Reprinted from

Canadian Journal of Zoology

Réimpression du

Journal canadien de zoologie

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Volume 54 • Number 9 • 1976

Pages 1571–1578

National Research Council Canada   Conseil national de recherches Canada

Recent limnological changes in southern Kootenay Lake, British Columbia

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Received February 18, 1976

CLOERN, J. E. 1976. Recent limnological changes in southern Kootenay Lake. British Columbia. Can. J. Zool. **54:** 1571–1578.

In response to a significant abatement of phosphate loading and the construction of a dam on its major inflow (the Kootenay River), southern Kootenay Lake experienced a number of limnological changes between 1969 and 1974. Water temperatures in 1974–1975 were similar to those previously reported for 1966–1969. However, water transparency has increased, particularly during the spring months.

Nitrate concentrations have remained unchanged since 1969, and ranged from 2 to 8 μM between 6 June 1974 and 22 May 1975. However, ammonium levels have been reduced in the winter months when mean concentration was about 1 μM. Dissolved phosphorus levels in 1966–1969 were consistently around 3 μM, but never reached I μM in 1974. Phytoplankton populations in 1974–1975 (measured as chlorophyll *a*) were lower than those during the 1966–1969 period, and evidence is presented that suggests that major shifts have occurred in the species composition of the phytoplankton. Whereas Kootenay Lake experienced blue–green and green algal blooms during the 1960's, no such phenomena were observed in 1974–1975 when the plankton was dominated by diatoms. Population maxima of the three most common zooplankters (*Cyclops bicuspidatus, Dinptomus ashlandi*, and *Diaphanosoma leuchtenbergianum*) have increased since 19661969.

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Une reduction importante du deversement de phosphates et la construction d'un barrage sur son tributaire le plus important (la riviere Kootenay) ont entraine des changements limnologiques au lac Kootenay Sud entre 1969 et 1974. Les temperatures de l'eau de 19761975 se rapprochent de celles enregistrees de 1966 a 1969. Cependant, la transparence de I'eau a augmente. particulierement au printemps.

Les concentrations de nitrates sont restees les mêmes depuis 1969, allant de 2 a 8 μM entre le 6 juin 1974 et le 22 mai 1975. Cependant. les concentrations d'ammonium ont subi une reduction durant les mois d'hiver, la moyenne se situant autour de 1 μM. Le phosphore dissous était en concentration d'environ 3 μM de 1966–1969, mais cette valeur n'a jamais atteint 1 μM en 1974. Les populations de phytoplancton en 19761975 (calcules en termes de chlorophylle a) etaient moins grandes que celles de 19661969 et certains indices portent a croire qu'il s'est produit des changements importants de composition au sein des populations de phytoplancton. Le lac Kootenay a souffert, durant les annees 1960, d'explosions de populations d'algues bleues–vertes et d'algues vertes, mais ce phenomene n'existait pas en 1974–1975, alors que les diatomees constituaient le groupe dominant. Les maxima des trois especes de zooplancton les plus communes (*Cyclops bicuspidatus, Diaptomus ashlandi* et *Diaphanosoma leuchtenbergianum*) ont augmente depuis 1966–1969.

[Traduit par le journal]

Introduction

Kootenay Lake is a large, typically oligotrophic lake located in the southeastern corner of British Columbia. Its main axis runs north–south for about 105 km; its average depth is 109 m and maximum width is 6.4 km (Zyblut 1970). Eighty percent of the lake's inflow comes from the Kootenay River entering from the south (Northcote 1972); the Duncan River enters the northern arm. The main basin is drained by a shallower west arm, which empties into the Columbia River via the Kootenay River (Fig. 1).

This lake has been of particular interest during the past 25 years because it has experienced a temporary, but dramatic, increase in phosphate loading. In 1953 a fertilizer plant near Kimberley, B.C., began operation on a tributary of the Kootenay River. Phosphate losses from this

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plant (which doubled its production in 1962 and tripled production in 1964) led to a dramatic increase in the dissolved phosphorus level of Kootenay Lake during the 1960's. Northcote (1973) reported a 50-fold increase in orthophosphate concentration in the surface waters of southern Kootenay Lake between 1949 and 1967. Physical and biological changes occurred during this time, including significant increases in zooplankton density, the appearance of algal blooms, a pH increase, and a decline in water transparency. These changes, which indicate an accelerated eutrophication of Kootenay Lake, have been described by Zyblut (1970), Taylor (1972), and Northcote (1972, 1973).

The Kimberley plant considerably reduced its fertilizer production in early 1969, and the result has been a 70–90% reduction in Kootenay Lake phosphate levels between 1969 and 1972 (Davis 1973). This investigation is intended to document the present (1974–1975) limnological status of southern Kootenay Lake, and to describe the important physical, chemical, and biological changes the lake has experienced in response to this reduced nutrient income. It is one of several Kootenay Lake studies under the direction of R. A. Parker.

Methods

Kootenay Lake's physical and biological nature are dominated by the Kootenay River, and this study concentrated on that section of the lake that is most directly influenced by the river, i.e., the southern arm. Previous workers (Taylor 1972 and Davis 1973) used sampling stations that were spaced along the north–south axis of the lake. This study involved sampling along an east–west transect located about 11 km from the mouth of the Kootenay River (Fig. 1). Station A was located about 0.9 km from the eastern shore; station B was in the middle of the lake (2.5 km from the eastern shore); and station C was about 1.1 km from the western shore.

At each station replicate water samples were taken from depths of 1, 5, and 10 m with a Kemmerer bottle. Two subsamples (200–500 ml) from each were then filtered through HA millipore filters. Filters and filtrates were frozen within 2 h of sampling, and were kept frozen until analyzed in the laboratory for chlorophyll *a*, phosphorus, nitrate, and ammonium concentration.

Chlorophyll a was estimated by soaking one set of filters in methanol for 4 h, and then measuring optical density of the extract with a spectrophotometer at 660 nm (Talling and Driver 1963). Fifty millilitres of each filtrate were used to measure ammonium concentration by the method of Solórzano (1969); another 50-ml sample was used for determination of nitrate by the phenoldisulfonic acid method (American Public Health Association *et al.* 1971); and a third filtrate sample was analyzed for total

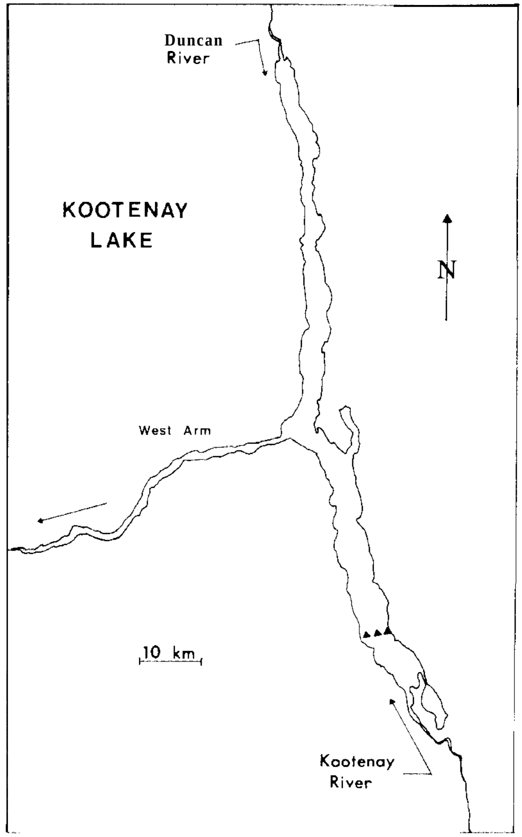

FIG. 1. Map of Kootenay Lake, showing the location of sampling stations (A).

soluble phosphorus by the ammonium molybdate method of Murphy and Riley (Strickland and Parsons 1965).

Phytoplankton samples were also taken from 1, 5, and 10 m at each station. These consisted of 250-ml water samples, which were preserved in about 1% Lugol's fixative containing 10% acetic acid. In the lab, 8- to 25-ml subsamples of each were gently filtered onto 47-mm membrane filters having 0.45-μm pore size. These filters were cleared by adding several drops of immersion oil and dried at room temperature overnight. Phytoplankton abundance was then estimated by direct counts on these cleared filters, using the method of McNabb (1960). Zooplankton tows were taken at all three stations and depths with a Clarke–Bumpus sampler having a No. 10 mesh nylon net. These samples were preserved in formalin and returned to the laboratory where five 1-ml subsamples from each were counted in a Sedgewick–Rafter cell.

Water temperature was measured at 1-m intervals, from the surface to a depth of 10 m, with a Whitney electronic thermometer. Light intensity was measured at the surface, and at depths of 1, 5, and 10 m, with a Whitney underwater photometer. The coefficient of light extinction (Hutchinson 1957) at each station was then computed from these four observations.

Results

Results of this study summarize the limnological status of southern Kootenay Lake between 6 June 1974 and 22 May 1975. Weekly samples were collected during the summer, biweekly samples during the fall and spring, and monthly samples during the winter. All results are presented as the mean of pooled measurements taken from stations A, B, and C at 1, 5, and 10 m. These are compared with the chemical and physical characteristics of southern Kootenay Lake (station B) during the time of maximum phosphorus loading (1966–1969) as described by Taylor (1972). Taylor's methods were the same as those described here, except he used 80% ethanol to extract chlorophyll *a*, and during the second half of his study he took continuous zooplankton tows instead of separate tows at discrete depths. His data are presented as monthly means for the 1966–1969 period.

Physical–Chemical Limnology

Although Kootenay Lake is thermally stratified to about 40 m from late June to October (Northcote 1972), the upper 10 m were generally homothermic. Slight temperature differences existed between stations, particularly during the period of maximum Kootenay River discharge (May and June), but no consistent pattern of temperature difference was evident. Figure 2 shows mean water temperatures for 1974–1975, and it gives mean monthly water temperatures in the upper 10 m for 1966–1969 (from Taylor 1972).

In 1972 Libby Dam was placed on the Kootenay River near Libby, Montana. Associated with the completion of this dam has been an increased light penetration in southern Kootenay Lake, and Fig. 3 demonstrates the decrease in light extinction coefficient, which has occurred since 1966–1969. This decrease is particularly dramatic in May and June. Taylor (1972) reported a mean 1966–1969 extinction coefficient of 2.81 m^{-1} for the month of June, while the maximum extinction coefficient during June 1974 was 0.71 m^{-1}. Kootenay Lake is still characterized by a spring peak in turbidity, followed by a gradual decline from August to April.

Mean nitrate concentrations in 1974 fluctuated around 3.5 μM from June to October, increasing during the winter months to a maximum of 7.83 μM in April 1975 (Fig. 4), a pattern similar to that reported by Taylor (1972) for 1966–1969. Ammonium levels within southern Kootenay Lake differ from those of 1966–1969 (Fig. 5). In 1974–1975, mean ammonium concentrations reached a maximum of 3.83 μM during the mid-

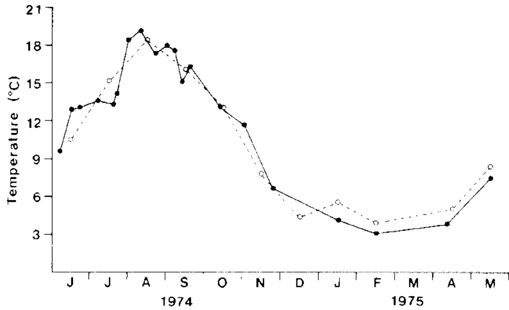

FIG. 2. Mean water temperature (°C) of southern Kootenay Lake's upper 10 m during 1974–1975 (0) and 1966–1969 monthly means (○) from Taylor (1972).

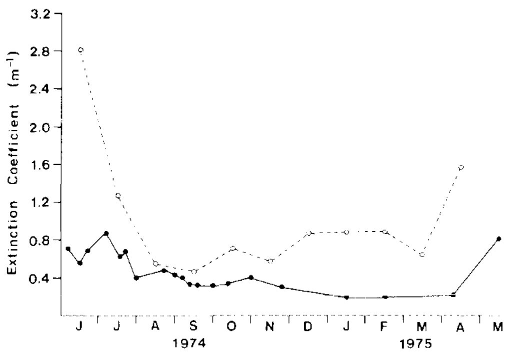

FIG. 3. Coefficient of light extinction (m^{-1}) in southern Kootenay Lake's upper 10 m during 1974–1975 (O), and 1966–1969 monthly means (○) from Taylor (1972).

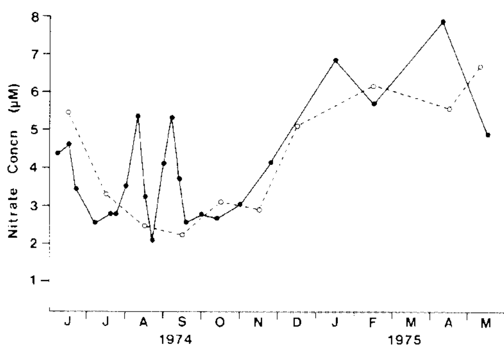

FIG. 4. Mean nitrate concentration (μM) in southern Kootenay Lake's upper 10 m during 1974–1975 (●), and 1966–1969 monthly means (○) from Taylor (1972).

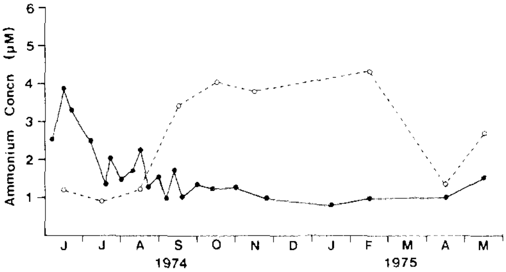

FIG. 5. Mean ammonium concentration (μM) in southern Kootenay Lake's upper 10 m during 1974–1975 (●), and 1966–1969 monthly means (○) from Taylor (1972).

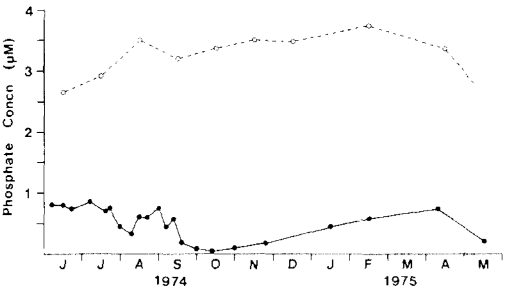

FIG. 6. Total soluble phosphorus concentration (μM) in southern Kootenay Lake's upper 10 m during 1974–1975 (●), and 1966–1969 monthly means (○), from Taylor (1972).

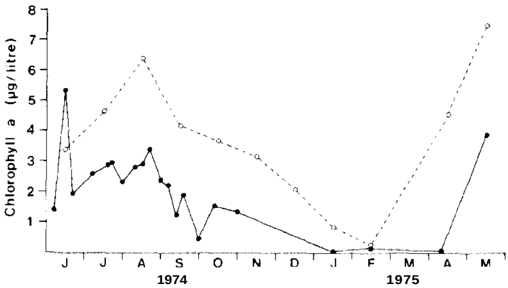

FIG. 7. Chlorophyll *a* density (µg/litre) in southern Kootenay Lake's upper 10 m during 1974–1975 (●), and 1966–1969 monthly means (○) from Taylor (1972).

dle of June, and then dropped to around I μM for the remainder of the year.

The most striking chemical change in southern Kootenay Lake has been the reduction in total dissolved phosphorus (Fig. 6). Throughout the 1966–1969 period mean phosphate levels were consistently around **3** μM, while 1974 phosphate levels never reached 1 μM, and were nearly undetectable in October. A similar reduction in particulate phosphorus has also occurred.

Phytoplankton

Mean chlorophyll a levels have decreased in southern Kootenay Lake since 1966–1969 (Fig. 7), thus suggesting that either the standing crop of phytoplankton has decreased, or that radical changes have taken place in the species composition of the algae, or both. **A** large chlorophyll peak in May–June, followed by a steady decline to very low levels in January and February, characterized both periods. Although not shown in Fig. 7 (no samples were taken for chlorophyll analysis), a moderate phytoplankton pulse was observed on 26 November 1974 (Fig. 8).

The species composition and pattern of seasonal succession of the phytoplankton are summarized in Table I. Winter months (December to mid-April) produced characteristically small standing crops. The spring plankton (April to June) was dominated by a large pulse of two diatoms (*Cyclotella* glomerata and Asterionella *formosa*), and it also included two Cryptomonads: the small (7–8 µm) Chroomonas *nordstedtii*, which had a large density in May–June, and a bigger form (20–28 pm), tentatively identified as Cryptomonas *ovata*. Dominant summer forms included three blue–greens (*Phormidium* tenue, Anabaena circinalis, and Anabaena *macro*spora), several flagellates, and two diatoms (*Fragilaria crotonensis* and Melosira crenulata). In the fall, Cryptomonas ovata, Mallomonas sp., and *Melosira crenulata* reappeared to exhibit second population peaks after a late-summer decline. Tabellariafenestrata and *Cyclotella meneg*hiniana predominated in October and November, and an unidentified microflagellate (< 5 µm) was common in October. Annual changes in the relative population densities of the twelve most common phytoplankters are presented in Fig. 8.

A peculiar assemblage, consisting of the last nine diatoms listed in Table 1, appeared briefly in May. Their appearance coincided with the peak flow of the Kootenay River, which suggests that these species are meroplanktonic; these genera are common constituents of Kootenay Lake's littoral benthic algae (Ennis 1975).

Zooplankton

The species composition of the crustacean zooplankton has apparently not changed in Kootenay Lake during the past 25 years. Two copepods (Cyclops bicuspidatus and *Diaptomus ashlandi*) existed throughout the year, and three

TABLE 1. Summary of 1974–1975 Kootenay Lake phytoplankton species composition, including maximum density and month of population maximum for each species

Species	Unit counted	Maximum density, No./ml	Month of maximum density
Diatoms			
Cyclotella glomerata	U[a]	4703	V, VI
Asterionella formosa	C	1708	VI
Tabellaria fenestrata	F	890	XI
Fragilaria crotonensis	F	194	VIII, IX
Cyclotella meneghiniana	U	52	XI
Melosira crenulata	F	43	VIII, IX
Synedra radians[b]	C	9	VIII
Synedra acus	U	5	VIII
Navicula spp.	U	3	VI
Melosira sp.	F	2	VII
Cocconeis sp.	U	r[c]	VII, VIII
Meridion sp.	U	r	V, VI
Cymbella sp.	U	r	V
Diatoma vulgare	U	r	V
Amphora sp.	U	r	V
Gomphonema sp.	U	r	V
Stauroneis sp.	U	r	V
Epithemia sp.	U	r	V
Hantschzia sp.	U	r	V
Fragilaria virescens[b]	F	r	V
Blue–greens			
Anabaena circinalis	F	149	VIII
Phormidium tenue[b]	F	96	VII
Anabaena macrospora	F	50	IX
Microcystis sp.	C	4	VIII, IX
Aphanizomenon flos-aquae	F	3	IX
Merismopedia punctata[b]	C	r	IX
Flagellates			
Chroomonas nordstedtii	U	1415	V, VI
Cryptomonas ovata[b]	U	77	VI, VII, X
Unknown microflagellate	U	50	X
Mallomonas sp.	U	10	X
Ceratium hirundinella	U	6	VIII, IX
Gymnodinium helveticum[b]	U	2	IV
Peridinium sp.	U	r	X
Green algae			
Dictyosphaerium pulchellum	C	3	IX, X
Botryococcus brauni	C	r	IX, X, XI
Staurastrum curvatum[b]	U	r	IX
Tetraedron hastatum	U	r	IX
Ankistrodesmus falcatus	U	r	IV

[a]U, unicells; C, colonies; F, filaments.
[b]Tentative species identification.
[c]Rare (= r) (maximum population density less than two individuals/ml)

cladoceran species (*Diaphanosoma leuchtenbergianum*, *Daphnia galeata*, and *Bosmina coregoni*) were found in the lake from August to early October. These five species have predominated in Kootenay Lake at least since 1949; but the total number of zooplankters has increased significantly since 1949, and *Diaphanosoma* has replaced *Daphnia* as the dominant cladoceran. Individuals of *Leptodora kindtii* and *Mysis relicta* were occasionally found. Figure 9 compares 1974–1975 zooplankton densities with the monthly means reported by Taylor (1972) for 1966–1969. Note that for each species, except *Daphnia galeata*, population densities were larger than mean densities during the 1966–1969 period. Taylor reported maximum *Diaptonzus* and *Cyclops* densities of 31.7 and 25.3 individuals per litre, respectively. In 1974–1975, maximum

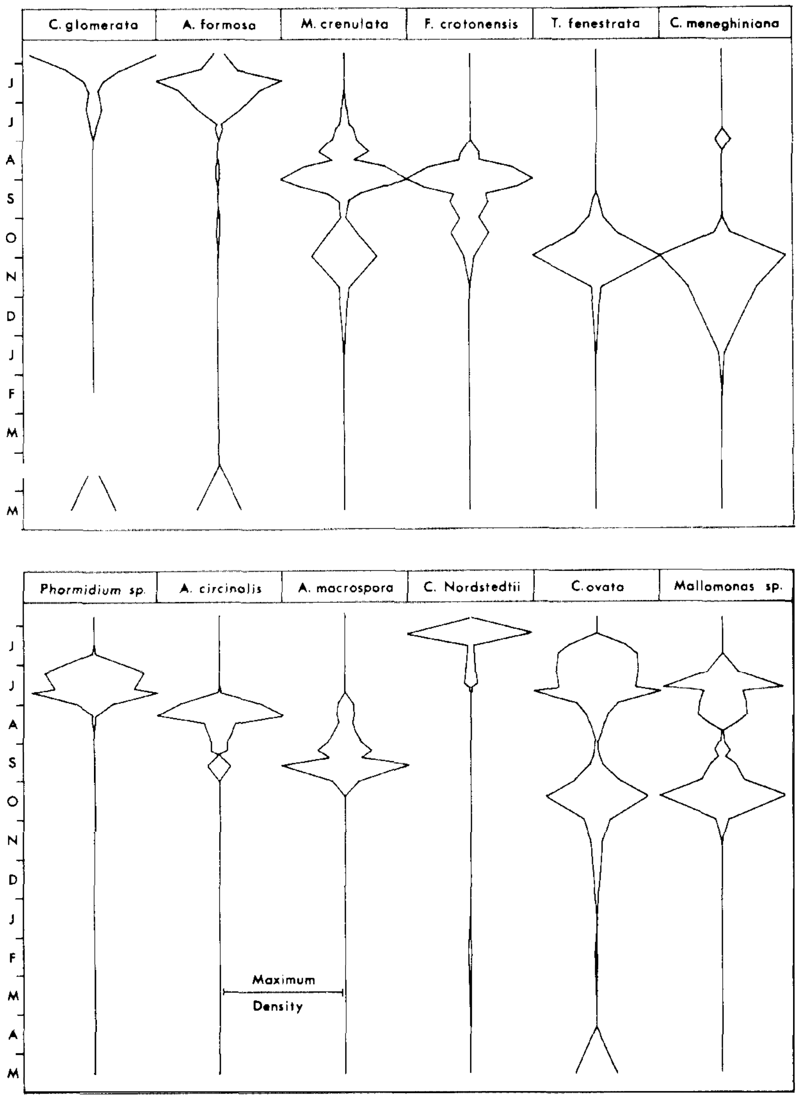

FIG. 8. Temporal changes in the relative population density (percentage of maximum density) of southern Kootenay Lake's most common phytoplankters during 1974–1975. Species included: *Cyclotella glomerata*, *Asterionella formosa*, *Melosira crenulata*, *Fragilaria crotonensis*, *Tabellaria fenestrata*, *Cyclotella meneghiniana*, *Phormidium tenue*, *Anabaena circinalis*, *Anabaena macrospora*, *Chroomonas nordstedtii*, *Cryptomonas ovata*, and *Mallomonas* sp.

densities of these two copepods were 59.3 and 59.7 individuals per litre. *Diaphanosoma*'s population maximum has increased similarly.

Discussion

Results of this study indicate that southern Kootenay Lake has experienced a number of limnological changes since 1969. The most notable physical change has been the increase in water transparency, which probably resulted from the construction of Libby Dam, which moderates peak flows of the Kootenay River, the reduction in phosphate loading, and the smaller standing crop of phytoplankton. Davis (1973) noted lowered water temperatures in southern Kootenay Lake during the summer of 1972, and attributed this change to the completion of Libby Dam. It appears now, however,

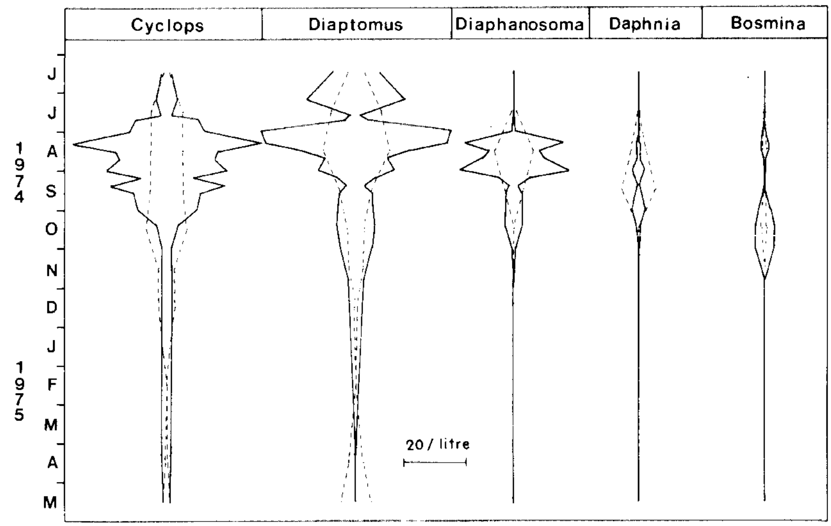

FIG. 9. Crustacean zooplankton densities (number per litre) of southern Kootenay Lake's upper 10 m during 1974–1975 (—), and 1966–1969 monthly means (- - -) from Taylor (1972). Species included: *Cyclops bicuspidatus, Diaptomus ashlandi, Diaphanosoma leuchtenbergianum, Daphnia galeata,* and *Bosmina coregoni.*

that construction of this dam has not significantly altered summer water temperatures, although water temperatures from January to May 1975 were slightly lower than means reported for these months during the 1966–1969 period.

Except for the months of July and August, the temporal pattern of nitrate concentrations throughout 1974–1975 closely approximated that of 1966–1969. Nitrate levels fluctuate erratically in Kootenay Lake, and the pattern of fluctuation tends to mirror fluctuations in chlorophyll *a* density, i.e., nitrate maxima generally coincide with chlorophyll a minima, and vice versa. This suggests that Kootenay Lake phytoplankters are using nitrate as a primary nitrogen source. While nitrate levels have essentially remained unchanged during the past 5 years, dissolved ammonium levels are lower throughout most of the year. The reason for this ammonium decline is unclear, but it may be related to the altered flow regime of the Kootenay River, or to the abatement of fertilizer production at Kimberley. Note that in 1966–1969 ammonium concentrations were highest from October to February, but in 1974–1975 these months were characterized by low levels of ammonium (Fig. 5). Again, the reasons for this change are unclear. While total inorganic nitrogen has declined somewhat since 1966–1969, phosphate levels have been greatly reduced, and during the past 5 years Kootenay Lake has gone from a state of phosphorus enrichment to a point where, at times, algal growth may be phosphorus limited.

An important biological change has been the reduction in phytoplankton standing crop as measured by chlorophyll *a* density. The general pattern of chlorophyll fluctuation throughout 1974–1975 was similar to the temporal pattern seen between 1966 and 1969. However, in 1974 Kootenay Lake exhibited a distinct mid-June pulse, which was absent in the late 1960's, and the large August peak seen in 1966–1969 was absent in 1974.

Since no published account of the composition of Kootenay Lake phytoplankton exists to date, we can only speculate about whether the recent physical–chemical changes have led to major shifts in the species composition of the algae. Northcote (1972) did report heavy blooms of green and blue–green algae during the summers of 1958, 1960, 1965, and 1967. This is in contrast with 1974–1975 when the phytoplankton of southern Kootenay Lake was dominated by diatoms (Table 1). The 'missing' August chlorophyll peak in 1974 also hints at a reduction in Cyanophyte population maxima. Blue–greens did contribute a significant part to the plankton from July to September 1974, but their densities did not approach bloom proportions. Green algae contributed only a negligible part of the phytoplankton throughout 1974-1975. These apparent changes in both the density and cpecies composition of the phytoplankton are probably the result of reduced phosphate loading, since nitrogen levels and water temperature have undergone comparatively little change. Increases in zooplankton population maxima may also have played a role in reducing algal densities.

Both Zyblut (1970) and Northcote (1972) interpreted Kootenay Lake's increased standing crop of zooplankton as an indicator of accelerated eutrophication. The continued population increases of Cyclops *bicuspidatus*, *Diaptomus* ashlandi, and Diaphanosoma *leuchtenbergianum* in 1974 are difficult to resolve, particularly in light of the other recent limnological changes that indicate a deceleration in the eutrophication process. The large populations seen in 1974 are consistent with those found in a preliminary Kootenay Lake study in 1973, thus minimizing the likelihood of 1974 being an unusually productive year. The reasons for *Daphnia*'s replacement by *Diaphanosoma* during the past 25 years are also unclear. Zyblut (1970) speculated that this may have resulted from changes in species composition of the phytoplankton and (or) selective predation by planktivorous kokanee salmon (*Oncorhynchus* nerka).

Since its significant abatement of phosphate loading in 1969, Kootenay Lake has undergone a number of changes that suggest a deceleration in its rate of cultural eutrophication, but the extent of this trend will become evident only with continued investigation of the lake's nutrient status and plankton populations.

Acknowledgements

Research was supported by grant R-800430 from the U.S. Environmental Protection Agency. I acknowledge the assistance of Leonard Henscheid, who helped in the field and performed all chemical analyses, G. W. Prescott, who graciously identified some of the more difficult algal species, Linda Cloern, who assisted in the field, and Jack Hargis, who kindly reviewed the manuscript. I am particularly indebted to R. A. Parker for his continual guidance.

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