earlier than most lakes. Only Frozen Lake and Snow Lake remained cold during the sampling season. Snow Lake received a considerable amount of cold surface waters from the rocky and north-facing watershed. Ice was floating on Frozen Lake during the first sampling trip (early August), and this late ice-out probably played a role in maintaining the low temperatures in this shallow lake during the second sampling trip (September).

Maximum temperature differences between surface and near bottom samples were related to lake depth. Lakes deeper than 14 m (plus Bench Lake) had the highest differences, between 10 and 15C. Only one subalpine lake (Crescent) was deep enough

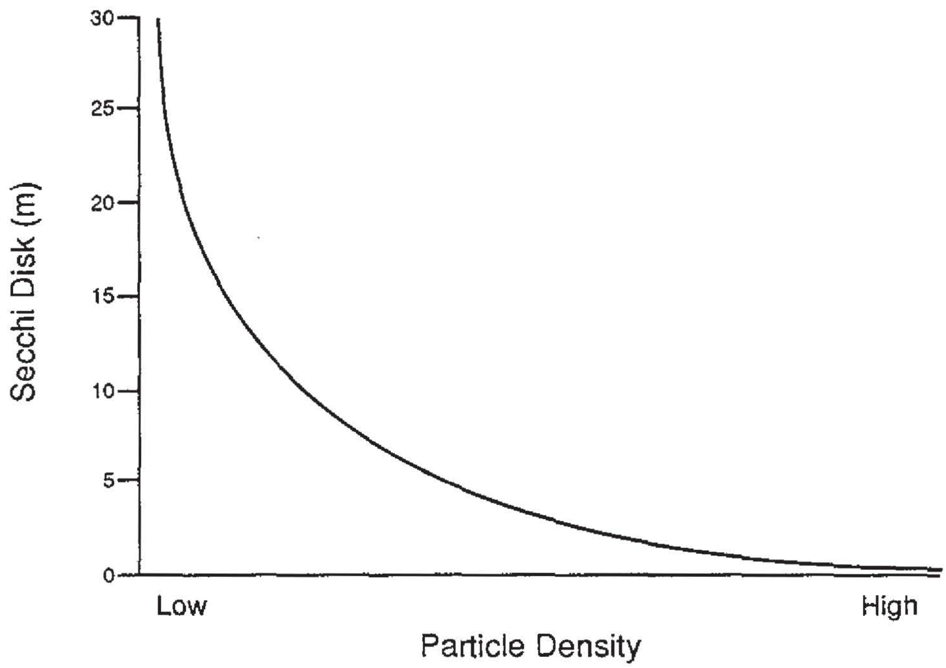


Figure 14. Hypothetical relationship between Secchi disk clarity and particle density (after Larson and Hurley, 1988).

to develop a stable thermocline. Oxygen deficits developed in the stratified lakes, and the magnitude of the deficit increased with lake depth, except in the two deepest forest lakes (Lake George and Mowich Lake) and Crescent Lake. These three lakes have large volumes and relativily small watershed/surface area ratios and are probably less productive in comparison to the other lakes.

Although near surface water quality of forest and subalpine lakes was similar, the general pattern indicated higher concentrations of dissolved substances in forest lakes. This pattern was consistent with our hypothesis that nutrient inputs increase with an increase in soil development and vegetation and a decrease in elevation. The data also indicate that morphology was an important factor affecting water quality. Those lakes which were deep enough to stratify were significantly different from unstratified lakes in near bottom dissolved oxygen, alkalinity, calcium, magnesium and sodium. Most of these stratified lakes were located in the forest vegetation type.

The hypothesis that forest lakes would be higher in phytoplankton density and biovolume was not substantiated statistically, but there was a trend for mean cell biovolume to be higher in forest lakes. Although some of the highest densities were recorded in forest lakes, more high densities were observed on the east side of the park in forest and subalpine lakes than on the west side. Phytoplankton assemblages in most lakes had similar taxonomic composition in July, but later in the summer, the assemblages developed some differences, with chrysophytes contributing in varying proportions to the communities. Chlorophytes were relatively abundant in communities of lakes on the east side of the park, especially in quadrant 3. Only Bench Lake and Mowich Lake differed substantially in taxonomic composition from the other lakes. Bench Lake was dominated by cyanobacteria, and Mowich Lake, although dominated by chrysophytes, was the only lake with an abundance of dinoflagellates.

The distribution of crustacean zooplankton was more closely related to park location than to lake type or morphology. Although *Diaptomus* was found in lakes around the park, it was most dominant in lakes in the northwest region of the park. In contrast, most lakes in the southeastern region of the park were dominated by cladocerans. In the southwest, *Diaptomus* was dominant in the lakes early in the summer and dominated by *Daphnia* later in the year. However, in the northwest region, some lakes were dominated by *Diaptomus* and others by cladocerans, although the latter were found mostly in the warmest lakes. Mowich Lake was conspicuously different from other lakes as the zooplankton assemblage did not include crustaceans. Larson (1973) found a similar result in 1967. He attributed the absence of crustaceans to predation by kokanee salmon (*O. nerka*) which had been introduced into the lake in 1961. Prior to that time, the lake was inhabited by a conspicuous unidentified red taxon, probably *Diaptomus*, often in high abundance. Since kokanee were still in the lakes in 1989, their presence probably accounted for the absence of crustacean taxa in the zooplankton assemblage of Mowich Lake. It is not known why a small bodied species of crustacean has not inhabited the lake (Brooks and Dodson, 1965). Since the taxonomic level of the crustacean zooplankton was not at the species level, it was not possible to determime shifts in species within a group which might have been associated with fish predation in the other study lakes.

Conochilus and *Polyarthra* were the only zooplankton taxa which were significantly different in abundance between forest lakes and subalpine lakes. The distribution of rotifers was associated with lake type and park location and did not change much seasonally. Although *Conochilus* was found throughout the park, it was generally dominant in the northwest corner and at low elevations. When dominant, *Kellicottia* was restricted to subalpine lakes, except Lake George, and was found in low densities. *K. cochlearis* was found primarily in the eastern portion of the park, especially the subalpine lakes in the northeast. *K. quadrata* was found in the northwest region of the park, while *Polyarthra* was found on the east side of the park. Lakes with very low or no rotifer taxa were either sampled in July (Allen) or were cold during the sampling season (Snow, Frozen and Mystic). Predation by *Diaptomus* (Zaret, 1980) may have been involved in these cases, as it was the only crustacean taxon present.

Chaoborus was present in lakes with and without fish. Since this taxon is highly vulnerable to predation by fish (Stenson,1978), its occurrence in lakes with fish suggests that the fish densities were low.

A limited amount of data from past studies were available from some of the same lakes examined in the present work (Table 27). Patterns in these data were similar to the results of the 1988 study, except that: 1) the Secchi disk readings were deeper in

Table 27. Comparative limnological data from studies of lakes in Mount Rainier National Park. Data from the study in 1988 are in parentheses.

Lake	Sample Period: July	August	September
Mowich Lake 1967			
(Larson 1973)			
Secchi disk (m)	14.2-25.2 (17.0)	26.9-29.1 (21.5)	27.1-24.8 (21.9)
Temp °C			
2-m	4.9-10.8 (6.8)	12.1-16.5 (14.2)	15.3-12.4 (13.2)
50-m	4.1-4.2 (4.0)	4.2-4.4 (4.5)	4.3-4.4 (4.5)
Dissolved oxgen (% sat.)			
2-m	100 (97)	102 (97)	100 (102)
50-m	60 (59-60)	61 (60-62)	74 (58-73)
Zooplankton types			
Crustacean*	None (None)	None (None)	None (None)
Rotifer**	KEL-KEH (KEH-CON)	KEL-KEH-CON (CON-KEH)	CON-KEH/KEL (CON-KEH)
Shadow Lake 1970-71			
(Hall 1973)			
Secchi disk (m)	Bottom (-)	Bottom (Bottom)	Bottom (Bottom)
Temp °C			
1-m 1970	~10 (-)	~16 (16.0)	~12 (14.0)
1-m 1971	1~6	8~20	~10
Zooplankton types			
Crustacean	DIA (-)	DAP/DIA (DIA-DAP)	DIA (DAP-DIA)
Rotifer	*Keratella**** (-)	*Keratella* (KEC)	*Keratella* (KEC)
Chaoborus	Present (-)	None (None)	Present (present)
Reflection Lake 1984-85			
(Funk et al., 1985)			
Secchi disk - 1984	- (7.5)	- (9.3)	9.5 (7.8)
Secchi disk - 1985	5.3****	-	-
Temp °C			
1-m 1984	- (9.0)	- (16.0)	7.5-10.3 (11.0)
1-m 1985	-	15.0	-
Zooplankton types			
Crustacean	- (DIA-BOS/HOL)	- (HOL-DAP/DIA)	HOL-BOS-DIA (DAP-HOL)
Rotifer	- (CON)	- (POA-CON)	KEL (CON-POA)

* *Eucyclops agilis* collected in some deep lake samples in 1967.
** KEH = *K. hiemalis*.
*** Probably *K. cochlearis* (KEC).
**** June 27.

August and September in 1967 in Mowich Lake; and 2) *Kellicottia* was abundant in Mowich Lake in 1967 (Larson, 1973) and Reflection lake (Funk et al, 1985) in 1984-5, but not in 1988.

In summary, the results of this study showed some trends which were consistent with our general hypotheses that the forest lake group should include more lakes with larger watersheds, larger surface areas, deeper maximum depths, and higher concentrations of nutrients than subalpine lakes. Deep lakes became thermally stratified, and this led to significant changes in some water quality variables in near lake bottom samples. Most of these stratified lakes were in the forest vegetation type. But the study also indicated that park location was important relative to near surface water temperatures and taxonomic composition of the phytoplankton and zooplankton. Whether the associations among phytoplankton-rotifer-crustacean assemblages were the results of their interspecific interactions, variations in habitat around the park, or both, is still unknown.

Recommendations

Two lake studies were initiated in 1988. One was the lake survey and the other was an intensive and extensive evaluation of the limnological characteristics of Mowich Lake. The objectives of the latter were to assess the characteristics of the lake relative to those observed by Larson (1973) in 1967 and to contribute selected data to the 1988 lake survey. The majority of the Mowich Lake data will be presented in a separate report.

The 1988 lake survey addressed several objectives which focused on assessing: 1) differences between forest and subalpine lakes; 2) effects of the west-east climate gradient on the limnological characteristics of the lakes; 3) and impacts of fish predation on the zooplankton communities. An underlying objective was to develop a baseline of data on the lakes which could be used to compare lake conditions in the future. Although most of these objectives were fulfilled, one field season did not provide much informtion about annual changes in the lakes. For this reason, the park, under the supervision of Barbara Samora, began a 5 year study to assess annual variation in selected lakes sampled in 1988 (Table 28). Multiple samples of each lake were collected each summer which included Secchi disk readings, vertical water column profiles of temperature, pH, and conductivity, alkalinity, dissolved oxygen and nutrients at 1-m and 1-m off the lake bottoms, chlorophyll at 1-m and at the Secchi depth, phytoplankton at 1-m and vertical net tows for zooplankton. Based on the results, evaluations, and interpretations in this report, the following recommendations are suggested for the 1992 and 1993 field seasons. Continue the sampling program as designed sampling each lake twice each season, with the exception of Mowich Lake. One sample should be taken shortly after ice-out and the other in late August. Based on this sampling schedule, seasonal and annual variations can be evaluated, especially for the zooplankton communities. Mowich Lake, however, should be sampled four times - July, mid-August, mid-September, and October. This schedule permits assessment of changing properties of the lake, especially Secchi disk readings and the rotifer community. Add Eunice Lake (subalpine) to the Mowich-Green set (forest), Lake Eleanor (forest) to the Clover-Upper Palisades set (subalpine), Shriner Lake (forest) to the Reflection-Louise-Bench-Snow set (forest to a transition between forest-subalpine), and Lake George (forest) as a representative lake in quadrant 4. These additions permit comparisons of physical, chemical, and biological characteristics between forest and subalpine lakes and among and within the sets. Collect chlorophyll samples at 1-m below surface and then at 1 or 2-m depth intervals depending on the depth of each lake. In Mowich Lake, sampling should follow the schedule outlined by Larson (1973). These data will be used to compare the concentrations and vertical distribution of chlorophyll among the lakes. Conduct a special comparative study of the effects of lake depth on temperature and dissolved oxygen (percent saturation) near the bottoms of Mowich, George, Green, Crescent, James, Ethel, Louise, Bench, Reflection and several shallow lakes in late August 1993 (see Figs. 11 and 12). Owing to their accessability and park locations, record temperature profiles in Lake Tipsoo and Shadow Lake during late August in 1992 and 1993 for comparative purposes.

In 1992, a proposal should be submitted to appropriate funding sources to process the phytoplankton and zooplankton samples, plus any additional samples such as amphibians and benthic macroinvertebrates collected between 1989 and 1993. Once the

Table 28. Lakes selected for annual monitoring between 1989 and 1993 in Mount Rainier National Park. Those lakes followed by an asterisk are suggested additions for 1992 and 1993.

Quadrant	Lake	Vegetation Type	Comment
1	Green	Forest	Lake of lowest elevation
	Mowich	Forest	Largest/deepest, rotifers only, data base available
	Eunice*	Subalpine	Compare with Mowich and Green
2	Upper Palisades	Subalpine	Precipitous watershed
	Clover	Subalpine	Parkland
	Eleanor*	Forest	Compare with Clover and Upper Palisades
3	Reflection	Forest	Mud-flow lake, high fish density, data base available
	Louise	Forest	*Holopedium* lake
	Snow	Forest	*Diaptomus* lake, no rotifers
	Bench	Forest	Seepage lake, *K. taurocephalus* lake
	Shriner*	Forest	Shallow, warm early in season
4	George*	Forest	Second largest/deepest

samples have been processed, the physical, chemical and biological data would be used to assess annual variability of the lakes relative to the 1988 data set. This evaluation would provide a data base to design a long-term lake monitoring program and additional studies. If funding does not become available in FY 1993, then the long-term monitoring program and special studies would be developed based on the report from the 1988 lake survey and all physical, chemical and chlorophyll data collected through 1993.

Lake surface areas, elevations and watershed areas should be determined using the park GIS. These data should be used to further evaluate the hypothesis that subalpine systems have fewer lakes with large watersheds and large surface areas than lakes in forest systems. This analysis would determine if the 1988 study was biased relative to these variables.

The impacts of fish predation on zooplankton could not be thoroughly evaluated in the study. Additional work will be required to determine the species composition of the zooplankton and their body sizes relative to the presence or absence of fish. This work will require additional funding. The final report from studies of the impact of fish on high mountain lake communities (benthic invertebrates, zooplankton, and amphibians) at North Cascades National Park Complex should be used to address this important issue at Mount Rainier National Park. The report will be available in the fall of 1992, and it should provide direction for assessing the impacts of stocked fish in MORA lakes. The park is encouraged to seek advice from a panel of professional fisheries biologists about methods which could be used to remove fish from park lakes (and streams).

The present study focused on a small portion of the hundreds of lakes and ponds in the park. The park is encouraged to continue even one-time samplings of the remaining bodies of water. These data, when compared to results from the ongoing studies at selected lakes, will increase the knowledge of the diversity of physical, chemical and biological properties of MORA lakes. Special attention should be given to the presence of benthic macro-invertebrates and amphibians, especially in relation to the presence and absence of fish.

Acknowledgments

We appreciated the support of Bob Dunnagan, Shirley Clark and Jim Larson of the National Park Service. We thank Michael Hurley, Derek Gale and Betsy Dix for their assistance in the field and Catherine Nisselson and Gregg Lomnicky for reviewing the manuscript. This research was supported in part by the Water Resources Division, National Park Service. Rebecca Chladek typed the manuscript.

Literature Cited

Aber, J.D. and J.M. Melillo. 1991. Terrestrial ecosystems. Saunders College Publishing. 429p.

Anderson, R. S. 1974. Crustacean plankton communities of 340 lakes and ponds in and near the national parks of the Canadian Rocky Mountains. J. Fis. Res. Bd. Can., 31:855 - 869.

Arvola, L. 1986. Spring phytoplankton of 54 small lakes in southern Finland. Hydrobiol. 137:125 - 134.

Bahls, P. F. 1990. Ecological implications of trout introductions to lakes of the Selway Bitterroot Wilderness, Idaho. Masters Thesis, Department of Fisheries and Wildlife, Oregon State University, 85p.

Brooks, J. L. and S. I. Dodson. 1965. Predation, body size and composition of plankton. Science, 150:28 - 35.

Earle, J. C., H.C. Duthie and D.A. Scrutin. 1986. Analysis of the phytoplankton composition of 95 Labrador lakes with special reference to natural and anthropogenic acidification. Can. J. Fish. Aquat. Sci. 43:1804 - 1811.

Fiske, R.S., C.A. Hopson and A.C. Waters. 1963. Geology of Mount Rainier National Park, Washington. USGS Professional Paper 444, 93p.

Franklin, J.F.,W.H. Moir, M.A. Hemstrom, S.E. Greene, and B.G. Smith. 1988. The forest communities of Mount Rainier National Park. National Park Service, Scientific Monograph Series No. 19, 194p.

Funk, W. H., B.C. Moore, D. L. Johnstone, J. P. Porter, S.T.J. Juul, C.K. Trout, and B. L. Becker. 1985. Baseline study of Reflection Lakes, Mount Rainier National Park. State of Washington Water Research Center, Washington State University and the University of Washington, Report 66, 58p.

Gran, G. 1952. Determination of the equivalence point in poteniometric titrations. Part II. Analyst. 77:661-671.

Hall, T.J. 1973. A limnological study of Shadow Lake, a subalpine lake at Mount Rainier National Park. Masters thesis, Central Washington State College, 80p.

Hill, M.O. and H.G. Gauch. 1980. Detrended correspondence analysis: an improved ordination technique. Vegetatio. 92:47 - 58.

Kerfoot, W. C. 1987. Cascading effects and indirect pathways. IN [Ed. W. C. Kerfoot and A. Sih] Predation, University Press of New England, p. 57 - 70.

Larson, G. L. 1973. A limnological study of a high mountain lake in Mount Rainier National Park, Washington State, USA. Arch. Hydrobiol. 72:10 - 48.

Larson, G.L. and M.D. Hurley. 1988. Interpreting variations in Secchi disk transparencies of Crater Lake, a deep caldera lake (Oregon). IN [Ed. I. G. Poppoff, C. R. Goldman, S. L. Loeb and L. B. Leopold] Proceedings of the International Mountain Watershed Symposium, Subalpine Processes and Water Quality, p. 544 -560.

Larson, G. L.,E. Karnaugh-Thomas, C. Hawkins and C. David McIntire. 1991. Limnological characteristics of isolated and connected high mountain lakes in Olympic National Park. National Park Service, Cooperative Studies Unit, Oregon State University, Report 91-4, 53p.

Lund, J.W.G., G.M. Kipling and E.D. LeCren. 1958. The inverted microscope method of estimating algal numbers and the statistical basis of estimates made by counting. Hydrobiol. 11:143 - 170.

Patalas, K. 1971. Crustacean zooplankton communities in forty- five lakes in the Experimental Lakes Area, Northern Ontario. J. Fish. Res. Bd. Can. 28:231 - 244.

Pechlaner, R. 1966. Die Finstertaler Seen (Kutai, Osterreich). I. Morphometrie, hydrographie, limnophysik, and limnochemie. Arch. Hydrobiol. 62:165 - 230.

Pechlaner, R. 1967. Die Finstertaler Seen (Kutai, Osterreich). II. Das phytoplankton. Arch. Hydrobiol. 63:145 - 193.

Pechlaner, R. 1971. Factors that control the production rate and biomass of phytoplankton in high-mountain lakes. Mitt. Internat. Verein. Limnol. 19:125 - 145.

Pennak, R. S. 1955. Comparative limnology of eight Colorado mountain lakes. Univ. of Colorado Studies, Series in Biology 2: 75p.

Pinel-Alloil, B., G. Methot, G. Verrault and Y. Vigneault. 1990. Phytoplankton in Quebec lakes: variation with lake morphology, and with natural and anthropogenic acidification. Can. J. Fish. Aquat. Sci. 47:1047 - 1057.

Richardson, D. 1972. Effects of snow and ice on runoff at Mount Rainier, Washington. Internat. Assoc. of Hydrology, Sci. Pub. 107 (2):1172 - 1185.

Stenson, J. A. E. 1978. Differential predation by fish on two species of Chaoborus (Diptera, Chironomidae). Oikos 31:98 - 101.

Stoddard, J. L. 1987. Microcrustacean communities of high- elevation lakes in the Sierra Nevada, California. J. Plankton Res. 9(4):631 - 650.

Stout, V. M. 1969. Lakes in the mountain region of Canterbury, New Zealand. Verh. Internat. Verein. Limnol. 17:404 - 413.

Vass, K. K. , A. Wanganeo, H. S. Raina, D. P. Zutshi and R. Wanganeo. 1989. Summer limnology and fisheries of high mountain lakes of Kashmir Himalayas. Arch. Hydrobiol. 114(4):603 - 619.

Warren, C. E. 1979. Toward classification and rationale for watershed management and stream protection. U.S. Environmental Protection Agency, Ecol. Res. Ser. EPA-600/3- 79-059.

Wetzel, R.G. 1975. Limnology. W.B. Saunders Comp. 743p.

Wolcott, E.E. 1961. Lakes of Washington. Volume 1. Western Washington. Division of Water Resources, Water Supply Bull. 14, 619p.

Zaret, T. M. 1980. Predation and freshwater communities. Yale University Press, New Haven.

APPENDIX 1

Secchi disk readings by sample period.

Lake	Sample Period	Secchi disk (m)
Bench	4	6.8
Crescent	1	21.6
Crescent	3	22.2
Ethel	3	14.5
Frozen	2	5.9
Frozen	4	5.4
George	3	18.2
Golden	2	10.0
Golden	3	10.4
Green	2	16.0
Green	3	19.5
James	2	12.2
James	4	12.5
Louise	1	11.5
Louise	3	13.8
Louise	4	11.3
Mowich	1	17.0
Mowich	3	21.5
Mowich	4	21.9
Reflection	1	7.5
Reflection	3	9.3
Reflection	4	7.8
Snow	4	8.8
Upper Palisades	2	10.6

Appendix 2. Chemical properties (water quality and nutrient concentrations) of the study lakes by sample period.

Lake	Date	Sample Period	Temperature (°C) 1-m	Temperature (°C) Bottom	Dissolved Oxygen (mg/l) 1-m	Dissolved Oxygen (mg/l) Bottom
Allen	7-18	1	12.5	8.0	9.8	11.1
Allen	8-21	3	15.0	14.0	8.450	8.560
Bench	8-23	2	19.5	10.0	.	.
Bench	9-13	4	16.1	14.5	7.7	4.8
Clover	8-10	2	15.0	9.0	8.6	8.420
Clover	9-13	4	14.5	13.5	8.060	8.050
Crescent	7-31	1	14.0	4.5	9.0	8.250
Crescent	8-31	3	14.0	5.5	8.950	9.190
Crystal	7-24	1	17.0	13.0	8.6	10.150
Crystal	8-16	3	17.0	17.0	7.8	7.9
Crystal	9-21	4	11.5	10.5	8.140	8.260
Eleanor	8-8	2	17.0	10.0	9.050	8.090
Eleanor	9-11	4	15.0	13.0	8.240	9.490
Ethel	8-16	3	13.7	6.0	8.5	1.8
Eunice	8-30	3	15.0	12.0	7.9	9.4
Frozen	8-9	2	9.0	7.0	9.150	9.1
Frozen	9-12	4	9.0	8.0	8.940	9.0
George	7-19	1	13.0	4.0	9.750	4.3
George	8-23	3	15.0	4.0	8.730	5.840
GO1	8-28	3	18.0	17.5	7.18	.
GO2	8-28	3	17.0	15.0	.	7.81
Golden	8-2	2	18.0	4.0	8.050	0.0
Golden	8-28	3	17.0	4.0	8.150	0.0
Green	8-1	2	11.5	5.0	10.650	3.250
Green	8-31	3	14.0	5.0	9.520	1.430
James	8-7	2	13.5	4.0	9.4	1.150
James	9-10	4	13.5	4.0	8.860	0.640
Louise	7-14	1	8.0	5.0	10.550	5.550
Louise	8-23	3	17.5	7.5	8.570	6.350
Louise	9-20	4	12.0	8.0	8.820	3.040
Mowich	7-14	1	6.8	4.0	9.8	5.4
Mowich	8-24	3	14.2	4.5	8.4	5.7
Mowich	9-13	4	13.2	4.5	8.8	6.060
Mystic	8-14	2	14.0	14.0	8.580	8.630
Mystic	9-18	4	9.0	9.0	9.120	9.140
Reflection	7-17	1	9.0	6.0	9.850	8.750
Reflection	8-23	3	16.0	11.0	8.070	8.150
Reflection	9-20	4	11.0	11.0	8.210	8.170
Shadow	8-9	2	16.0	15.0	7.760	7.810
Shadow	9-12	4	14.0	12.0	8.0	7.960
Shriner	7-26	1	20.0	19.5	6.650	7.650
Shriner	8-17	3	16.0	15.5	7.7	7.740
Snow	7-15	1	5.0	4.0	10.9	11.2
Snow	8-24	3	11.0	8.0	10.0	10.240
Snow	9-19	4	8.0	7.0	9.910	9.950
St. Andrews	9-12	4	14.0	.	8.0	.
Sunrise	8-24	2	17.5	16.5	7.5	7.0
Sunrise	9-7	4	17.2	16.9	7.3	7.1
Three	8-9	2	17.0	16.5	.	.
Three	9-8	4	18.8	18.0	7.5	7.6
Tipsoo	7-25	1	15.0	.	8.4	.
Tipsoo	8-16	3	14.5	.	8.210	.
Upper Palisades	9-7	4	14.0	14.0	9.5	8.0
Uppal Palisades	8-3	2	13.3	8.1	7.9	9.8

Appendix 2. (continued)

Lake	pH		Alkalinity (mg/l)		Conductivity (μmhos/cm)	
	1-m	Bottom	1-m	Bottom	1-m	Bottom
Allen	7.270	6.610	22.908	24.342	56.120	63.780
Allen	7.540	7.500	22.925	22.103	59.740	63.940
Bench	.	.	.	2.339	4.300	5.970
Bench	6.350	5.630	12.0	1.800	.	.
Clover	.	.	.	.	12.920	14.250
Clover	7.210	7.0	5.543	6.037	.	.
Crescent	6.920	6.440	3.508	2.585	6.610	8.030
Crescent	6.840	6.270	2.172	1.724	.	.
Crystal	7.180	6.970	9.865	7.563	14.980	15.610
Crystal	7.250	7.230	6.874	8.508	14.850	14.690
Crystal	7.210	7.230	5.174	6.963	.	.
Eleanor	.	.	.	.	20.200	21.610
Eleanor	7.320	6.950	7.027	7.631	.	.
Ethel	7.460	6.370	7.800	10.0	23.300	30.400
Eunice	7.010	6.450	2.300	2.400	.	.
Frozen	.	.	.	.	4.010	4.160
Frozen	6.650	6.560	1.281	1.322	.	.
George	7.160	6.400	11.378	11.071	21.510	25.950
George	7.210	6.560	8.944	10.605	21.940	26.230
GO1	6.150	.	.	.	6.00	.
GO2	6.040	.	0.604	.	5.67	.
Golden	6.190	6.660	3.133	40.386	9.360	80.260
Golden	6.770	6.910	2.865	59.760	.	.
Green	6.940	6.430	9.518	12.474	19.710	34.050
Green	7.120	6.320	12.605	9.044	.	.
James	.	.	.	.	10.210	17.020
James	6.890	6.100	4.292	7.530	.	.
Louise	6.660	5.660	1.743	2.726	5.370	7.360
Louise	6.830	6.040	1.743	2.726	7.250	7.170
Louise	6.760	6.780	1.919	2.344	.	.
Mowich	6.170	6.250	4.250	5.800	12.350	15.470
Mowich	6.890	.	4.990	6.100	.	.
Mowich	7.0	.	.	.	11.950	15.020
Mystic	.	.	.	.	14.270	14.300
Mystic	7.300	7.200	7.442	7.495	.	.
Reflection	6.830	6.160	5.260	3.683	6.380	10.100
Reflection	6.860	6.230	3.173	2.966	8.270	9.880
Reflection	7.140	6.900	3.582	3.676	.	.
Shadow	.	.	.	.	7.410	7.940
Shadow	6.840	6.810	2.875	2.833	.	.
Shriner	7.130	7.130	8.556	5.723	17.020	17.560
Shriner	7.220	7.190	5.501	6.773	18.210	18.210
Snow	6.950	6.900	2.664	2.175	8.680	8.100
Snow	7.130	7.070	4.084	3.378	10.340	11.200
Snow	7.310	7.250	4.652	4.649	.	.
St. Andrews	6.510	.	0.500	.	.	.
Sunrise	.	.	2.200	1.800	.	.
Sunrise	6.890	6.830	3.600	2.100	.	15.100
Three	.	.	.	.	.	.
Three	7.320	7.260	6.200	6.0	25.900	26.200
Tipsoo	7.450	.	14.293	.	24.970	.
Tipsoo	7.800	.	14.701	.	.	.
Upper Palisades	.	.	5.0	4.500	.	.
Upper Palisades	7.250	6.860	4.100	4.400	23.400	25.0

Appendix 2. (continued)

Lake	Orthophosphate-P (mg/l) 1-m	Orthophosphate-P (mg/l) Bottom	Total Phosphorus (mg/l) 1-m	Total Phosphorus (mg/l) Bottom
Allen	0.0	0.0	.	.
Allen	0.006	0.006	0.047	0.014
Bench	0.003	0.003	0.012	0.015
Bench	0.002	0.001	0.004	0.005
Clover	0.006	0.006	0.003	0.007
Clover	.	.	.	.
Crescent	0.008	0.008	0.003	0.004
Crescent	.	.	.	.
Crystal	0.003	0.005	0.014	0.019
Crystal	0.003	0.003	0.003	0.005
Crystal	.	.	.	.
Eleanor	0.005	0.005	0.010	0.012
Eleanor	.	.	.	.
Ethel	0.011	0.012	0.019	0.022
Eunice	0.006	0.007	0.0	0.0
Frozen	0.006	0.006	0.003	0.009
Frozen	.	.	.	.
George	0.0	0.0	.	.
George	0.003	0.003	0.013	0.015
GO1	.	.	0.012	.
GO2	.	.	0.005	.
Golden	0.009	0.017	0.014	0.060
Golden	.	.	.	.
Green	0.008	0.008	0.005	0.008
Green	.	.	.	.
James	0.001	0.003	0.014	0.023
James	.	.	.	.
Louise	0.0	0.0	.	.
Louise	0.002	0.003	0.008	0.015
Louise	.	.	.	.
Mowich	0.005	0.008	0.0	0.0
Mowich	0.006	0.006	0.006	0.006
Mowich	0.002	0.001	0.011	0.011
Mystic	0.006	0.008	0.017	0.017
Mystic	.	.	.	.
Reflection	0.0	0.0	.	.
Reflection	0.003	0.004	0.013	0.010
Reflection	.	.	.	.
Shadow	0.006	0.006	0.003	0.010
Shadow	.	.	.	.
Shriner	0.004	0.004	0.012	0.013
Shriner	0.003	0.003	0.010	0.009
Snow	0.0	0.0	.	.
Snow	0.004	0.003	0.009	0.013
Snow	.	.	.	.
St. Andrews	.	.	0.007	.
Sunrise	.	.	.	.
Sunrise	0.002	0.004	0.006	0.007
Three	.	.	.	.
Three	0.005	0.006	0.007	0.009
Tipsoo	0.003	.	0.012	.
Tipsoo	.	.	.	.
Upper Palisades	.	.	.	.
Upper Palisades	0.006	0.008	0.017	0.014

Appendix 2. (continued)

Lake	Kjeldahl-Nitrogen (mg/l) 1-m	Kjeldahl-Nitrogen (mg/l) Bottom	Nitrate-N (mg/l) 1-m	Nitrate-N (mg/l) Bottom	Ammonia-N (mg/l) 1-m	Ammonia-N (mg/l) Bottom
Allen	0.022	0.021	0.005	0.006	0.001	0.003
Allen	0.042	0.040	0.0	0.001	0.003	0.007
Bench	0.081	0.069	0.001	0.0	0.001	0.001
Bench	0.094	0.096	0.001	0.001	0.007	0.008
Clover	0.039	0.041	0.0	0.0	0.002	0.003
Clover	.	.	.	.	.	.
Crescent	0.024	0.033	0.012	0.011	0.002	0.019
Crescent	.	.	.	.	.	.
Crystal	0.062	0.046	0.001	0.0	0.001	0.001
Crystal	0.114	0.045	0.001	0.026	0.005	0.004
Crystal	.	.	.	.	.	.
Eleanor	0.105	0.051	0.001	0.0	0.0	0.001
Eleanor	.	.	.	.	.	.
Ethel	0.027	0.060	0.001	0.002	0.009	0.023
Eunice	0.043	0.039	0.001	0.001	0.005	0.007
Frozen	0.017	0.011	0.005	0.005	0.0	0.0
Frozen	.	.	.	.	.	.
George	0.033	0.041	0.008	0.033	0.002	0.009
George	0.038	0.023	0.001	0.016	0.004	0.003
GO1	0.181	.	.001	.	0.010	.
GO2	0.097	0.087	.001	0.0	0.007	0.004
Golden	0.040	1.925	0.001	0.001	0.002	2.039
Golden	.	.	.	.	.	.
Green	0.013	0.098	0.010	0.077	0.006	0.062
Green	.	.	.	.	.	.
James	0.025	0.078	0.001	0.076	0.0	0.038
James	.	.	.	.	.	.
Louise	0.038	0.021	0.0	0.008	0.004	0.013
Louise	0.024	0.035	0.0	0.0	0.002	0.002
Louise	.	.	.	.	.	.
Mowich	0.027	0.028	0.0	0.011	0.004	0.015
Mowich	0.048	0.035	0.0	0.003	0.003	0.002
Mowich	0.056	0.036	0.0	0.0	0.005	0.001
Mystic	0.028	0.022	0.0	0.0	0.0	0.0
Mystic	.	.	.	.	.	.
Reflection	0.034	0.031	0.0	0.0	0.005	0.001
Reflection	0.037	0.043	0.0	0.0	0.002	0.002
Reflection	.	.	.	.	.	.
Shadow	0.045	0.042	0.0	0.0	0.0	0.001
Shadow	.	.	.	.	.	.
Shriner	0.066	0.059	0.0	0.0	0.001	0.001
Shriner	0.100	0.095	0.044	0.001	0.002	0.002
Snow	0.038	0.021	0.019	0.016	0.005	0.003
Snow	0.012	0.010	0.004	0.008	0.0	0.001
Snow	.	.	.	.	.	.
St. Andrews	0.082	.	0.002	.	0.004	.
Sunrise	.	.	.	.	.	.
Sunrise	0.091	0.100	0.001	0.001	0.004	0.006
Three	.	.	.	.	.	.
Three	0.120	0.099	0.001	0.001	0.008	0.010
Tipsoo	0.070	.	0.0	.	0.0	.
Tipsoo	.	.	.	.	.	.
Upper Palisades	.	.	.	.	.	.
Upper Palisades	0.032	0.021	0.0	0.0	0.006	0.0

Appendix 3. Cation and silica concentrations in the study lakes by sample period.

Lake	Sample Period	Calcium (mg/l) 1-m	Calcium (mg/l) Bottom	Magnesium (mg/l) 1-m	Magnesium (mg/l) Bottom	Sodium (mg/l) 1-m	Sodium (mg/l) Bottom	Potassium (mg/l) 1-m	Potassium (mg/l) Bottom	Silica (mg/l) 1-m	Silica (mg/l) Bottom
Allen	1	8.819	9.797	0.862	0.964	1.108	1.190	.	.	2.982	2.763
Allen	3	8.972	8.913	0.910	0.910	1.164	1.163	.	.	2.151	2.177
Bench	2	0.309	0.437	0.077	0.101	0.363	0.399	.	.	0.152	0.168
Bench	4	0.320	0.560	0.088	0.137	0.400	0.490	0.068	0.110	0.618	0.362
Clover	2	1.780	1.992	0.157	0.155	0.562	0.539	.	.	2.087	1.372
Clover	4	1.663	1.707	0.138	0.144	0.554	0.556	.	.	1.301	1.322
Crescent	1	0.576	0.655	0.074	0.081	0.540	0.567	.	.	0.733	0.713
Crescent	3	0.523	0.586	0.058	0.066	0.524	0.547	.	.	0.377	0.417
Crystal	1	2.159	2.201	0.130	0.137	0.550	0.510	.	.	1.763	1.735
Crystal	3	2.112	2.113	0.128	0.127	0.513	0.511	.	.	1.190	1.304
Crystal	4	2.114	2.092	0.129	0.133	0.511	0.511	.	.	1.121	1.063
Eleanor	2	2.402	2.581	0.440	0.476	0.828	0.865	.	.	2.345	1.817
Eleanor	4	2.388	2.411	0.443	0.458	0.814	0.841	.	.	1.854	1.203
Ethel	3	1.820	2.446	0.306	0.361	1.120	1.350	0.460	0.520	5.362	5.682
Eunice	3	0.590	0.610	0.071	0.069	0.540	0.540	0.080	0.080	0.599	0.557
Frozen	2	0.197	0.203	0.043	0.034	0.425	0.414	.	.	0.465	0.685
Frozen	4	0.176	0.200	0.027	0.037	0.449	0.450	.	.	0.289	0.301
George	1	2.925	3.607	0.268	0.340	0.747	0.875	.	.	1.802	1.957
George	3	2.936	3.447	0.297	0.326	0.748	0.842	.	.	1.337	1.613
GO1	4	0.169	0.169	0.067	.	0.613	.	.	.	0.106	.
GO2	4	0.239	0.239	0.079	0.080	0.481	0.484	.	.	0.077	0.089
Golden	2	0.856	8.711	0.191	0.816	0.818	2.215	.	.	1.077	6.976
Golden	3	0.733	7.954	0.161	0.759	0.774	2.174	.	.	0.589	6.447
Green	2	2.828	4.590	0.177	0.300	0.793	1.243	.	.	1.801	3.197
Green	3	3.180	4.600	0.185	0.291	0.872	1.229	.	.	1.691	2.569
James	2	1.068	1.867	0.142	0.245	0.709	0.983	.	.	1.738	2.513
James	4	1.170	1.799	0.141	0.225	0.761	0.933	.	.	1.234	1.973
Louise	1	0.480	0.621	0.080	0.105	0.403	0.528	.	.	0.635	0.817
Louise	3	0.621	0.581	0.080	0.093	0.498	0.521	.	.	0.417	0.253
Louise	4	0.635	0.623	0.087	0.108	0.490	0.555	.	.	0.453	0.339
Mowich	1	1.492	1.972	0.168	0.222	0.525	0.652	.	.	0.151	0.178
Mowich	3	1.475	1.831	0.170	0.210	0.576	0.643	.	.	0.144	0.159
Mowich	4	1.483	1.814	0.197	0.221	0.581	0.655	.	.	0.153	0.155
Mystic	2	1.243	1.249	0.155	0.161	1.146	1.146	.	.	3.174	3.148
Mystic	4	1.379	1.362	0.183	0.178	1.366	1.349	.	.	4.021	4.423

Lake	Sample Period	Calcium (mg/l)		Magnesium (mg/l)		Sodium (mg/l)		Potassium (mg/l)		Silica (mg/l)	
		1-m	Bottom	1-m	Bottom	1-m	Bottom	1-m	Bottom	1-m	Bottom
Reflection	1	0.570	0.833	0.108	0.177	0.533	0.745	.	.	1.015	1.405
Reflection	3	0.708	0.784	0.145	0.171	0.636	0.674	.	.	0.570	0.446
Reflection	4	0.795	0.806	0.168	0.176	0.705	0.692	.	.	0.545	0.692
Shadow	2	0.556	0.703	0.117	0.120	0.635	0.693	.	.	1.405	1.630
Shadow	4	0.468	0.501	0.108	0.122	0.679	0.692	.	.	0.648	0.703
Shriner	1	2.217	2.210	0.268	0.274	0.677	0.665	.	.	1.737	1.765
Snow	3	1.194	1.222	0.097	0.104	0.641	0.646	.	.	0.933	0.780
Snow	4	1.368	1.366	0.105	0.108	0.720	0.717	.	.	1.250	1.345
St. Andrews	4	0.200	.	0.056	.	0.400	.	0.100	.	.	0.752.
Sunrise	2	.	.	.	.	.	.	.	.	.	.
Sunrise	4	0.630	0.630	0.073	0.069	0.380	0.386	0.110	0.110	0.699	0.699
Three	4	2.230	2.210	0.273	0.269	0.850	0.820	0.110	0.090	1.301	1.289
Tipsoo	1	4.079	.	0.187	.	0.688	.	.	.	1.924	.
Tipsoo	3	4.591	.	0.221	.	0.739	.	.	.	1.120	.
Upper Palisades	2	1.410	1.380	0.210	0.206	0.900	0.810	0.170	0.150	3.363	2.987

APPENDIX 4

List of phytoplankton taxa collected from the lakes of Mount Rainier National Park in 1988. Acronyms: chlorophyte (CHL), chrysophyte (CHR), cryptophyte (CRY), diatom (BAC), cyanobacteria (CYN) and unknown (UNK).

Code No.	Group	Taxon
100	CHL	*Chlamydomonas* sp. 1
101	CHL	*Diogenes* sp. 1
102	CHR	*Ochromonas minuscula* Conrad
103	CHR	*Dinobryon* sp. cysts
104	CHR	*Ochromonas silvarum* Dofl.
105	CRY	*Chroomonas acuta* Utermohl
106	PYR	*Gymnodinium* sp. 1
107	CHR	*Chromulina pseudonebulosa* Pascher
108	CHR	*Ochromonas sphagnalis* Conrad
109	BAC	*Synedra radians* Kutz.
110	CHR	*Ochromonas nana* Dofl.
111	CHR	*Chrysocapsa planctonica* (W. & G.S. West) Pascher
112	CYN	*Synechocystis* sp. 1
113	UNK	cyst/spore
114	BAC	*Synedra tenera* W. Smith
115	CHL	unknown
116	CHR	*Heliapsis mutabilis* Pascher
117	CHR	*Dinobryon bavaricum* Imhof
118	CRY	*Cryptomonas* sp. 1
119	UNK	unknown
120	CHR	*Chromulina sphaeridia* Schiller
121	BAC	*Synedra amphicephala* Kutz.
122	CHL	*Oocystis parva* West & West
123	UNK	cyst/spore
124	CHR	*Chromulina minuta* Dofl.
125	BAC	*Melosira distans* var. *Pfaffiana* (Reinsch) Grun.
126	CHL	*Cosmarium phaseolus* Breb.
127	CRY	*Cryptomonas erosa* Ehr.
128	CHL	*Tetraedron* sp.
129	CYN	*Anabaena affinis* Lemmermann
130	CHL	*Crucigenia fenestrata* Schmidle
131	UNK	cyst/spore
132	CYN	*Chroococcus dispersus* var. *minor* G.M. Smith
133	CYN	*Aphanocapsa delicatissima* West & West
134	CHR	*Centritractus dubius* Printz
135	CHR	*Ochromonas elegans* Dofl.
136	BAC	*Diatoma hemiale* var. *mesodon* (Ehr.) Grun.

Code No.	Group	Taxon
137	CHR	*Arthrodesmus incus* (Ehr.) Hasr.
138	UNK	unknown
139	CHR	*Chrysococcus rufescens* Klebs.
140	BAC	unknown pennate (girdle view)
141	BAC	*Cyclotella* sp. 1
142	CHR	*Chrysapsis* sp. 1
143	CHR	*Ochromonas tenera* H. Meyer
144	CHL	*Tetraedron minimum* (A. Braun) Hansgirg
145	CHR	*Epipyxis* sp. 1
146	CRY	*Rhodomonas* sp. 1
147	CHL	*Oocystis pusilla* Hansgirg
148	BAC	*Navicula* sp. 1
149	BAC	*Melosira italica* (Ehr.) Kutz.
150	CHL	*Ankistrodesmus braunii* (Naeg.) Brunnthaler
151	BAC	*Cymbella* sp. 1
152	CHR	*Mallomonas* sp. 1
153	CHR	*Diceras phaseolus* Fott
154	CHR	*Chrysococcocystis elegans* Dofl.
155	BAC	*Achnanthes clevei* var. *rostrata* Hust.
156	BAC	*Fragilaria construens* (Ehr.) Grun
157	BAC	*Scenedesmus quadricauda* (Turp.) Breb.
158	PYR	*Gymnodinium* sp. 2
159	BAC	*Cyclotella stelligera* Cl. u. Grun.
160	CHR	*Epipyxis* sp. 2
161	CYN	*Chroococcus* sp. 1
162	BAC	*Actinella punctata* Lewis
163	UNK	unknown cyst/spore
164	CHL	*Selenastrum* sp. 1
165	CYN	*Aphanocapsa elachista* var. *Conferta* West & West
166	EUG	unknown euglenoid
167	CYN	*Anabaena* sp. 1
168	CHR	*Dinobryon sertularia* (Ehr.)
169	CHR	*Synura* sp.
170	CHR	? *Bumilleriopsis* sp. 1 ?
171	CHL	*Chlorella* sp. 1
172	CYN	*Oscillatoria angustissima* West & West
173	CYN	*Microcystis incerta* Lemm.
174	CHL	*Scroederia setigera* (Schroed.) Lemm.
175	CYN	*Cyanarcus* sp. 1
176	CHL	*Chlamydomonas globosa* Snow
177	CYN	combined with #129
178	CHL	*Elakatothrix gelatinosa* Wille
179	CML	*Sphaerocystis schroeteri* Chodat
180	CHR	*Gloeobotrys limneticus* (G.M. Smith) Pascher

Code No.	Group	Taxon
181	CHR	*Chrysidiastrum catenatum* Lauterborn
182	CHL	*Mougeotia* sp. 1
183	CHL	*Spondylosium* sp. 1
184	CYN	combined with #161
185	BAC	*Anomoeoneis serians* var. *brachysira* (Breb. ex Kutz.) Hust.
186	CHL	*Cosmarium tumidum* Lund
187	CHL	*Scenedesmus bijuga* var. *alternans* (Reinsch) Hansgirg
188	CYN	*Merismopedia minima* Beck
189	CYN	*Oscillatoria chlorina* Kutz. ex Gomont
190	PYR	unknown pyrrhophyta sp. 1
191	CHL	*Staurastrum crenulatum* Naeg. (Delp.)
192	CHL	*Tetradesmus smithii* Prescott
193	CHR	*Goniochloris* sp. 1
194	BAC	unknown pennate diatom (girdle view)
195	UNK	unknown cysts/spores
196	CHL	*Euastrum* sp.1
197	CHL	*Ulothrix subconstricta* G.S. West
198	CHL	*Crucigenia tetrapedia* (Kirch.) West & West
199	CHL	*Quadrigula closteriodes* (Bohlin) Printz
200	CHR	*Tribonema affine* G.S. West
201	BAC	*Achnanthes* sp. 1
202	PYR	unknown pyrrhophyta sp. 2

APPENDIX 5

Geographic Information numbers for the study lakes.

Lake	Number
Allen	LNO3
Bench	LZ27
Clover	LW20
Crescent	LC35
Crystal	LW29
Eleanor	LH02
Ethel	LF04
Eunice	LM01
Frozen	LW37
GO1	LM37
GO2	LM26
George	LN02
Golden	LM17
Green	LC07
James	LF05
Louise	LZ21
Mowich	LM04
Mystic	LF12
Reflection	LN19
Shadow	LW38
Shriner	L012
Snow	LZ30
St. Andrews	LP12
Sunrise	LW26
Three	L019
Tipsoo	L002
Upper Palisades	LH14

As the nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for enjoyment of life through outdoor recreation. The department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people. The department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

NPS D-211 February 1992