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Limnological surveys were conducted on four large lakes (Atlin, Tagish, Marsh and Laberge) of the Yukon River system on four occasions during 1982 and 1983. Nutrient levels are very low, as are algal and zooplankton biomass, indicating that the lakes are ultraoligotrophic. Physical factors (i.e. flushing, turbidity, etc.) have pronounced effects on the chemistry and biology of these lakes. Comparisons are made to other northern Canadian and European lakes. Observations on possible effects of future development are made as well as recommendations for further research.

Résumé

En quatre occasions, en 1982 et 1983, on a étudié les caractéristiques limnologiques de quatre grands lacs (Atlin, Tagish, Marsh et Laberge) du bassin du fleuve Yukon. Comme le montrent les très faibles concentrations d'éléments nutritifs et la très faible biomasse des algues et du zooplancton, ces lacs sont ultra-oligotrophes. Les facteurs physiques (c'est-à-dire, le renouvellement de l'eau des lacs, la turbidité, etc.) ont un effet prononcé sur les caractéristiques chimiques et biologiques des lacs. Des comparaisons sont établies entre ces lacs et d'autres lacs du Nord du Canada et de l'Europe. Des observations portent sur les effets possibles de mises en valeur ultérieures, tandis que des recommandations portent sur la recherche à faire.

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INTRODUCTION

Increased interest in the development of the Canadian North has focused attention on hydroelectric projects, linear installations (pipelines, highways), and mining. These types of projects, particularly hydro-development, have the potential for significant environmental impacts on lakes, reservoirs and rivers. Major developments have been proposed in the area of the Yukon River and its large headwater lakes (Canada, Yukon and British Columbia, 1979). Detailed limnological information on this system has not been collected in any consistent manner over the years since the initial studies by Withler (1956). In addition, as little is known about the limnology of large northern lakes, new data on their chemistry and microbiology will be helpful in understanding the processes influencing northern freshwaters. The development and modification of techniques for doing limnological work in northern environments were also considered of value for both the current study and for future investigations in the North.

The two principal concerns (potential development and lack of understanding of processes) provided the impetus for the National Water Research Institute to undertake a reconnaissance study of four of the headwater lakes of the mainstem Yukon River: Atlin, Tagish, Marsh and Laberge (Fig. 1).

The study area is in the northwest corner of British Columbia and the southwest Yukon Territory, spanning 60° N latitude. With a yearly mean temperature of about -1°C and an elevation of 600-700 m, the vegetation/climate is subalpine/subarctic.

The lakes are aligned south to north, extending from the Boundary range of the Coast mountains onto the Yukon plateau (Bostock, 1946). Their morphometric parameters are summarized in Table 1 (Pharo 1981a, b; Pharo and Chamberlain, 1983a).

Inflows to the system are derived from glaciers to the south and west and snowmelt/surface runoff to the east and north. Snowmelt is complete by late May or early June at which time ice-out usually occurs. Peak flows from glacial sources occur later, about mid-August.

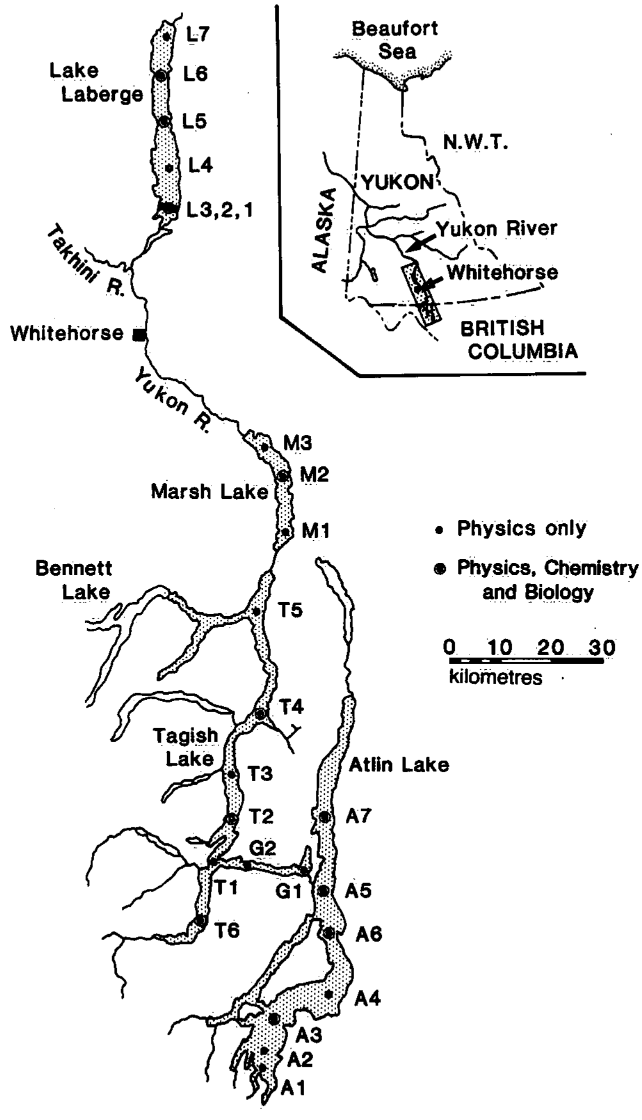

Figure 1. Location map of the study area.

Table 1. Lake Morphometry

Lake	Elevation (m)	Z_{max} (m)	Z_{mean} (m)	Length (km)	Width (km)	Area (km^2)	Volume (km^3)
Atlin*	670	283	86	103	5.7	589	54.4
Tagish	656	307	62	108	3.7	353	21.8
Marsh	654	52	13	30	3.2	96	1.2
Laberge	628	146	54	48	4.2	201	10.8

* Withler (1956).

METHODS

A synoptic sampling strategy, combining chemical and biological sampling with a physical limnology survey, was adopted. Sampling was conducted throughout one limnological cycle but was constrained by time, cost and manpower limitations to four trips.

The survey area presented some difficult technical problems as a result of its size and climatic extremes. The sampling details are outlined in Table 2.

The use of a boat (18-ft runabout) in June 1982 permitted the collection of the largest number of samples per station, and the largest volume of water for each sample. However, this sampling routine only permitted sampling at six of the ten intended chemistry stations (Fig. 1); no "physics only" stations were monitored, and it required five days of calm weather for sample collection. An additional two to three days were required to process samples.

Subsequent monitors were carried out using aircraft, but this necessitated a reduction in the number of samples per station and the volume sampled. Sampling from a float-equipped aircraft (Cessna 206) was done using a hand-cranked winch system attached directly to the aircraft's seat tracks. Through-ice sampling was done using the same winch package on a removable base platform (Marles, 1985). Monitoring by aircraft required four to seven days in total, depending primarily on weather and the rate at which samples could be processed in the field laboratory at Whitehorse, Yukon Territory.

The March trip required a further reduction in the number of samples taken per station because of the decreased capacity of the smaller ski-equipped aircraft and the necessity of carrying winter survival gear.

Physical data (conductivity, temperature and depth) were collected at each station using an Applied Microsystems CTD system (Carmack and Marles, 1986). Chemistry and biology samples were then collected at selected stations. Dissolved oxygen samples (modified Winkler method) were fixed immediately; zooplankton samples (collected with a 0.25-m^2 Wisconsin net, 110-μm mesh) were preserved with borax-buffered 4% formalin/sucrose solution (Haney and Hall, 1973).

Samples for the dissolved nutrient species (reactive silica, phosphorus, ammonia, nitrate + nitrite, and total dissolved nitrogen) were pressure-filtered (Sartorius SM 11106, 0.45-μm cellulose acetate filters presoaked in D.I. water) at the end of each sampling day. The soluble reactive phosphorus (SRP) samples were preserved with chloroform. All samples were kept cool and dark.

Dissolved oxygen titrations were completed within 48 h. Other chemistry samples were shipped by air and analyzed at the Water Quality Branch Laboratory in North Vancouver, B.C., within two weeks. The procedures used by the laboratory are outlined in their *Analytical Methods Manual* (Environment Canada, 1981).

Epilimnion samples for algal species identification and volume measurement were stored in 125-mL opaque plastic bottles and preserved with 2 mL of Lugol's solution. These samples were enumerated at a later date, at 125× and 500× magnification using the method of Utermohl (1958). Cell volume estimates were calculated on samples collected in March, using length/diameter measurements and formulae for simple geometric shapes.

Aliquots (2–3 mL) of the preserved zooplankton samples were transferred to a petri dish for identification and enumeration under a dissecting microscope. Estimates of the dry weight of zooplankton obtained in each haul were made by converting numbers of the various stages of the copepods to dry weight using a constant factor for each stage. The cladocerans were calculated using relationships of length and weight most appropriate to the species. The rotifers were converted from numbers to weight using a constant factor based on geometric shapes and a specific gravity of one. (Details are listed in Appendix C.)

Table 2. Sampling Schedule

Date	Transport	No. of samples per station	Volume sampled at each depth (L)
June 1982	Boat	12	8.0
August 1982	Float aircraft (Cessna 206)	6	2.5
October 1982	Float aircraft (Cessna 206)	6	2.5
March 1983	Ski-aircraft (Cessna 185)		
	Helicopter (Bell 206)	3	2.5

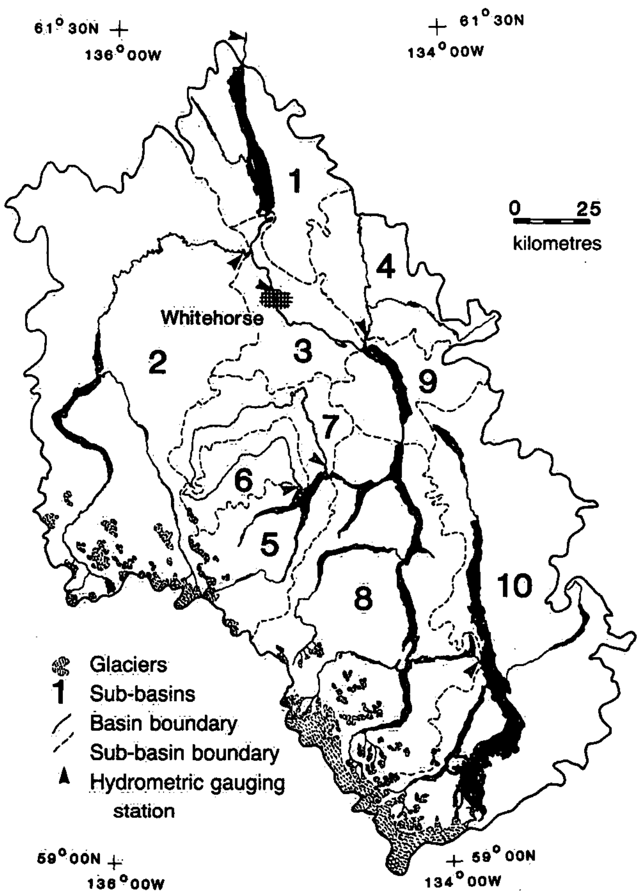

Figure 2. Drainage basins and hydrometric gauging stations.

RESULTS

Hydrology

Measured values of runoff and river flows (from hydrometric stations on Figure 2), and calculations of lake residence times are given in Appendix A. The most important results are summarized in Table 3. The minimum and maximum residence times, R_{min} and R_{max}, are calculated from the mean flow extremes, as listed in Appendix A.

A simplified schematic chart showing the percentage of the flow out of each lake originating from various sources is given in Figure 3.

DIRECT INFLOW	PERCENTAGE OF DOWNSTREAM LAKE INPUT	MAJOR TRIBUTARIES
100%	⟶ ATLIN	
	44%	
	\ /	
39%	⟶ TAGISH ⟵	17% BENNETT
	97%	
	\ /	
3%	⟶ MARSH	
	75%	
	\ / ⟵	19% TAKHINI
6%	⟶ LABERGE	

Figure 3. Schematic flowchart of the study area.

Table 3. Residence Times

Lake	Volume (km^3)	Residence time (yr)			Flushing rate (yr^{-1})		
		R_{mean}	R_{min}	R_{max}	R_{mean}^{-1}	R_{min}^{-1}	R_{max}^{-1}
Atlin	54.4	18.4	13.7	24.2	0.05	0.07	0.04
Tagish	21.8	3.25	2.42	4.27	0.31	0.41	0.23
Marsh	1.2	0.17	0.13	0.23	5.8	7.6	4.3
Laberge	10.8	1.06	0.80	1.41	0.93	1.3	0.71
Bennett	6.0	5.37	4.01	7.06	0.19	0.25	0.14

Chemistry

Only representative or summary data are shown. Full data listings are presented in a preliminary data report (Kirkland and Marles, 1983).

Conductivity

The range of specific conductivities (C_{25}) measured was small; most samples were between 85 and 105 $\mu S \cdot cm^{-1}$. The lowest values were found at the south Tagish station (and in a Bennett Lake surface sample). Atlin Lake had specific conductivities typically 20% higher than those of Tagish Lake. It is not known whether this was due to an overall lower salinity of Tagish inputs or to in-lake changes such as a higher evaporation rate in Atlin (Appendix A).

The linear regression between specific conductivity and the sum of ions (in milliequivalents) in deep samples from all lakes (June 1982) has a relatively high correlation coefficient.

Sum of ions = C_{25} (0.021) - 0.062 $R^2 = 0.947$ n = 36

The good correlation indicates that ratios between the various ions are relatively constant among the lakes and, therefore, the specific conductivity is a good measure of the sum of ions in these lakes.

A linear regression of the sum of ions (in parts per million) plus non-ionic reactive silica versus C_{25} also has a high correlation.

TDS (ppm) = C_{25} (0.479) + 6.405 $R^2 = 0.892$ n = 36

Nutrient Chemistry

To follow the effects of biological uptake and nutrient additions via rivers, lakewide average concentrations were calculated. The depth of the metalimnion at each station was assigned after inspection of the continuous temperature profiles (Carmack and Marles, 1986). Data at each station from the surface to the top of the metalimnion were integrated and then averaged with the other stations of each lake to produce the lakewide average concentrations.

Stations A3 in Atlin Lake and T6 in Tagish Lake, however, had nutrient values that differed considerably from the other stations in each lake. Both A3 and T6 are adjacent to inflow rivers that are mainly glacial in origin, and results from these stations produced a disproportionate weighting of lakewide averages. Therefore, results from these two stations were excluded from most averages of nutrient and biological parameters and were handled separately.

Annual and growing season averages were calculated for all data. The growing season was defined as including the June, August and October sampling dates.

Phosphorus

All phosphorus values were very low; total phosphorus (TP) rarely reached 10 ppb. The dissolved fraction (DP) was usually less than 5 ppb and was often at or below the detection limit of the method (1 ppb or $\mu g \cdot L^{-1}$).

Intra-lake TP values were almost uniform, with the particulate phosphorus (PP) fraction being the largest component. Near the inlet of Laberge during June, PP reached 10 ppb, likely due to riverine suspended sediment. Similar high values of PP were noted at the southern Atlin and Tagish stations in August when glacial runoff was greatest.

Differences in lakewide concentrations of the various phosphorus fractions (Table 4) throughout the year were minimal. Average lakewide PP values for Atlin and Tagish were highest in October, whereas Marsh and Laberge values

Table 4. Average Phosphorus Concentrations in the Epilimnion during Each Sampling

Sampling trip	TP	DP	SRP	PP
Atlin				
June	2.4	1.0	1.5	1.4
August	2.6	1.25	0.75	1.3
October	4.25	1.5	2.2	2.75
March	2.4	1.5	2.3	1.0
Atlin (-A3)				
June	2.3	1.0	1.3	1.3
August	1.9	1.1	0.5	0.8
October	3.0	1.0	1.5	2.0
March	2.25	2.1	2.0	0.1
Tagish (-T6)				
June	1.9	1.2	1.3	0.7
August	2.3	1.2	0.6	1.1
October	2.5	1.2	1.2	1.3
March	2.5	1.5	2.0	1.0
Marsh				
June	3.8	1.0	1.5	2.8
August	3.4	1.6	1.1	1.8
October	2.8	1.3	1.1	1.5
March	4.5	2.6	1.4	1.9
Laberge				
June	6.7	1.3	2.0	5.4
August	5.2	1.7	0.9	3.5
October	3.8	1.8	1.6	2.0
March	4.9	2.5	1.8	2.4

were highest in June. The DP values for all the lakes are highest in March and lowest in June.

Growing season (GS) and annual (An) averages (Table 5) generally increased downstream. Although the growing season dissolved components are less than their annual averages and particulate phosphorus is higher during the growing season, many of these averages are close to analytical detection limit.

Table 5. Annual and Growing Season Average Phosphorus Concentrations in the Epilimnion

	TP		DP		SRP		PP	
Lake	GS	An	GS	An	GS	An	GS	An
Atlin	3.1	2.9	1.25	1.3	1.5	1.7	1.8	1.6
At (−A3)	2.4	2.4	1.0	1.3	1.1	1.3	1.4	1.1
Ta (−T6)	2.2	2.3	1.2	1.3	1.0	1.3	1.0	1.0
Marsh	3.3	3.6	1.3	1.6	1.2	1.3	2.0	2.0
Laberge	5.2	5.2	1.6	1.8	1.5	1.6	3.6	3.3

GS – Growing season.
An – Annual.

Nitrogen

The nitrogen concentrations in these lakes were low but only rarely below detection limit. Depth-weighted mean values (Tables 6a and 6b) for the nitrogen fractions in the epilimnion of each lake are shown in Figures 4 to 7.

The three largest lakes (Atlin, Tagish and Laberge) had similar seasonal patterns with progressively higher concentrations occurring downstream. Both total dissolved nitrogen (TDN) and dissolved organic nitrogen (DON) were highest in these lakes in June. The dissolved inorganic nitrogen (DIN), also highest in June, reached a minimum in August.

Marsh Lake had nitrogen values that were quite different from those of the other lakes, with higher peaks for dissolved inorganic nitrogen (DIN) and particulate nitrogen (PN), as well as lower and more protracted minima for the inorganic nitrogen species. Marsh also had a marked decrease in the concentration of DIN between March and June, particularly in nitrate + nitrite nitrogen (NN).

The differences between growing season and annual averages (Table 7) were generally small except for Marsh Lake. In this lake the largest seasonal variation was in DIN, with the GS value only about one third of the An value. Dissolved organic nitrogen (DON) was always the largest TDN component especially in Marsh Lake where, during the growing season, more than 80% of TDN was DON.

Table 6a. Epilimnion Nitrogen Values ($\mu g \cdot L^{-1}$)

	TDN				PN				NN			
Lake	June	August	October	March	June	August	October	March	June	August	October	March
Atlin	85	43	52	65	3	4	7	6	20	2	22	20
A-A3	86	40	48	64	3	4	5	4	19	2	7	21
Tagish	83	53	66	67	5	9	5	7	22	14	21	35
T-T6	83	45	67	68	5	7	5	7	22	6	19	36
Marsh	69	52	56	100	15	21	5	15	2	1	2	33
Laberge	118	57	90	90	9	10	5	9	25	2	22	37

	AN				DIN				DON			
Lake	June	August	October	March	June	August	October	March	June	August	October	March
Atlin	15	6	6	11	34	9	28	31	51	35	24	34
A-A3	15	4	6	7	34	5	13	28	52	35	35	36
Tagish	14	5	10	10	36	19	31	45	47	35	35	23
T-T6	14	5	11	6	36	11	30	42	47	34	36	27
Marsh	12	4	4	30	14	6	5	63	55	47	51	37
Laberge	18	3	13	8	43	6	35	45	75	51	55	45

Table 6b. Whole Lake Nitrogen Values ($\mu g \cdot L^{-1}$)

	TDN				PN				NN			
Lake	June	August	October	March	June	August	October	March	June	August	October	March
Atlin	118	57	53	72	3	6	5	4	22	17	24	27
Tagish	91	68	72	74	4	8	5	4	29	28	30	38
Marsh	69	57	59	114	14	19	5	9	4	5	2	26
Laberge	129	77	94	99	7	7	5	5	30	29	30	44

	AN				DIN				DON			
Lake	June	August	October	March	June	August	October	March	June	August	October	March
Atlin	16	8	12	10	37	24	35	37	81	33	18	35
Tagish	13	7	8	16	41	35	38	54	50	32	34	20
Marsh	14	8	4	35	18	13	5	61	51	44	54	53
Laberge	14	4	11	6	43	33	41	51	85	43	53	48

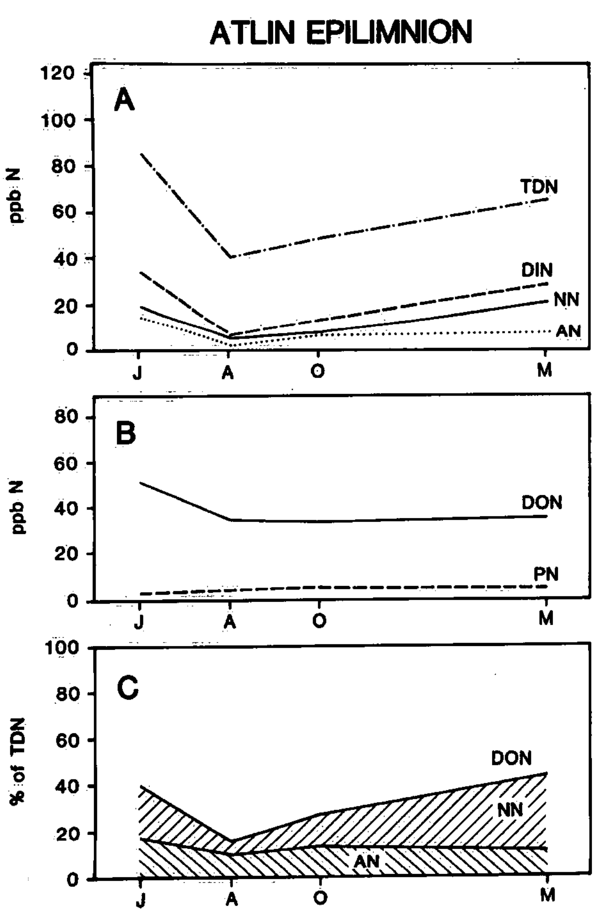

Figure 4. Atlin Lake – epilimnion nitrogen species concentrations and composition.

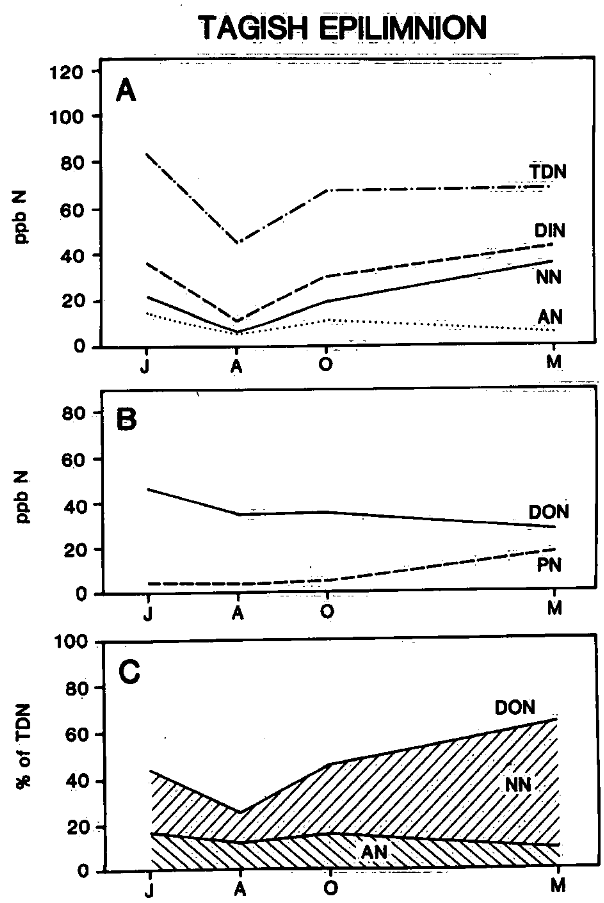

Figure 5. Tagish Lake – epilimnion nitrogen species concentrations and composition.

Table 7. Annual and Growing Season Average Nitrogen Concentrations in the Epilimnion

Lake	TN		TDN		DIN		DON		PN	
	GS	An	GS	An	GS	An	GS	An	GS	An
Atlin	65	66	60	61	23	26	37	36	4.3	4.75
AT (-A3)	62	64	58	60	17	20	41	40	3.8	3.8
TA (-T6)	71	72	65	66	26	30	39	36	5.7	5.9
Marsh	73	83	59	69	8	22	51	48	14	14
Laberge	96	97	88	89	28	32	60	57	8.0	8.3

GS – Growing season.
An – Annual.

With many of the phosphorus results near the analytical detection limit, the use of N:P ratios as a guide to the relative limitations on biological growth is difficult to interpret for these lakes. In June, the epilimnetic ratio is high, typically > 30, dropping to < 10 during August.

Oxygen

The dissolved oxygen values remained high (generally greater than 10 $mg \cdot L^{-1}$) in all lakes throughout the year. The percent saturation, corrected for temperature and elevation (after Mortimer, 1981), also remained high. The minimum observed was 79% saturation at 138 m in Lake Laberge during March.

Biology

Phytoplankton-Chlorophyll

Chlorophyll concentrations were low (0.06-0.8 $mg \cdot m^{-3}$) during the growing season. Lakewide averages are given in Table 8. The seasonal patterns in Tagish and Marsh were similar to those given in Figure 8a, with spring and fall maxima, and distinct summer minima. Atlin Lake had a somewhat similar pattern but without the strong spring peak. Laberge differed, its highest average occurring in the summer.

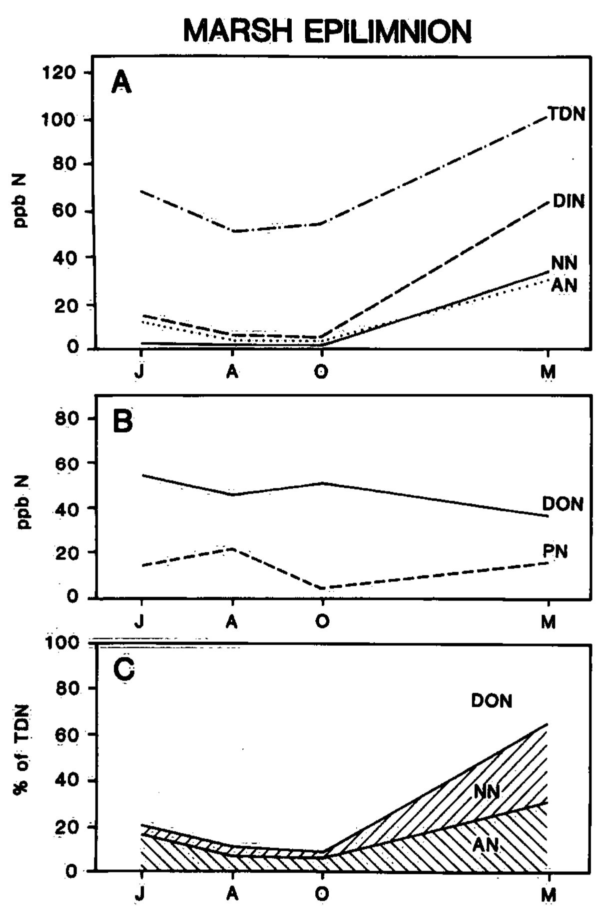

Figure 6. Marsh Lake – epilimnion nitrogen species concentrations and composition.

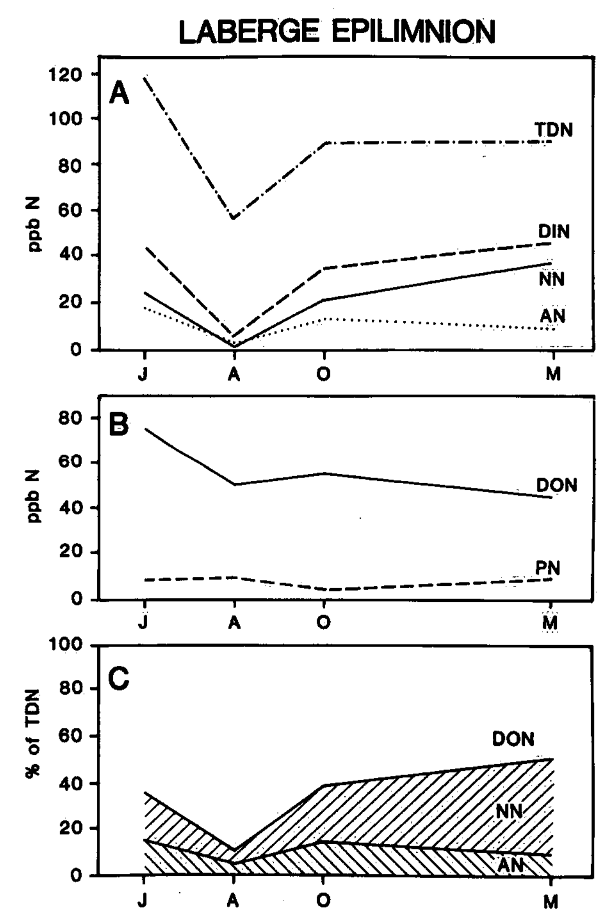

Figure 7. Lake Laberge – epilimnion nitrogen species concentrations and composition.

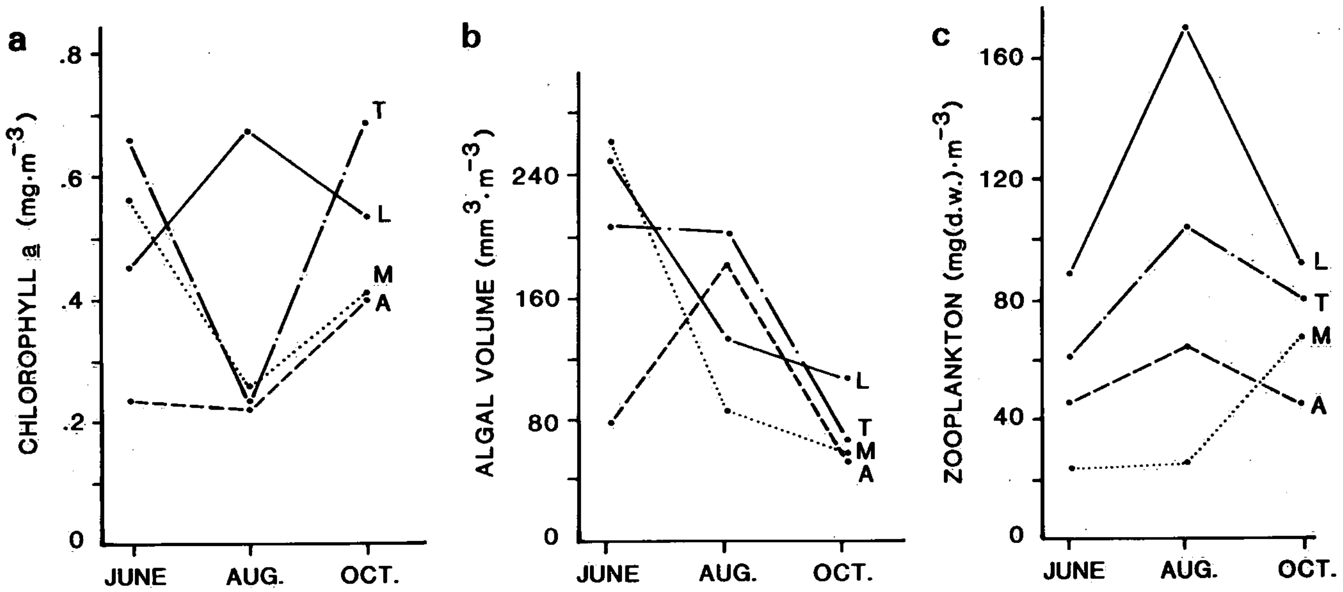

Figure 8. Lakewide average (a) chlorophyll concentrations, (b) algal volumes and (c) zooplankton concentrations.

These averages and seasonal patterns are crude, as the number of samples collected in August and October were reduced to two per station. The potential for missing significant chlorophyll accumulation was high in August when the mid-depth (10 m) sample was used for algae species enumeration. During October, however, samples were more representative because of rapid mixing of the epilimnion.

Table 8. Chlorophyll ($mg \cdot m^{-3}$)

Lake	Growing season Mean	Growing season Percent pheophytin	Annual Mean	Annual Percent pheophytin
Atlin (-A3)	0.28	31	0.27	28
Tagish (-T6)	0.53	27	0.44	26
Marsh	0.41	39	0.35	38
Laberge	0.56	29	0.47	28

Note: Annual mean for A3 was 0.16 $mg \cdot m^{-3}$.

The only pronounced horizontal gradients observed within any given lake were from Atlin and Tagish. Values at the southern ends of these lakes were very low and were omitted from calculations of lakewide averages.

Phytoplankton Biovolume and Numbers

Algal volumes ranged from 30 to 306 $mm^3 \cdot m^{-3}$ during the growing season. Growing season and annual averages for the epilimnion are listed in Table 9. Two contrasting seasonal patterns are apparent (Fig. 8b): in Atlin and Tagish peak volumes were in August, and in Marsh and Laberge the peaks were in June.

Table 9. Average Algal Volumes ($mm^3 \cdot m^{-3}$)

Lake	Growing season	Annual
Atlin (+A3)	99	81
Tagish (-T6)	158	123
Marsh	135	116
Laberge	163	130

For several reasons, these values are only rough estimates of the total algal volume. First, they are based on only one sample per station, except in June when two samples were collected. Second, they are calculated from volume estimates for species observed in March and from literature values for species that were only observed during the growing season.

Cell numbers varied from 0.17 to 4.1 million cells per litre. The lowest values were obtained from samples 1 m below the ice in March, and the highest numbers were seen in June and August. Seasonally, the pattern of cell numbers was similar to the pattern for algal biovolume.

Phytoplankton Taxonomy

Chrysophyceae were the dominant algal group, both by number and volume (Appendix B). Cryptophytes and diatoms were the next most important groups, depending on lake and season. Occasionally, dinoflagellates and chlorophytes also made up significant volumes. The magnification used in counting (500x) was not high enough to enumerate quantitatively the picoplankton (including cyanobacteria) which were observed.

The most common alga observed was an unidentified chrysophyceaen just under 8 µm in size. Other chrysophytes were *Chromulina mikroplankton, Ochromonas elegans* and *O. silvarum.* Common cryptophytes were *Rhodomonas lacustris* and *R. minuta* var. *nannoplanktonica*. Diatoms were represented by *Cyclotella glomerata* and colonial *Asterionella formosa*. A large *Periodinium* sp. (diameter 20 µm) was the greatest contributor to the dinoflagellate biomass and was often observed in Marsh Lake.

Zooplankton Volume and Weight

Hauls for zooplankton were done vertically from 50 m in the deeper lakes and 25 m in Marsh. The average results are shown in Table 10. These values are not corrected for net efficiency (normally 60% to 70% with the Wisconsin net used).

Table 10. Average Growing Season Zooplankton Standing Stock (dry weight)

Lake	Zooplankton standing stock	
	$mg \cdot m^{-3}$	$mg \cdot m^{-2}$
Atlin (+A3)	4.5	227
Tagish (-T6)	8.2	410
Marsh	3.9	99
Laberge	11.9	593

The three deeper lakes show the same seasonal pattern with maximum zooplankton biomass in August (Fig. 8c). Marsh Lake had the lowest summer concentration observed and had its peak in October.

Zooplankton Taxonomy

The dominant groups were copepods and rotifers. Cladocera were also present, but only developed significant numbers in Marsh and Laberge. The numbers of animals collected in each haul are tabulated in Appendix C.

The most numerous species was the carnivorous copepod *Cyclops scutifer* (1.2 mm female and 0.95 mm male). The herbivorous copepod *Diaptomus pribilofensis* (0.9 mm) was usually the next most common. Much less frequent were *Senecella calanoides* (2.3 mm) (in Laberge only) and *Heterocope septentrionalis* (2.3 mm). All four species had sizes at the low end of the ranges cited in the literature.

The most common rotifers were *Kellicottia longispina* and *Conochilus unicoris*. During August, a *Synchaeta* sp. was the dominant rotifer in Marsh. Rotifer populations are probably underestimated, as the plankton net used had 110-µm mesh through which these narrow organisms could escape.

Daphnia longiremis was the most common cladocera, with *D. pulex* (var. *middendorffiana?) and D. rosea* (var. *longispina?*) also present. *Eubosmina coregoni* (var. *longispina?*) was frequently found but was never numerous. *Leptodora kindtii*, caught only in Marsh and Laberge, were only 6 mm long compared with literature values of 20 mm.

Species assemblages (Table 11) show three different patterns. Atlin and Tagish have similar relative proportions, although Atlin has somewhat lower numbers. Marsh has more cladocera, in particular the large predator *Leptodora*. Chironomids were also frequently caught in Marsh. Laberge was characterized by large populations of both rotifers and copepods.

Table 11. Zooplankton Assemblages

Lake	Rotifers	Copepods	Cladocerans
Atlin and Tagish	*Kellicottia++* *Conochilus++*	*C. scutifer+++* *D. pribilofensis++*	*D. pulex+* *Eubosmina+*
Marsh	*Synchaeta+++* *Kellicottia++*	*C. scutifer+* *D. pribilofensis+*	*D. longirenis++++* *Leptodora++*
Laberge	*Conochilus++++* *Keillicottia+*	*C. scutifer++++* *D. pribilofensis+++* *Senecella+*	*D. longirenis++* *D. rosea+* *Leptodora+*

Relative abundance + = few, ++++ = very many.

DISCUSSION

In discussing the nutrient and biological characteristics of these lakes, two factors are particularly important for assessing the generality of the conclusions. First, the data were collected over only one year and therefore interannual variation is not known. Second, both the sampling frequency and number of samples collected in each lake were typical of a reconnaissance survey.

Physics

Physical factors have pronounced effects on the chemistry and biology of these lakes, with low temperatures, deep mixing, flushing and turbidity all being important.

Temperature

The temperature of the lakes is sufficiently low that biological production is likely reduced. The ice cover starts and ends late (December-May) and thus the growing season is short (May-October), starting under ice cover.

Mixing

In the early growing season (June), after ice-out, the large lakes (Atlin, Tagish and Laberge) are very weakly stratified and are thus subject to deep mixing by wind events. Deep mixing can mask biologically induced changes in nutrient levels. Not only are changes in concentration diluted over a large volume of water but algal production is likely inhibited by mixing to depths below the photosynthetic compensation point.

Flushing

The flushing rates of the epilimnion in these lakes during summer are shorter than the annual rates (Table 3). If the flushing is rapid enough, algal biomass accumulation may be reduced. This is probably the case in Marsh and, to a lesser extent, in Laberge because the epilimnion residence times can be as low as 27 and 77 days, respectively (volume to 30 m divided by average August discharge; 1943-1982).

Turbidity

The two principal sources of (inorganic) turbidity in this drainage basin are glacial flour and resuspended glaciolacustrine sediments. Glacial flour is imported to the lakes primarily via rivers entering from the southwest and is particularly noticeable in Atlin and Tagish during late summer. Both the Yukon River, near Whitehorse, and the Takhini River pass through cutbanks of glaciolacustrine deposits. Maximum riverine turbidity likely accompanies maximum flow and occurs during early summer.

Nutrient Chemistry

Phosphorus

Total phosphorus values were lower than those observed in smaller Yukon Lakes (Shortreed and Stockner, 1985). Indeed, the growing season (summertime) average (3.3 $\mu g \cdot L^{-1}$) is only about half that measured in the smaller lakes (6.0 $\mu g \cdot L^{-1}$).

The major component of TP was PP (61% of the GS total P) and the PP was highest when riverine suspended sediment concentrations were highest. Although the bioavailability of PP was not determined, it would have a significant effect on the overall phosphorus (TP) bioavailability (Gray and Kirkland, 1982). For instance, in the southern areas of Atlin and Tagish, the suspended sediments are likely high in apatite, and if so, the bioavailability of PP (and TP) would be low. Thus for these lakes, TP may be a poor indicator of biologically available phosphorus (BAP).

Dissolved phosphorus (DP) concentrations decrease rapidly between March and June with Marsh, Laberge and Atlin (-A3) dropping by a factor of two. During the rest of the growing season, however, there are no significant changes in the DP concentration. The routine chemical methods used were inadequate to follow the phosphorus dynamics, and direct measurement of phosphorus turnover times would be useful.

Soluble reactive phosphorus (SRP) values were, within experimental error, the same as those of DP. Many of the analyses gave results that were less than the detection limits, and often the SRP measurements were marginally greater than DP. These results suggest that dissolved organic P concentrations were extremely low.

Nitrogen

The average growing season TN value (76 $\mu g \cdot L^{-1}$) is only 20% of that noted in smaller Yukon lakes (Shortreed and Stockner, 1985). As PN was only a small fraction of TN, variations in TN were related to changes in the components of TDN. Like most lakes, for all four of these Yukon headwater lakes the highest values of TDN occurred early in the growing season (March-June) before uptake of DIN by algae.

Dissolved organic nitrogen (DON) in these lakes is usually the largest component of TDN. The DON values are highest in June and decrease by August. Phytoplankton production and/or inputs from snowmelt runoff are possible sources for the increase (Daley *et al*., 1981). If this organic matter is from autochthonous sources, then these lakes have considerable production under ice. By August, heterotrophic bacterial uptake could be responsible for the decrease. These bacteria would subsequently be a carbon and nitrogen source for some of the zooplankton. Dilution by glacial runoff low in DON may also explain some of the decrease.

The NN concentration drops rapidly during spring and is sometimes lower than the ammonia concentration. However, average growing season epilimnion nitrate values remained above the detection limit, in all of these lakes, while for nine of the 19 smaller Yukon lakes (Shortreed and Stockner, 1985) averages were below the detection limit. The optimal time for algal uptake of nitrate is, perhaps, between snowmelt and ice-out. During this time there is probably adequate light for photosynthesis and an absence of wind-induced mixing. Under-ice uptake in Marsh could explain the very low nitrate concentration observed in mid-June.

The presence of moderate amounts of ammonia during the growing season indicates a supply larger than the demand. Zooplankton excretion of ammonia is the probable source. During August it was likely that the phytoplankton, at the very low P levels encountered, were P-limited and therefore could not use the ammonia at the rate it was produced.

Particulate nitrogen values remain so low that seasonal variations were not significant. The composition of this component (algae, bacteria, nauplii, detritus, etc.) was not determined.

Although the four large lakes show TP values 50% lower than the smaller Yukon lakes (Shortreed and Stockner, 1985), typical TN values are less than 20% of these other lakes. Despite the lower nitrogen levels, however, DIN remains above the detection limit throughout the year. While the N:P ratio drops from >30 in June to <10 by August, the very low nutrient levels make the use of this ratio suspect. Both the accuracy and precision of the DP method are significant factors in considering the accuracy and utility of the ratio. As well, the proportion of both N and P available for production and their relative turnover rates are not known. The absence of blue-green algae is indirect evidence that the BAN:BAP (biologically available nitrogen to biologically available phosphorus) ratio remains consistently high (>10).

Specific Physical-Chemical Interactions

Physical processes, specific to each lake, modify the general patterns noted above.

Atlin and Tagish

These are the deepest lakes of the group examined and have the longest residence times. Deep convective mixing early in the growing season (likely common to all of these lakes) is quite evident in Atlin and Tagish and biomass accumulations are inhibited. Both lakes also have pronounced horizontal turbidity gradients. The turbidity at the southernmost stations, primarily from glacial sources, is typically several times that observed at other stations. (Secchi depths, during August, are 1.0 m at T6 and 11.0 m at T4.) Light penetration is reduced so significantly that it may limit biological production. During August, the biomass of phytoplankton in the southern portions of both Atlin and Tagish was less than that observed at the other stations in each lake. Lower chlorophyll concentrations were also noted in October. Lakewide algal biomass peaks occurred in August between the mixing and turbidity events.

Marsh

Of the four lakes studied, Marsh is the smallest, shallowest and warmest. In addition, it usually has the lowest turbidity. Marsh warms up more quickly than the other lakes, and thus its biomass peak likely occurs earlier. The early heating of Marsh Lake is significantly different from that of the other lakes and should be investigated further. Of special interest is the large area of shallow water near the exit of Tagish Lake, which serves to warm the water before it enters the river on its way to Marsh.

In Marsh, the shallow depth and warm temperatures increase the potential for sedimented material to be quickly regenerated and recycled and also increase the importance of benthic organisms. However, Marsh Lake also has the shortest residence time and the largest percentage of water entering from an upstream lake (Fig. 3). Therefore the physical effect of flushing of the epilimnion, which in summer extends to near the lake bottom, is likely to be a major factor affecting nutrient values and biological parameters. During summer, most of the water entering Marsh (from the epilimnion of Tagish) is already stripped of nutrients. Thus, a very short water residence time combines with low nutrient inputs to prevent a summertime accumulation of phytoplankton; hence the biomass peak was observed in early summer.

Laberge

Because of its intermediate residence time, Lake Laberge also exhibits riverine effects. The Takhini River provides a substantial input of water (19%), and during times of high flow, large amounts of glacially deposited sediments erode from its banks. The Yukon River downstream from Marsh Lake also entrains sediment. This turbid river water, upon entering Lake Laberge, experiences a Coriolis effect, follows the right-hand shoreline and produces eddies of sediment-laden water that are clearly visible over the entire 48-km length of the lake (Ball, 1983). A denser sampling pattern would undoubtedly show pronounced lateral variations in chemistry and biology.

Laberge had the highest nutrient values of the four lakes studied, receiving additional inputs from both the Takhini River and the city of Whitehorse (population 12 000) sewage treatment plant (STP). Preliminary estimates, using data from Jack *et al.* (1983) and Bethell (1981), indicate that the STP may increase the TP concentration of the river at Whitehorse by about 4 $\mu g \cdot L^{-1}$ at low flow (winter-spring) and 1 $\mu g \cdot L^{-1}$ during high flow conditions. This increase is approximately 10% to 20% of the ambient value of the river, and much of this added TP may be readily available to algae in the lake. There may also be significant loading of ammonia from the STP; the data, however, although sparse, suggest increases of only 1-4 $\mu g \cdot L^{-1}$ (<5% of background TDN level). Despite these extra nutrient loadings, summertime accumulation of biomass in the lake may be inhibited by the turbidity. The peak in algal biomass was observed in June, although chlorophyll peaked in August. Overall, Laberge is likely the most productive of the four lakes, since its exhibits, in addition to the highest nutrient levels, the largest wintertime decrease in oxygen in the hypolimnion.

Biology

Phytoplankton

Algal biomass was very low in all four lakes, as would be expected from the low nutrient concentrations and relatively severe physical conditions. In comparison, many of the smaller lakes (1.6-90 km^2) in the Yukon River drainage basin have higher mean biomass during summer (Shortreed and Stockner, 1985). Deeper mixing and/or higher turbidity in the larger lakes studied here, together with their lower nutrient concentrations, are likely responsible for the lower biomass levels.

Relationships between chlorophyll and both TP and TN were not significant at the 5% level (Table 12). Of course the small number of data pairs (4) requires a very high regression coefficient for the relationship to be significant. In the Shortreed and Stockner study (1985), 35% of variation in chlorophyll could be predicted by TP at the 1% level of significance after log transformation of 19 data pairs. The four lakes in our study had a lower ratio of chlorophyll to TP than in the lakes of their study. If the lower ratio is confirmed after more extensive sampling, it may indicate a lower biological availability of TP in the epilimnion of these large headwater lakes.

Algal indicators from the growing season were regressed against late winter NN and SRP concentrations. These two values could represent large fractions of the biologically available nutrient supply for the spring and summer. The relationships between NN under the ice in March and both growing season chlorophyll and biovolume were significant at the 5% level (Table 12). On the other hand, the relationships between SRP and these biological indicators were not significant. Thus, while with this small data set the relative degree of springtime N or P limitation is not definitive, the importance of N appears to be greater than that of P.

The seasonal pattern of biomass development is best demonstrated by biovolume (Nicholls and Dillon, 1978). In both Marsh and Laberge, there were distinct early summer maxima (Fig. 8b). Atlin and, to some extent, Tagish accumulated biomass in midsummer. These differences could be due to the negative effect on biomass of rapid flushing and high turbidity in Marsh and Laberge, respectively, in midsummer as well as to the negative effect

Table 12. Regression Relationships between Values During the Growing Season

Dependent variable	Independent variable	Intercept	Slope	n	r^2	r^{2*}
Chlorophyll *a*	TP	0.29	0.049	4	0.27	0.90
Log chlorophyll *a*	Log TP	-0.55	0.377	4	2.23	0.90
Chlorophyll *a*	TN	-0.07	0.0068	4	0.60	0.90
Biovolume	TP	117	6.67	4	0.091	0.90
Biovolume	TN	29	1.45	4	0.50	0.90
Zooplankton	TP	2.5	1.6	3	0.47	0.99
Zooplankton	TN	-8.5	0.21	3	0.87	0.99
Zooplankton	Chlorophyll *a*	0.45	18	3	0.82	0.99
Zooplankton	Biovolume	-4.9	0.093	3	0.81	0.99
Chlorophyll *a*	NN_S	-0.08	0.0166	4	0.91	0.90
Chlorophyll *a*	SRP_S	0.46	-0.008	4	0.0003	0.90
Biovolume	NN_S	24	3.63	4	0.95	0.90
Biovolume	SRP_S	202	-34	4	0.193	0.90

Note: The r^{2*} is the r^2 required for 5% level of significance.
NN_S, SRP_S – Springtime values of NN and SRP, respectively.

of prolonged deep mixing during early summer in Atlin and Tagish.

The algal species composition was more typical of some fjord lakes of Norway than other large oligotrophic lakes in Canada at this latitude. Norwegian lakes with chlorophyll concentrations of less than 2 $mg \cdot m^{-3}$ had algal assemblages dominated by chrysophytes and cryptophytes (Rognerud and Kjellberg, 1984) as were these Yukon lakes. Diatoms were dominant in most large lakes in the Northwest Territories and Labrador (Duthie, 1979; Moore, 1980). Although in some large lakes in the Territories the chrysophyte *Dinobryon bavericum* was the most frequently encountered species (Moore, 1978), *Dinobryon* sp. were not common in the Yukon lakes studied here.

For the three deepest lakes the differences in algal composition were not great. The large proportion of dinoflagellates in Marsh suggests that its shallower depth and warmer temperatures fundamentally affect species composition. However, all four lakes have low blue-green algal biomass, a common feature of most subarctic lakes (Holmgren, 1985).

The vertical distribution of algae cannot be ascertained from our limited data. However, using the relationship between algal volume and chlorophyll from June

$$\text{Chl } (mg \cdot m^{-3}) = 0.0737 + 0.0015 \text{ algal volume } (mm^3 \cdot m^{-3})$$

$$R^2 = 0.717 \qquad p < 0.01 \qquad n = 10$$

and applying it to the August volume data, estimates of chlorophyll from an intermediate depth in August can be calculated. Thus in August, Laberge had a near-surface biomass peak, whereas Atlin and Tagish had generally higher biomasses at deeper depths. The effect of our low sampling density is to bias the average chlorophyll value upward in Laberge and down in Atlin and Tagish during August. The bias in algal volume is the reverse. The biomass was probably homogenous during October sampling, as the temperature profiles indicated deep convective mixing.

Zooplankton

Zooplankton biomass values were very low, far lower than any of the smaller lakes in the region (Shortreed and Stockner, 1985). Although temperature and predation have effects on zooplankton biomass, strong correlations to growing season chlorophyll content (food concentration) have been observed in other lakes. For instance, Rognerud and Kjellberg (1984) found that for 28 Norwegian lakes, the growing season average biomass of zooplankton (top 20 m) was linearly related to the growing season average chlorophyll (top 10 m):

$$\text{Zoop } (mg \cdot m^{-3}) = 0.65 + 18 \text{ Chl } (mg \cdot m^{-3})$$

$$R^2 = 0.62 \qquad p < 0.01 \qquad n = 28$$

For the three deep Yukon lakes excluding Marsh and using zooplankton data for 0–50 m and chlorophyll data for 0–30 m, a similar linear relationship was found (Table 12), although it was not significant at the 5% level. (As Marsh Lake appears to have a different zooplankton/phytoplankton relationship [due to its shallow depth and rapid flushing], data from Marsh were not used in any of the subsequent correlation analyses.) This result must be taken as very preliminary due to the scanty data base. However, it is suggestive of a strong dependence of zooplankton on algal biomass in these big Yukon headwater lakes. There was also a similar correlation between zooplankton and algal volume.

The correlation between growing season mean zooplankton biomass and TN was almost significant at the 5% level (Table 12). The relationship with TP was not significant. The zooplankton relationship to TN is perhaps a reflection of nitrogen incorporation into zooplankton protein. Thus for these lakes, the total available nitrogen could be a measure of the potential zooplankton crop.

The species dominance pattern (Table 11) suggests that there are fundamental differences in the structures of the food webs in the four lakes. Marsh Lake with an assemblage quite different from the deeper lakes is not too surprising, considering its shallow depth and warm temperatures. It is likely that the populations of benthic organisms are high enough to affect the biomass and species composition of zooplankton in this lake. The highest growing season concentration of zooplankton was in Lake Laberge. The success of rotifers and filter-feeding cladocerans suggests that there are larger quantities of bacteria and picoplankton available than in the upstream lakes. In Atlin and Tagish, the lower relative abundances of rotifers imply a smaller forage base for these organisms.

There was a consistent difference in the cladoceran species composition between Atlin/Tagish and Marsh/Laberge. The large *Daphnia pulex* was the dominant cladoceran in the upper two lakes and was rarely observed in the lower lakes where the smaller daphnids *D. rosea* and *D. longiremis* were common. Archibald (1977) found that the large daphnid *D. middendorffiana* was dominant in the absence of *planktivorous* fish like *Coregonus clupeaformis* and *C. sardinella* in the Yukon lakes he sampled. This suggests that predation by planktivorous fish may have affected the zooplankton species composition in Marsh and Laberge.

Finally, the presence of *Senecella calanoides* in Laberge extends the known range of this species. The only other lake in the Yukon drainage basin where it has been previously reported is Kusawa Lake, on the Takhini River system upstream from Lake Laberge (Lindsey *et al.*, 1981).

A summary of lake characteristics is presented in Table 13.

EFFECTS OF FUTURE DEVELOPMENT

Potential hydro-development plans for the area include damming the Atlin River with diversion of its flow south through a different drainage basin and/or regulating the flow of the Atlin River as it is now.

Diversion of the Atlin River through a new exit to the south would not change the annual bulk residence time of Atlin Lake but would increase those of the other lakes (as they would have decreased inflows). Biological production in the central part of Atlin may increase slightly because of increased nutrients available within this part of the lake with less dilution of lake water by nutrient-poor glacial meltwater. In addition, if the turbidity plume from the glacier exits the lake with less mixing into this area there would be decreased turbidity in the central portion of Atlin. The effects on seasonal patterns would depend on the specifics of the operations at the control structure(s) involved.

Residence times of Tagish and Marsh lakes would increase about 1.7 times and of Laberge, about 1.4 times. While these are not large changes, Tagish Lake may show larger shifts in the residence times of its various arms. For instance, Graham Inlet, connecting Tagish with Atlin, would have a very large change in residence time. The mixing characteristics of the sediment plume from the Swanson River entering at the south end of Tagish may be altered and the turbidity gradient changed. The conductivity of Tagish would likely decrease and the nutrient level increase if the Atlin Lake outflow is diverted south.

Marsh Lake would still flush quickly (less than four months on a yearly basis). However, decreased summer flows could produce a significant lengthening of the residence time during the growing season. If the present Marsh Lake control structure is used to store water in summer (for electric power generation during the winter and spring), an additional increase in the growing season residence time will occur. The nutrient levels would, however, probably remain very low.

In Lake Laberge, the nutrient levels would likely increase with less dilution of the inputs from the Whitehorse sewage treatment plant and the Takhini River. The turbidity of the lake would increase as a greater percentage of input flow would come from the turbid Takhini River.

Simple regulation, rather than diversion, of the Atlin River would not alter the present yearly bulk residence times of the four lakes but would shift the seasonal patterns. Storage of water in Atlin Lake during the growing season would increase the downstream potential for biomass accumulation by decreasing washout (Reid Crowther, 1983). Increased winter flows may alter the spring ice characteristics (particularly in Graham Inlet) and change the early growing season (under-ice) nutrient dynamics.

The cumulative chemical and biological changes resulting from either of these hydrologic alterations may be complex (Daley *et al.*, 1981). Although the average general limnology of the system is unlikely to change, local and site-specific alterations may be significant. More detailed studies while the projects are still in the planning stages would be desirable.

Table 13. Summary of Lake Characteristics

Parameter	Atlin and Tagish	Marsh	Laberge
Residence time	Long	Short	Medium
Turbidity	Glacial plumes	Little	Takhini River
TDS (ppm)	45-55	47	50-55
Summer nutrient input	Low	Very low	Takhini River/ Whitehorse sewage
Algal biomass	Lowest and moderate	Moderate	Highest
Algal biomass maximum	August	June	June
Zooplankton dominance	Copepods	Cladocera	Rotifer/copepod

Despite the pronounced effects of physical processes, biological productivity in these lakes is still likely limited by the nutrients. In fact, nutrient levels in all of the lakes are so low that moderate increases are likely to have positive impacts. Artificial increases or fertilization is thus a possible management option for enhancing fisheries production. Atlin Lake, with the longest residence time and lowest nutrients, would retain added nutrients longest and, therefore, has the greatest potential for increased biomass production. Marsh Lake, with its relatively warm temperatures and low growing season nutrients, is also an enhancement candidate, despite its rapid flushing rate.

Our data do not indicate a need for tertiary treatment technology at the city of Whitehorse sewage treatment plant. Indeed, future growth in the size of Whitehorse, with concomitant increases in effluent nutrients, would likely result in some positive biological responses in Lake Laberge. Algal biomass levels in Lake Laberge are not a problem at present and the decrease in oxygen concentration over winter is small. If the zooplankton and fish are food-limited, then increased nutrients may enhance fisheries production to varying degrees in each of these four large headwater lakes.

FUTURE WORK

Several research opportunities and future information requirements are apparent from this preliminary study. In terms of nutrient cycling, the most dramatic changes occur under-ice in the early spring. Unfortunately, this is a difficult and expensive time to sample. Overflow and melting ice necessitate the use of costly helicopters for safe sampling. After ice-out, when a boat could be used as a sampling platform, limited access and low water levels make launching difficult. Although expensive, the use of a small hovercraft may solve this problem.

To obtain more precise information on the potential biological productivity of these lakes, a more intensive sampling routine is required. Direct measurements of primary production are needed throughout the limnological cycle. The percentage of production taking place under-ice and estimates of carbon transfer rates within the food web would be of value. As well, nutrient budgets for each lake would be required.

For lakewide nutrient budgets and fluxes, better analytical methods and more intensive sampling are necessary. The extremely low nutrient concentrations encountered in these Yukon lakes presented problems. Procedures with reduced detection limits and increased precision are needed, particularly for phosphorus. The Applied Microsystems CTD instrument used during this survey did not permit interrogations between the physics sampling casts and the chemistry sampling. If this were possible, chemistry depths could be selected to sample the thermally defined intervals better. A longer (multi-year) study would permit more knowledgeable selection of sampling locations and afford better estimates of both lakewide mean values and inter-annual variability. The latter may be greater than either the intra-annual or inter-lake variation.

Additional research on the bioavailability of the various nutrient supply components in these lakes is also needed. Correlations between TP and chlorophyll were poor; information on the bioavailability of the TP components may resolve this discrepancy. Similarly, knowledge of the biologically available nitrogen (BAN) along with the sources, make-up, and fate of DON would be useful. Significant proportions of these materials may be unavailable for biological production, and therefore, estimates from them of potential phytoplankton and fish yields would be in error.

More detailed studies on the interactions among phytoplankton, zooplankton and fish on an annual basis would be of value in assessing the fisheries potential of these lakes. The trophic efficiency of northern food chains and the importance of bacteria and picoplankton within them should also be studied.

Marsh Lake was the most dynamic of the lakes studied, and further work on this fast flushing system would be of value to reservoir and riverine system modellers. The timing and extent of the early spring heating of Marsh should be investigated; this heating is perhaps associated with the extensive shallow areas of Tagish Lake adjacent to the exit about 5 km upstream from Marsh Lake.

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REFERENCES

Archibald, C.P. 1977. The effects of planktivorous fish predation, lake morphometry, and lake productivity on the limnetic zooplankton of Yukon lakes. M. Sc. Thesis, University of Manitoba, Winnipeg, 96 pp.

Ball, A.J. 1983. Temperature-Turbidity Relationships of Southern Lake Laberge, June 13 to July 20. Inland Waters Directorate, Pacific and Yukon Region, Vancouver, B.C.

Bethell, G. 1981. Start-up characteristics and performance evaluation of an anaerobic sewage lagoon north of 60°, Whitehorse, Yukon Territory. Regional Program Report No. 81-9, Environmental Protection Service, Environment Canada.

Bostock, H.S. 1946. Physiography of the Canadian Cordillera with special reference to the area north of the Fifty-fifth Parallel. Geol. Surv. Can. Mem. 247.

Bottrell, H.H., A. Duncan, Z.M. Gliwicz, E. Grygierek, A. Herzig, A. Hillbricht-Ilkowska, A. Kurasawa, P. Larsson and T. Weglenska. 1976. A review of some problems in zooplankton production studies. Norw. J. Zool. 24: 419-456.

Canada, Yukon and British Columbia. 1979. Yukon River Basin Preplanning Task Force Report. Inland Waters Directorate, Vancouver, B.C.

Canadian National Committee, IHD. Canadian Survey on the Water Balance of Lakes. The Secretariat, Canadian National Committee, International Hydrological Decade, Environment Canada, Ottawa.

Carmack, E.C. and E.W. Marles. 1986. Physical Results from the N.W.R.I. Hydro-limnology Survey of the Yukon River system. National Water Research Institute, Environment Canada. In press.

Daley, R.J., E.C. Carmack, C.B.J. Gray, C.H. Pharo, S. Jasper, and R.C. Wiegand. 1981. The effects of Upstream Impoundments on the Limnology of Kootenay Lake, B.C. National Water Research Institute, Environment Canada.

Duthie, H.C. 1979. Limnology of subarctic Canadian lakes and some effects of impoundment. Arct. Alp. Res. 11(2): 145-158.

Environment Canada. 1981. Analytical Methods Manual Update. Inland Waters Directorate, Water Quality Branch, Ottawa, Canada.

Environment Canada. 1983. Historical Streamflow Summary Yukon and Northwest Territories, to 1982. Inland Waters Directorate, Water Resources Branch, Ottawa, Canada.

Gray, C.B.J. and R.A. Kirkland. 1982. Nutrient Composition and Bioavailability in Major Tributaries and Interconnecting Rivers of the Okanagan Basin. National Water Research Institute, Pacific and Yukon Region, Environment Canada.

Haney, J.F. and D.J. Hall. 1973. Sugar-coated *Daphnia*: a preservation of technique for cladocera. Limnol. Oceanogr. 18(2): 331-333.

Holmgren, S. 1985. Phytoplankton in a polluted subarctic lake before and after nutrient reduction. Water Res. 19(1): 63-71.

Jack, M.E., T.R. Osler and B.E. Burns. 1983. Water Quality Work Group Report No. 1, Yukon River Basin Commission, Indian and Northern Affairs Canada.

Kirkland, R.A. and E.W. Marles. 1983. Chemistry Data Atlin, Tagish, Bennett, Marsh, Laberge, and Teslin, June 1982-March 1983. Northern Hydro Limnology Program, National Water Research Institute, Pacific and Yukon Region. Unpublished Data Report.

Lindsey, C.C., K. Patalas, R.A. Bodaly and C.P. Archibald. 1981. Glaciation and the physical, chemical and biological limnology of Yukon lakes. Can. Tech. Rep. of Fisheries and Aquatic Sciences No. 966.

Marles, E.W. 1985. Limnological survey techniques from small aircraft. Tech. Bull. No. 139, Inland Waters Directorate, Environment Canada, Vancouver, B.C.

McCauley, E. 1984. The estimation of the abundance and biomass of zooplankton in samples. *In* A Manual on Methods for the Assessment of Secondary Productivity in Fresh Waters, J.A. Downing, and F.H. Rigler (eds.), Blackwell Pub., Oxford, England.

Moore, J.W. 1978. Composition and structure of zooplankton communities in eighteen arctic and subarctic Lakes. Int. Rev. Gesamten Hydrobiol. 63(4): 545-565.

Moore, J.W. 1980. Seasonal distribution of phytoplankton in Yellowknife Bay, Great Slave Lake. Int. Rev. Gesamten Hydrobiol. 65(2): 283-293.

Mortimer, C.H. 1981. The oxygen content of air-saturated fresh waters over ranges of temperature and atmospheric pressure of limnological interest. Mitt. Int. Ver. Theor. Angew. Limnol. No. 22.

Nicholls, K.H. and P.J. Dillon. 1978. An evaluation of phosphorus-chlorophyll-phytoplankton relationships for lakes. Int. Rev. Gesamten Hydrobiol. 63: 141-154.

Persson, G. and G. Ekbohm. 1980. Estimation of dry weight in zooplankton populations: methods applied to crustacean populations from lakes in the Kuokkel Area, Northern Sweden. Arch. Hydrobiol. 89: 225-246.

Pharo, C.H. 1981a. Lake Laberge – Bathymetry. National Water Research Institute, Pacific and Yukon Region, Environment Canada.

Pharo, C.H. 1981b. Marsh Lake – Bathymetry. National Water Research Institute, Pacific and Yukon Region, Environment Canada.

Pharo, C.H. and V.A. Chamberlain. 1983a. Tagish Lake – Bathymetry. National Water Research Institute, Pacific and Yukon Region, Environment Canada.

Pharo, C.H. and V.A. Chamberlain. 1983b. Bennett Lake – Bathymetry. National Water Research Institute, Pacific and Yukon Region, Environment Canada.

Reid Crowther & Partners Ltd. 1983. Environmental and Socio-Economic Study, Atlin Lake Storage Project. Vol. 1. Executive Summary Report prepared for Northern Canada Power Commission, Edmonton, Alberta.

Rognerud, S. and G. Kjellberg. 1984. Relationships between phytoplankton and zooplankton biomass in large lakes. Verh. Int. Ver. Theor. Angew. Limnol. 22: 666-671.

Rosen, R.A. 1981. Length-dry weight relationships of some freshwater zooplantkon. J. Freshwater Ecol. 1: 225-229.

Ruttner-Koliski, A. 1977. Suggestions for biomass calculations of plankton rotifers. Arch. Hydrobiol. Beih. Ergeb. Limnol. 8: 71-76.

Shortreed, K.S. and J.G. Stockner. 1985. Trophic status of 19 subarctic lakes in the Yukon Territory. Can. J. Fish. Aquat. Sci. In press.

Utermohl, H. 1958. Zur Vervollkommnung der Quantitativen Phytoplankton-Methodik. Mitt. Int. Ver. Theor. Angew. Limnol. 9: 1-18.

Withler, I.L. 1956. A Limnological Survey of Atlin and Southern Tagish Lakes. Management Publication No. 5, British Columbia Game Commission.

APPENDIX A

YUKON BASIN HEADWATER HYDROLOGY

The information on the hydrology of the study area was derived from Water Survey of Canada records (Environment Canada, 1983) and Bathymetry of Yukon Lakes (Pharo 1981a,b; Pharo and Chamberlain, 1983a,b).

The upper Yukon River basin (Fig. 2) is made up of ten sub-basins. Long-term surface water volume records are available from seven locations throughout the study area (Table A-1). This table also lists the maximum and minimum flows measured from these areas. The net yearly flow at the outlet of five of the sub-basins of interest is given directly (Environment Canada, 1983). Dividing the basin areas by their flow yields the net runoff depth. This is the depth of water over the entire sub-basin required to supply the measured outflow (Tables A-2a and A-2b).

The volume of runoff from sub-basin 1, Laberge, can be estimated from the Laberge outflow minus the inflow (YukonRiver at Whitehorse + Takhini River). The volumes for sub-basins 3 (Yukon River) and 9 (Marsh Lake) can be approximated, assuming that the runoff depth of these areas is equal to that of sub-basin 4 (McClintock). Reasons for this assumption are the similar degree of glaciers (zero) and similar topography and elevation.

The remaining areas, 8 (Tagish) and 5 (Bennett), can be estimated by assuming they have similar runoff depths and their total runoff accounts for the water necessary to make up that measured at the Whitehorse station.

With the estimates of the flows out of each sub-basin given in Table A-2b, selected subtotals can be calculated. These permit calculation of the residence times for each of the lakes (Table A-3). The minimum and maximum

Table A-1. Measured Sub-basin Flows

River	Sub-basin No.	Outflow volume (km^3) Mean	Maximum	Minimum	Percentage max/mean	Percentage min/mean
Atlin	10	2.96	3.88	2.06	131	70
Watson	7	0.162	0.183	0.128	113	79
Wheaton	6	0.234	0.390	0.176	167	75
McClintock	4	0.316	0.384	0.227	122	72
Takhini	2	1.92	2.91	1.52	151	79
Laberge outlet (all sub-basins)		10.1	12.5	8.17	124	81
Yukon at Whitehorse (basins 3–10)		7.54	10.0	5.86	132	78
Mean value of extremes					134±19	76±4

Table A-2a. Measured Outflows

Area	Sub-basin No.	Area (km^2)	Outflow (km^3)	Runoff depth (m)
Atlin	10	6593	2.96	0.449
Watson	7	1172	0.162	0.138
Wheaton	6	849	0.234	0.276
McClintock	4	1624	0.316	0.195
Takhini	2	8279	1.92	0.232

Table A-2b. Calculated Outflows

Area	Sub-basin No.	Area (km^2)	Outflow (km^3)	Runoff depth (m)
Laberge	1	2189	0.64	0.292
Yukon River	3	1390	0.271	0.195
Marsh	9	1218	0.238	0.195
Tagish	8	5509	2.64	0.479
Bennett	5	1510	0.72	0.479

residence times, R_{min} and R_{max}, are calculated from the extreme values listed in Table A-1.

Estimates of the relative magnitudes of the evaporation volumes are listed in Table A-4 (from Canadian Survey on the Water Balance of Lakes, Canadian National Committee, IHD). These volumes are not accounted for in Table A-2 and are only a significant inflow/outflow balance difference for Atlin Lake where sub-basin sources are not considered.

Table A-3. Residence Times

Lake	Volume (km^3)	Residence Time (yr)			Flushing rate (yr^{-1})		
		R_{mean}	R_{min}	R_{max}	R_{mean}^{-1}	R_{min}^{-1}	R_{max}^{-1}
Atlin	54.4	18.4	13.7	24.2	0.05	0.07	0.04
Tagish	21.8	3.25	2.42	4.27	0.31	0.41	0.23
Marsh	1.2	0.17	0.13	0.23	5.8	7.6	4.3
Laberge	10.8	1.06	0.80	1.41	0.93	1.3	0.71
Bennett	6.0	5.37	4.01	7.06	0.19	0.25	0.14

Table A-4. Evaporation Losses

Lake	Volume evaporation ($km^3 \cdot yr^{-1}$)	Evaporation as percentage of outflow
Atlin	0.239	8.1
Tagish	0.143	2.1
Marsh	0.039	0.5
Laberge	0.077	0.7

APPENDIX B

ALGAL DATA

Table B-1. Algal Numbers, Volumes, and Volume Percentage by Division or Class, June

Station	Depth (m)	No. ($10^6 \cdot m^{-3}$)	Volume ($mm^3 \cdot m^{-3}$)	Volume percentage (by class or division) CHR	CRY	BAC	DIN	CHL	CYA
A3	2	480	30.5	51	9	35	<1	5	<1
A3	10	681	49.3	64	16	10	4	5	<1
A5	2	907	99.1	74	5	17	4	<1	<1
A5	10	1234	120	65	16	10	3	5	<1
T4	5	1176	250	72	7	13	5	3	<1
T4	20	1181	166	63	12	19	5	1	<1
M2	2	3922	281	78	2	10	10	1	<1
M2	14	2975	244	61	4	24	10	2	<1
L2	2	4114	276	75	8	14	2	<1	<1
L2	10	3732	281	55	21	20	4	<1	<1
L5	2	1807	138	72	18	5	4	<1	<1
L5	10	2237	306	44	25	15	6	10	<1

CHR – Chrysophytes (excluding diatoms).
CRY – Cryptophytes.
BAC – Bacillariophyceae (diatoms) (class).
DIN – Dinoflagellates (class).
CHL – Chlorophytes (greens).
CYA – Cyanophytes (blue-greens).

Table B-2. Algal Numbers, Volumes, and Volume Percentage by Division or Class, August

Station	Depth (m)	No. ($10^6 \cdot m^{-3}$)	Volume ($mm^3 \cdot m^{-3}$)	Volume percentage (by class or division) CHR	CRY	BAC	DIN	CHL	CYA
A3	15	3003	166	54	4	37	5	<1	<1
A5	15	1261	196	51	6	24	4	15	<1
A7	10	966	150	54	9	19	17	1	<1
T2	10	2020	123	46	3	46	4	1	<1
T4	10	3297	278	50	2	44	4	<1	<1
T6	10	2571	62.7	86	4	9	<1	<1	<1
M2	5	885	84.4	40	3	8	48	1	<1
L2	10	1609	133	77	12	5	5	<1	<1
L5	10	874	109	60	21	9	10	<1	<1
L6	10	1085	153	54	19	11	14	2	<1

CHR – Chrysophytes (excluding diatoms).
CRY – Cryptophytes.
BAC – Bacillariophyceae (diatoms) (class).
DIN – Dinoflagellates (class).
CHL – Chlorophytes (greens).
CYA – Cyanophytes (blue-greens).

Table B-3. Algal Numbers, Volumes, and Volume Percentage by Division or Class, October

Station	Depth (m)	No. ($10^6 \cdot m^{-3}$)	Volume ($mm^3 \cdot m^{-3}$)	Volume percentage (by class or division) CHR	CRY	BAC	DIN	CHL	CYA
A3	10	1558	50.6	72	10	14	3	2	<1
T2	15	756	69.4	42	20	17	15	5	<1
T4	15	632	63.3	32	19	33	14	1	<1
T6	15	913	28.4	71	9	15	4	<1	<1
M2	5	807	57.7	47	20	16	16	1	<1
L2	4	932	61.5	54	21	21	2	1	1
L5	15	1134	105	46	19	32	<1	2	1
L6	15	878	149	29	37	31	1	3	<1

CHR – Chrysophytes (excluding diatoms).
CRY – Cryptophytes.
BAC – Bacillariophyceae (diatoms) (class).
DIN – Dinoflagellates (class).
CHL – Chlorophytes (greens).
CYA – Cyanophytes (blue-greens).

Table B-4. Algal Numbers, Volumes, and Volume Percentage by Division or Class, March

Station	Depth (m)	No. ($10^6 \cdot m^{-3}$)	Volume ($mm^3 \cdot m^{-3}$)	Volume percentage (by class or division) CHR	CRY	BAC	DIN	CHL	CYA
A3	1	341	25.0	34	64	<1	<1	<1	1
A5	1	297	27.0	31	33	29	4	1	2
T4	1	178	16.5	25	47	4	22	<1	1
T6	1	296	20.2	27	56	<1	16	<1	1
M2	1	674	56.6	38	36	10	8	6	2
L2	1	809	38.8	56	23	17	2	1	1
L5	1	532	31.9	40	23	30	5	<1	1
L6	1	394	20.5	33	66	<1	<1	<1	<1

CHR – Chrysophytes (excluding diatoms).
CRY – Cryptophytes.
BAC – Bacillariophyceae (diatoms) (class).
DIN – Dinoflagellates (class).
CHL – Chlorophytes (greens).
CYA – Cyanophytes (blue-greens).

APPENDIX C

ZOOPLANKTON DATA

Table C-1. Length-Dry Weight Relationships*

Species	a	b	Reference	Species†
Cyclops scutifer	1.0866	1.5493	Bottrell *et al.* (1976)	
Diaptomus pribilofensis	1.5013	1.730	Rosen (1981)	*D. pallidus*
Heterocope septentrionalis	1.8551	1.9756	Bottrell *et al.* (1976)	*H. saliens*
Senecella calanoides	1.2431	2.634	Bottrell *et al.* (1976)	*D. gracilis*
Daphnia rosea	1.0727	2.8915	Bottrell *et al.* (1976)	*D. longispina*
D. longiremis	1.0727	2.8915	Bottrell *et al.* (1976)	
D. pulex	1.4663	3.1932	Bottrell *et al.* (1976)	
Eubosmina coregoni	2.7839	2.505	Persson and Ekbohm (1980)	
Leptodora kindtii	- 0.822	2.67	Rosen (1981)	

* These relationships are summarized in McCauley (1984), where ln (weight) = a + b ln (length) (units are in micrograms and millimetres).
† Where statistics for species listed in column 1 were not available, the measurements from similar species below were used.

Table C-2. Rotifer Weight Based on Geometric Shape*

Genera	L (mm)	W (mm)	D (mm)	Volume formula	Weight (μg)
Asplanchna	0.320			$0.23\ L^3$	0.75
Cephalodella	0.295	0.180	0.10	0.52 LWD	0.28
Conochilus	0.10	0.075		$0.26\ LW^2$	0.015
Kellicottia	0.110	0.050		$0.26\ LW^2$	0.007
Keratella	0.10	0.050		$0.13\ LW^2$	0.003
Polyarthra	0.060			$0.28\ L^3$	0.006
Synchaeta	0.200			$0.1\ L^3$	0.080

* Ruttner-Kolisko (1977); specific gravity = 1; dry weight = 10% wet weight.

L = Length.
W – Width.
D – Depth.

Table C-3. Zooplankton (except rotifers) (individuals/sample)

Lake	Station	Date	*Diaptomus pribilofensis* Nauplii	*Diaptomus pribilofensis* Copepodids	*Diaptomus pribilofensis* Adults	*Cyclops scutifer* Nauplii	*Cyclops scutifer* Copepodids	*Cyclops scutifer* Adults	*Heterocope* or (*Senecella*)	*Daphnia* *D. rosea*	*Daphnia* *D. longiremis*	*Daphnia* *D. pulex*	*Eubosmina coregoni*	*Leptodora kindtii*
Atlin (50 m)	A3	82-06-17	9 081	28	714	3 995	3 458	1 540	2					
	A3	82-08-19	1 668	4 600	1960	27 448	21 960	3 760	103					
	A3	82-10-14	–	949	1124	17 573	6 357	814	21					
	A5	82-06-17	6 112	39	2172	14 104	6 305	2 424	20			9	5	
	A5	82-08-19	1 060	6 738	3588	6 546	14 175	918	403			26		
	A7	82-08-19	2 475	5 178	6288	17 917	10 800	528	647			34		
Tagish (50 m)	T2	82-08-20	242	10 539	8025	48 175	13 803	321	1268			50	10	
	T2	82-10-17	30	4 655	3134	8 962	42 687	159	277		10	18		
	T4	82-06-15	24 600	25	800	3 900	17 025	1 975	3196			4	75	
	T4	82-08-20	4 203	9 608	5251	65 191	10 132	1 313	638			29	1575	
	T4	82-10-17	108	5 724	4212	10 044	64 800	182	139			8	864	
	T6	82-08-20	256	2 672	475	6 954	6 771	1 623	20	3	6		61	
Marsh (25 m)	M2	82-06-16	8 487	2 067	86	540	1 855	619	22		141		18	
	M2	82-08-18	166	762	22	753	986	102			3 494		426	81
	M2	82-10-14	–	585	54	5 850	9 165	78			14 000		663	3
Laberge (50 m)	L2	82-06-19	30 863	–	2418	95 059	5 022	14 508	(265)	186	10		10	
	L2	82-08-24	489	20 428	186	64 494	51 612	1 684	(93) 5	2385	9 257	3	47	1
	L2	82-10-16	–	1 624	1995	41 183	45 999	86	(6)	1226	5 444		485	
	L5	82-06-19	17 300	273	3417	88 900	6 526	6 321	(419) 15	13	4	2	23	
	L5	82-08-24	855	11 020	1140	204 500	55 290	3 230	(115) 5	5130	7 695		1045	1
	L5	82-10-16	20	1 120	2590	75 780	36 500	70	(2)	525	4 130		175	
	L6	82-08-24	734	9 870	105	58 013	65 940	2 993	(107) 6	6983	11 666		263	3
	L6	82-10-16	30	510	1275	24 092	10 594	28		623	7 252		283	

Table C-4. Rotifers (individual sample)

Lake	Station	Date	*Conochilus*	*Keratella*	*Kellicottia*	*Asplanchna*	*Cephalodella* or *Polyarthra*	*Synchaeta*
Atlin (50 m)	A3	82-06-17			42		40(P)	
	A3	82-08-19	1 000		1 800			
	A3	82-10-14		20	760			
	A5	82-06-17			58			
	A5	82-08-19	3 412		11 681			
	A7	82-08-19	8 280		8 376			
Tagish (50 m)	T2	82-08-20	10 432		5 778		54(P)	
	T2	82-10-17			1 330		32(P)	
	T4	82-06-15	200	25	200		50(C)	
	T4	82-08-20	24 830		11 290	20	53(P)	
	T4	82-10-17	27 972		24 786	54		
	T6	82-08-20	1 232		1 891			
Marsh (25 m)	M2	82-06-16	144	53	6 289		18(P) 495(C)	2 400
	M2	82-08-24	156	269	8 915		5532(C)	48 070
	M2			624	15 483		156(C)	4 134
Laberge (50 m)	L2	82-06-19	1 054		686			
	L2	82-08-24	33 847	47	2 291	94	47(P)	
	L2	82-10-16	2 889	29	2 024	15	285(P)	
	L5	82-06-19	444		854			
	L5	82-08-24	29 735	190	5 890		475(P)	
	L5	82-10-16	2 385		2 170			
	L6	82-08-24	165 533		4 624	5	53(P)	
	L6	82-10-16	2 633		1 841	1 105		

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