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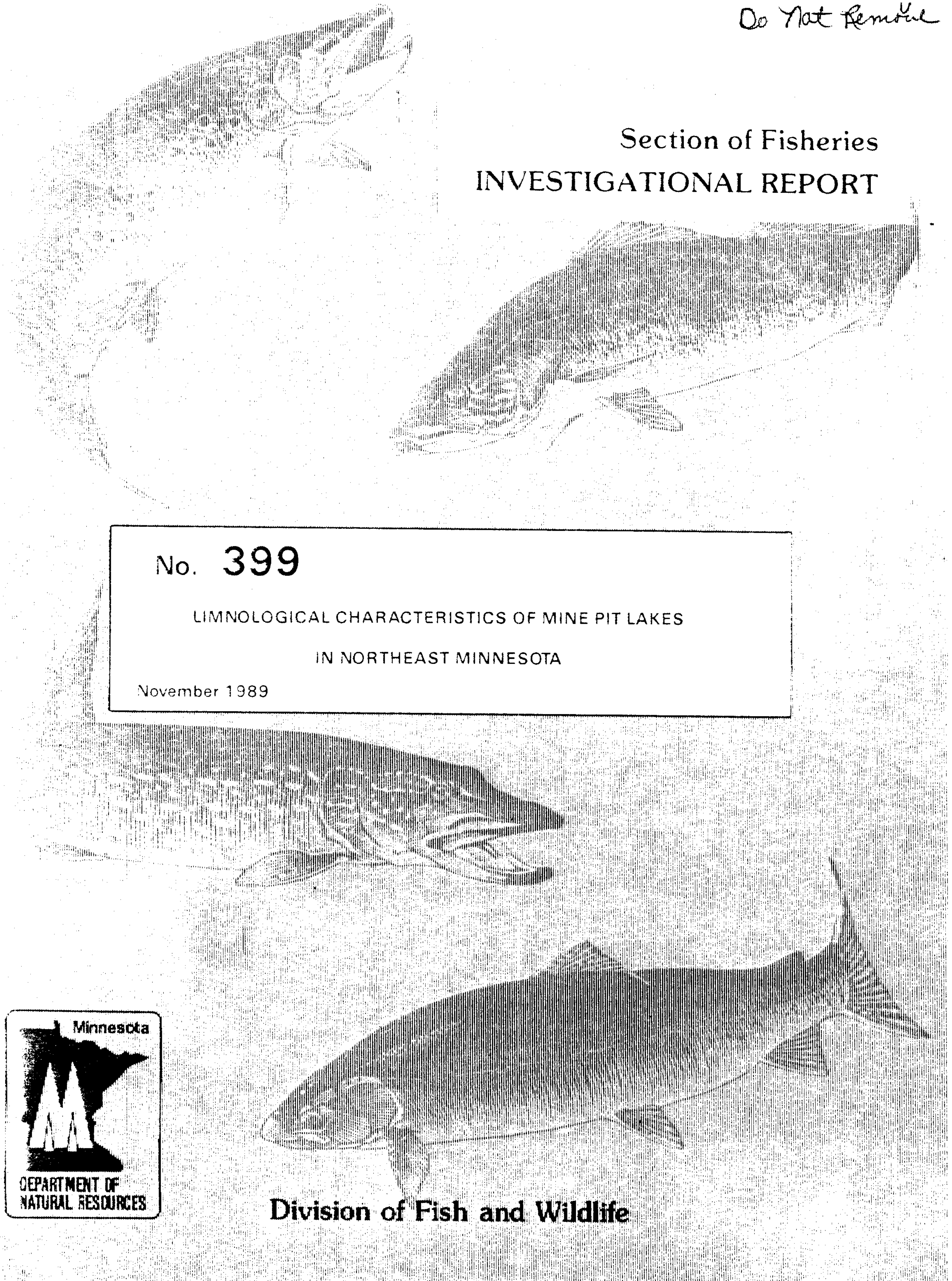

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LIMNOLOGICAL CHARACTERISTICS OF MINE PIT LAKES IN NORTHEAST MINNESOTA

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Limnological Characteristics of Mine Pit Lakes in Northeast Minnesota[1]

by

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Abstract

This study describes the fish food organisms and the physical and chemical characteristics of lakes formed in inactive iron mine pits in northeast Minnesota. Stratification and water quality were studied in 13 lakes stocked with various species of trout. Thermal or chemical stratification resulted in depletion of hypolimnetic dissolved oxygen in six of the lakes. Stratification reduced the total volume of water available to fish in midsummer, but oxygen depletion did not occur in depths where preferred temperatures for trout were found.

Measurements of all water quality parameters varied greatly during the study with differences observed among lakes and seasons of the year as well as with depth in the water column. Nonetheless, some consistencies were observed. High sulfate concentrations were one of the more distinguishing characteristics of mine pit water quality, and total alkalinity, hardness, and inorganic nitrogen levels were also high. High sulfate levels in the mine pits may indirectly affect fish by limiting their movements and by affecting aquatic plants. High levels of copper, iron, manganese and zinc measured in some water samples suggest that further investigation of heavy metals is warranted. Phosphorus was the nutrient limiting primary production.

Colonizing macroinvertebrates, benthos, and zooplankton were sampled in four lakes. Both density and diversity of invertebrates colonizing artificial substrates were low, especially below the littoral zone. Benthos and zooplankton densities were lower than or similar to densities measured in oligotrophic natural lakes. Chironomidae or oligochaeta were the most important benthos taxa in each lake. Chironomidae and *Ephemera* were the only two taxa present in all four lakes. Calanoida, cyclopidae and *Daphnia* dominated the zooplankton communities though some seasonal changes in relative abundance of these taxa were observed.

Estimates of potential yearly fish yields based on the morphoedaphic index for the four lakes were 2.8-4.3 kg per ha. Introductions of prey organisms such as forage fish or large-bodied invertebrates may not be useful in mine pit lakes managed for rainbow trout since planktivorous or insectivorous prey organisms may compete directly with rainbow trout.

Introduction

Lakes formed in abandoned iron mines have the potential to provide additional fishing opportunities in northeast Minnesota. The Minnesota Department of Natural Resources and Iron Range Resources and Rehabilitation Board (IRRRB) have created new fisheries in some mine pit lakes by stocking rainbow trout (Oncorhynchus mykiss), brook trout (Salvelinus fontinalis) and lake trout (Salvelinus namaycush). The limited information we have shows that water temperatures and dissolved oxygen concentrations are suitable for trout; however, the carrying capacities of these lakes are not known. The apparent hypotrophic characteristics of some lakes suggest that they are not productive enough to permit good trout growth at current stocking densities. Lack of information about limnological parameters and productivity of the lakes has precluded making adequate long-term management plans. Knowledge of water chemistry, plankton and benthos is needed for management plans. The purpose of this study was to characterize the present status of fish food organisms, and the physical and chemical characteristics of mine pit lakes in northeast Minnesota.

Study Sites

Thirteen mine pit lakes in the Cuyuna, Mesabi and Vermilion iron ranges (Table 1) were chosen for the study because of available boat or walk-in accesses and because of previous attempts to establish fisheries in these lakes by

Table 1. Location, age, and size of mine pit lakes studied during April 1987-February 1988. Lake maps were not available for Embarrass, Miners, Mott and Sagamore pit lakes. Closing dates indicate when the pits were allowed to begin filling with water.

Mine pit	County	Closing date	Surface area (ha)	Maximum depth (m)
Embarrass	St. Louis	1977	-	approx. 165
Forsyth	St. Louis	1956	3	18
Gilbert	St. Louis	1971	90	135
Huntington	Crow Wing	1961	40	79
Judson	St. Louis	1961	7	25
Kinney	St. Louis	1937	21	49
Miners (Pioneer)	St. Louis	1967	-	approx. 48
Mott	St. Louis	1951	-	approx. 24
Pennington	Crow Wing	1960	23	79
Sagamore	Crow Wing	1969	-	approx. 43
St. James	St. Louis	1963	40	116
Stubler	St. Louis	1957	5	11
Tioga	Itasca	1961	21	69

stocking.

Due to their common origin from iron mining, the lakes have many similar characteristics. They are typified by rock substrates, steep sides with limited littoral area, and are deep in relation to their surface area. Surface areas ranged from 3 to 90 ha and maximum depth from 11 to 165 m. Littoral areas (depths less than 4.6 m) of lakes for which contour maps were available ranged from 7-32% of the total surface areas though only one small lake, Forsyth, was greater than 17%. Mine pit lakes are relatively new features on the landscape in northeast Minnesota with the age of the study lakes ranging from 10 to 50 years.

Methods

Water Quality and Stratification

Water temperature, dissolved oxygen, and conductivity profiles were obtained from deep-water locations during winter and summer stratification, after ice-out in the spring, and before freeze-up in the fall. Sampling dates were 24-26 April, 11-14 July, 12-23 November 1987, and 13-15 February 1988. Measurements were made using an air-calibrated oxygen meter with a 30 m or 65 m probe cable and a conductivity meter with a 15 m or 183 m probe cable. The shorter cables for each instrument were used during spring 1987 when longer cables were unavailable. Secchi disc transparencies were measured during spring and summer sampling periods using the method described by Lind (1979).

Water samples were obtained from the epilimnion, metalimnion, and near the bottom of each lake during spring, summer, and winter sampling periods with a Kemmerer water sampler. Epilimnetic samples consisted of water from near the surface and metalimnetic samples were taken from depths of 6-9 m with the sampling depths based on temperature profiles for each lake. Samples were refrigerated and kept in the dark during storage and transportation to the chemistry laboratory where they were evaluated. Sulfate ion, total and ortho phosphate, nitrate, nitrite and total Kjeldahl nitrogen, pH, total and phenolphthalein alkalinity, total hardness, total dissolved solids, and chlorophyll _a_ were analyzed using the methods listed in Table 2. Since

Table 2. Standard methods (APHA 1975) used to evaluate water quality of mine pit lakes.

Water quality characteristic	Method
Alkalinity	Potentiometric titration
Aluminum	Flame photometric
Boron	Flame photometric
Cadmium	Flame photometric
Calcium	Flame photometric
Chlorophyll a	Spectrophotometric
Chromium	Flame photometric
Copper	Flame photometric
Hardness	EDTA titration
Iron	Flame photometric
Lead	Flame photometric
Magnesium	Flame photometric
Manganese	Flame photometric
Nickel	Flame photometric
Nitrite	Diazotization
Nitrate	Cadmium reduction
Organic nitrogen	Kjeldahl
pH	Specific ion electrode
Phosphate	Ascorbic acid
Phosphorus	Flame photometric
Potassium	Flame photometric
Sodium	Flame photometric
Sulfate	Turbidimetric
Total dissolved solids	Evaporation at 180 C
Zinc	Flame photometric

24-72 hours elapsed between sample collection and their arrival at the chemistry lab, the chemical analyses also reflect the storage and transportation periods.

Hypolimnetic water samples for heavy metals analyses were obtained from most of the study lakes in the Vermilion and Mesabi ranges (Miner's Lake, St. James, Embarrass, Gilbert, Kinney, Forsyth, Judson, and Tioga) on 8 September 1986. Flame photometric analyses for phosphorus, potassium, calcium, magnesium, aluminum, iron, sodium, manganese, zinc, copper, boron, lead, nickel, chromium, and cadmium were conducted at the University of Minnesota. Ammonia concentrations were determined in surface samples taken at the same time.

The morphoedaphic index (Ryder 1965) was used to estimate potential fish yields for Gilbert, Huntington, Kinney, and St. James lakes. July concentrations of total dissolved solids were used to calculate the index. Carlson's trophic status indices (Carlson 1977) were calculated using July total phosphate, chlorophyll a, and secchi disc readings for all 13 lakes.

Colonizing Macroinvertebrates

Artificial substrates for colonizing macroinvertebrates were placed in four lakes considered to be representative of mine pit lakes (Kinney, St. James, Gilbert, and Huntington) for the eight week period from 9 June to 3 August 1987. Cylindrical metal baskets with concrete spheres of known surface area (Jacobi 1971) were used as artificial substrates since they provided a surface similar to the rock available to benthic organisms in mine pit lakes. Three baskets, tied to a single rope at distances of 9, 30, and 60 m, were placed in each lake by attaching the rope to shore and stretching the rope into deep water. Actual depths for each basket were estimated using a sonar depth sounder. Invertebrates were scrubbed from artificial substrates in the field, preserved in formalin, and subsequently identified and enumerated in a laboratory.

Benthos

Benthic macroinvertebrates were sampled in Kinney, St. James, Gilbert, and Huntington lakes during 11-14 August 1987. Bottom samples were obtained from a depth of 3 m at three locations in each lake with a 232 cm^2 petite Ponar grab (Merritt and Cummins 1978). Samples were sieved through a No. 30 (595 micron) mesh screened wash bucket and preserved in formalin. Invertebrates were sorted from debris, identified and counted in the laboratory. Kruskal-Wallis tests (Hollander and Wolfe 1973) were used to compare benthos densities between pits. Probability values for the Kruskal-Wallis statistic were computed using a Chi-square approximation. Standard errors for Shannon diversity indices were calculated using the formula of Lloyd et al. (1968).

Zooplankton

Zooplankton were sampled in Kinney, St. James, Gilbert, and Huntington pit lakes during 3-6 May, 16-22 June, 11-14 August, 28 September-2 October 1987, and 11-16 January 1988. A 150 micron mesh nylon plankton net, 0.5 m in diameter and 1.5 m long, was towed vertically at dusk from 60 m or the bottom. From each lake, three replicate samples were preserved in formalin, settled volumes of zooplankton measured in the lab (APHA 1975) and organisms identified and counted in a 4 ml subsample. The volume of water filtered in a net haul was determined by multiplying the mouth area of the net by the length of the tow.

Results

Stratification

Summer thermoclines were located at greater depths in deep pits than in shallow pits. Thermoclines in midsummer were 3-7 m thick and were located between 4-13 m deep in the water column. The shallowest thermocline (Stubler pit) was located at 4-7 m and the deepest (Embarrass and St. James pits) between 7-13 m in the water column. Depth of the thermocline appeared to be related more to the maximum depth of a lake than its surface area. Temperatures in the epilimnia were 21-24 C during the July sampling period.

In addition to thermal stratification, Miners, Pennington, and Sagamore lakes showed evidence of chemical stratification in all seasons. The evidence consisted of increased conductivity and temperature with depth in the hypolimnion. For example, conductivity measured in July nearly doubled (increase from 421-820 micromhos/cm) between 45-55 m depth in the water column of Pennington lake (Figure 1). July water temperatures below the chemocline were higher than in other levels of the hypolimnion. Water temperatures in Pennington lake were 5-6 C from 14-45 m but increased to 8 C below 45 m. Chemoclines of the three lakes appeared to remain at the same depth in all seasons and monimolimnetic water was consistently devoid of dissolved oxygen (D.O.)

Thermal or chemical stratification resulted in depletion of D.O. in hypolimnia of half of the lakes

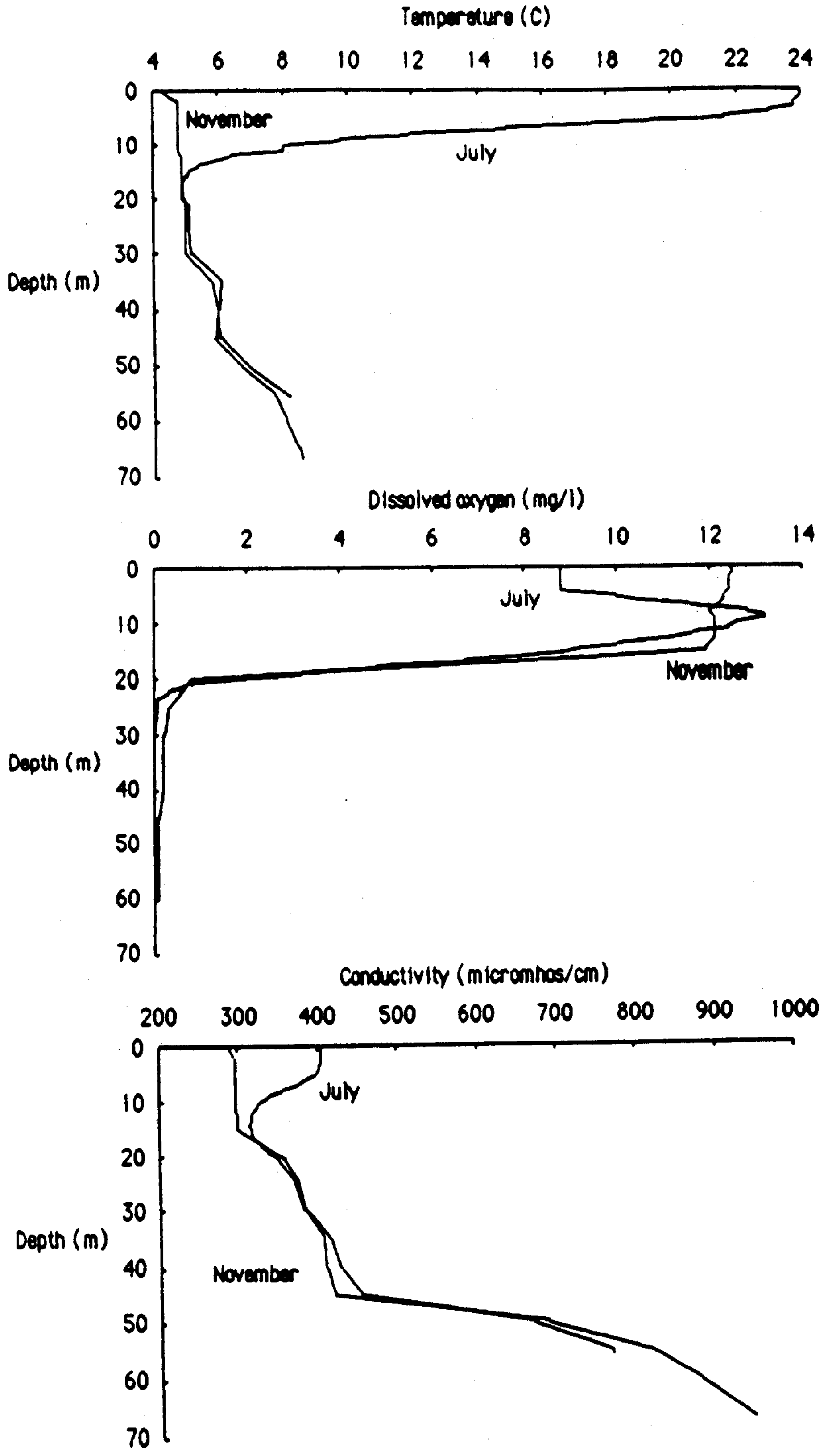

Figure 1. Temperature, dissolved oxygen, and conductivity profile for Pennington mine pit lake, 11 July and 23 November 1987.

(Tables 3-6). D.O. levels near zero were recorded from Forsyth, Miners, Mott, Pennington, Sagamore, and Stubler lakes in July. D.O. levels less than 5 mg/l were first encountered between depths of 6-30 m in those lakes. The other lakes maintained well-oxygenated water (7-12 mg/l) in depths down to 67 m. All but the shallowest lake, Stubler, exhibited positive heterograde oxygen curves in midsummer.

An unusual increase in D.O. readings with depth was recorded in Miners Lake in July. D.O. readings of 0 mg/l were recorded between 15-30 m, but readings of 4.4-5.8 mg/l were recorded below 35 m. D.O. readings at depths below 35 m in the water column were artifacts of the presence of an interfering gas, hydrogen sulfide (APHA 1975). Water samples below the chemocline in Miners Lake had the "rotten egg" odor characteristic of hydrogen sulfide.

Water Chemistry

Measurements of all water quality parameters varied greatly during the study with differences observed among lakes and seasons of the year as well as with depth in the water column of each lake. Seasonal changes in epilimnetic water quality were most apparent in sulfate levels and in nutrients such as nitrogen and phosphorus. Kjeldahl nitrogen levels were lowest in February (Table 7). Sulfur and phosphorus appeared to be very active. Average sulfate and total phosphate levels were approximately twice as high in April as in July or February. Sulfate levels as high as 300 mg/l in St. James and 350 mg/l in Huntington Lake were found during April.

Table 3. Range of temperature, dissolved oxygen and conductivity measured in mine pit lakes during May 1987.

Lake	Maximum depth sampled (m)	Temperature (C)	Dissolved oxygen (mg/l)	Conductivity (micromhos/cm)
Embarrass	30	4.0-8.8	9.3-11.7	228-240
Forsyth	17	4.3-12.4	0.1-11.0	146-181
Gilbert	30	4.1-9.5	10.0-12.0	255-273
Huntington	30	3.2-10.8	8.0-11.2	355-390
Judson	21	4.2-12.0	8.2-11.3	277-300
Kinney	30	3.5-11.5	6.8-12.1	207-220
Miners	30	3.9-10.5	0-11.0	245-260
Mott	22	4.3-11.4	3.0-11.2	163-169
Pennington	30	3.9-12.0	0.1-11.4	279-300
Sagamore	30	3.8-11.6	0.1-11.1	250-280
St. James	30	4.2-8.8	10.8-11.8	363-403
Stubler	11	6.0-12.0	8.0-14.0	174-182
Tioga	30	3.2-11.3	11.1-12.4	248-265

Variable water quality with depth in the water column was only evident in lakes which stratified chemically or exhibited hypoxic hypolimnetic conditions. For example, July sampling in Sagamore Lake (an example of a meromictic lake) provided total phosphate levels ranging from 0.008-0.091 mg/l, total Kjeldahl nitrogen of 0.60-1.25 mg-N/l, total alkalinity of 129-254 mg-$CaCO_3$/l, total dissolved solids of 318-484 mg/l, and hardness of 199-391 mg-$CaCO_3$/l. Highest levels of each parameter were measured in monimolimnetic water. Comparable ranges in St. James pit which contained a well-oxygenated hypolimnion were 0.008-0.008 mg/l total phosphate, 0.61-0.82 mg/l Kjeldahl

Table 4. Range of temperature, dissolved oxygen and conductivity measured in mine pit lakes during July 1987.

Lake name	Maximum depth sampled (m)	Temperature (C)	Depth of thermocline (m)	Dissolved oxygen (mg/l)	Conductivity (micromhos/cm)
Embarrass	120	4.9-21.9	7-13	8.6-12.1	350-470
Forsyth	17	5.0-21.5	4-9	0-11.7	181-293
Gilbert	130	4.7-22.0	7-12	8.2-12.0	308-403
Huntington	75	4.2-23.1	6-13	7.8-12.4	570-800
Judson	21	5.6-21.0	5-10	7.0-12.4	336-438
Kinney	44	3.7-21.0	4-9	2.7-12.1	245-355
Miners	48	4.4-22.5	5-10	0-9.6	289-1380
Mott	24	4.5-21.5	5-9	0-10.8	199-250
Pennington	67	5.0-23.7	5-12	0-13.2	316-950
Sagamore	43	4.7-23.4	5-11	0-14.1	341-770
St. James	110	4.2-21.7	7-13	7.5-11.9	500-700
Stubler	10	12.9-21.0	4-7	0.1-8.8	257-374
Tioga	65	4.3-24.1	5-11	8.0-13.2	277-387

Table 5. Ranges of temperature, dissolved oxygen and conductivity measured in mine pit lakes during November 1987.

Lake name	Maximum depth sampled (m)	Temperature (C)	Dissolved oxygen (mg/l)	Conductivity (micromhos/cm)
Embarrass	195	5.0-5.8	7.8-11.2	243-363
Forsyth	17	4.3-5.8	0.3-11.3	150-288
Gilbert	115	4.3-7.8	6.8-11.2	273-440
Huntington	70	5.2-7.0	10.8-11.6	416-580
Judson	20	5.0-5.5	11.9-12.0	297-313
Kinney	30	4.0-5.0	8.5-8.8	238-247
Miners	40	3.9-7.6	0-9.5	258-770
Mott	22	4.4-4.6	9.2-10.0	167-188
Pennington	56	4.3-8.2	0.1-12.4	289-771
Sagamore	40	4.2-6.1	0.2-12.4	283-570
St. James	80	4.3-5.5	7.0-11.8	408-630
Stubler	8	4.0-4.2	12.2-12.7	176-178
Tioga	63	4.9-6.9	8.4-12.6	266-327

Table 6. Ranges of temperature, dissolved oxygen and conductivity measured in mine pit lakes during February 1988.

Lake name	Maximum depth sampled (m)	Temperature (C)	Dissolved oxygen (mg/l)	Conductivity (micromhos/cm)
Embarrass	110	0-5.1	9.0-12.4	239-317
Forsyth	16	0-4.9	0.3-12.0	48-259
Gilbert	145	0-5.2	6.8-12.8	350-408
Huntington	74	0.8-4.8	9.9-10.7	700-900
Judson	20	0-4.2	8.1-12.6	359-381
Kinney	44	0-4.2	7.7-9.9	175-290
Miners	43	2.0-7.2	0-8.8	249-870
Mott	22	0.2-4.0	7.1-11.4	166-293
Pennington	75	0.9-9.0	0-11.5	277-960
Sagamore	22	0-4.8	1.1-12.0	150-356
St. James	95	0-6.0	7.1-13.4	383-660
Stubler	9	0-4.7	3.8-12.9	173-211
Tioga	63	1.8-5.0	8.5-12.9	287-389

Table 7. Means and ranges (in parentheses) of mine pit water quality characteristics measured in April and July 1987 and February 1988. Means were calculated using epilimnetic samples; ranges include all depths.

Water quality parameter	Mean concentration		
	April	July	February
Total phosphate (mg/l)	0.015 (.001-.486)	0.008 (<.001-.091)	0.007 (<.001-.046)
Ortho phosphate (mg/l)	0.006 (<.001-.428)	0.003 (<.001-.070)	0.001 (<.001-.038)
Nitrate + nitrite (mg-N/l)	0.21 (.02-1.98)	0.25 (<.01-2.40)	0.24 (.01-2.02)
Total Kjeldahl nitrogen (mg-N/l)	0.57 (.37-.91)	0.76 (.52-1.32)	0.15 (<.01-1.12)
Chlorophyll *a* (micrograms/l)	1.6 (0.2-9.0)	2.4 (0.8-11.8)	4.2 (<.01-30.1)
Sulfate (mg/l)	108 (12-400)	43 (10-70)	57 (10-80)
pH[a]	(6.6-8.2)	(7.3-8.5)	(6.6-7.7)
Total alkalinity (mg-$CaCO_3$/l)	132 (77-439)	126 (79-254)	138 (86-180)
Phenolphthalein alkalinity (mg-$CaCO_3$/l)	4 (0-13)	7 (0-10)	1 (0-4)
Total dissolved solids (mg/l)	246 (122-585)	308 (174-566)	312 (176-500)
Total hardness (mg/l)	203 (109-495)	203 (105-391)	224 (125-353)

[a] Range only.

nitrogen, 133-139 mg/l total alkalinity, 496-538 mg/l total dissolved solids, and 301-327 mg/l hardness.

Differences in water quality between lakes were apparent in nitrate, sulfate, dissolved solids, hardness, and phosphate measurements. Inorganic nitrogen levels were exceptionally high in Kinney pit but were also high in Gilbert pit. Mean nitrate + nitrite concentration in the epilimnia were 2.05 mg-N/l in Kinney and 0.26 mg/l in Gilbert pit whereas means in other pits were 0.03-0.15 mg/l. Huntington and St. James pits exhibited the highest levels of dissolved materials such as sulfates, total dissolved solids and hardness ions in epilimnetic waters (Table 9). High total phosphate levels were found in monimolimnetic waters of Miners, Sagamore, and Pennington lakes (Table 8). Monimolimnetic ortho-phosphate levels were correspondingly high in Miners and Sagamore lakes. Differences in chemical characteristics between pits did not appear to be related to their geographic location.

In spite of differences in water quality observed among lakes, some consistencies were also noted. High sulfate concentrations were one of the more distinguishing characteristics of mine pit lake water quality. Sulfates ranged from 10-400 mg/l (Table 9) with an overall mean epilimnetic value of 69 mg/l. In contrast, most Minnesota lakes have sulfate concentrations of 10 mg/l or less. Mean sulfate concentrations for each pit lake were correlated with mean levels of total hardness (R^2=0.73; F=29.2;

Table 8. Means and ranges (in parentheses) of concentrations of phosphates, nitrate + nitrite nitrogen, Kjeldahl nitrogen and chlorophyll a encountered in each pit lake. Means were calculated using epilimnetic values for all months sampled; ranges include all depths.

	Mean concentration				
Lake	Total phosphate (mg/l)	Ortho phosphate (mg/l)	Nitrate + nitrite nitrogen (mg/l)	Total Kjeldahl nitrogen (mg/l)	Chlorophyll a (microgram/l)
Embarrass	.006	<.001	.05	.4	2.5
	(<.001-.029)	(<.001-.003)	(.02-.10)	(.04-.80)	(0.4-4.3)
Forsyth	.004	.006	.09	.5	2.9
	(<.001-.011)	(<.001-.015)	(.04-.20)	(.07-1.05)	(1.4-5.3)
Gilbert	.008	.004	.26	.4	2.0
	(<.001-.034)	(<.001-.012)	(.25-.33)	(.04-.90)	(1.2-4.2)
Huntington	.004	<.001	.08	.5	1.9
	(<.001-.017)	(<.001-.001)	(.02-.17)	(<.01-.91)	(0.5-3.4)
Judson	.007	.009	.06	.4	1.4
	(<.001-.029)	(<.001-.030	(.02-.13)	(.13-.80)	(0.5-5.0)
Kinney	.005	.004	2.05	.6	3.0
	(<.001-.026)	(<.001-.012)	(1.11-2.40)	(.14-.90)	(0.9-11.8)
Miners	.009	.002	.05	.5	2.9
	(<.001-.486)	(<.001-.428)	(.01-.26)	(.16-1.12)	(0.8-9.0)
Mott	.009	.001	.15	.5	1.3
	(<.001-.023)	(<.001-.004)	(.02-.26)	(.08-.97)	(1.1-2.8)
Pennington	.030	<.001	.04	.5	2.1
	(.003-.072)	(<.001-.030)	(.01-.12)	(.08-.78)	(0.2-8.8)
Sagamore	.014	<.001	.05	.4	1.9
	(.001-.111)	(<.001-.110)	(.01-.07)	(.11-.86)	(1.3-4.3)
St. James	.011	.001	.07	.4	1.6
	(.003-.028)	(<.001-.011)	(.06-.18)	(<.01-.82)	(0.3-2.6)
Stubler	.013	.007	.03	.7	10.8
	(.006-.023)	(<.001-.022)	(.01-.07)	(.11-1.32)	(0.7-30.1)
Tioga	.011	.005	.03	.4	1.4
	(.003-.020)	(<.001-.022)	(.00-.85)	(.06-.82)	(0.2-2.9)

Table 9. Means and ranges (in parentheses) of concentrations of phosphates, nitrate + nitrite nitrogen, Kjeldahl nitrogen and chlorophyll a encountered in each pit lake. Means were calculated using epilimnetic values for all months sampled; ranges include all depths.

	Mean concentration				
Lake	Sulfates (mg/l)	Total alkalinity (mg/l)	Total dissolved solids (mg/l)	Total hardness (mg/l)	pH[a]
Embarrass	70	130	274	199	-
	(40-100)	(120-141)	(230-306)	(192-209)	(7.5-8.4)
Forsyth	50	94	159	124	-
	(30-55)	(86-163)	(122-215)	(119-169)	(6.6-8.1)
Gilbert	78	161	292	217	-
	(35-125)	(150-172)	(258-323)	(203-233)	(7.1-8.4)
Huntington	165	157	462	324	-
	(70-400)	(146-173)	(405-517)	(301-391)	(7.1-8.2)
Judson	82	155	349	243	-
	(65-100)	(125-160)	(308-390)	(233-258)	(7.2-8.5)
Kinney	62	130	250	175	-
	(45-75)	(125-134)	(194-285)	(159-190)	(6.6-8.4)
Miners	38	152	260	199	-
	(13-100)	(150-337)	(230-546)	(194-372)	(6.6-8.4)
Mott	35	82	180	127	-
	(10-50)	(77-90)	(132-232)	(111-156)	(7.0-8.3)
Pennington	40	165	291	218	-
	(25-100)	(152-439)	(257-566)	(199-495)	(7.0-8.3)
Sagamore	57	135	300	224	-
	(45-100)	(129-262)	(260-484)	(199-391)	(7.3-8.4)
St. James	148	135	478	339	-
	(70-300)	(132-141)	(184-538)	(301-353)	(7.3-8.4)
Stubler	12	94	169	116	-
	(10-19)	(89-110)	(127-500)	(105-133)	(7.2-8.1)
Tioga	65	124	286	221	-
	(50-100)	(118-135)	(245-308)	(202-241)	(7.7-8.4)

[a] Only range given.

d.f.=2,11; $P<0.0001$) and mean total dissolved solids ($R^2=0.67$; F=22.0; d.f.=2,11; P=0.0001) but no relationship was found between mean sulfate concentration and mean total alkalinity in each lake ($R^2=0.09$; F=1.1; d.f.=2,11; P=0.362).

Total alkalinity and hardness levels were also high. Most lakes contained hard (121-180 mg-$CaCO_3$/l) or very hard (greater than 180 mg/l) water (Table 9). Hardness was comprised mostly of calcium and magnesium (Table 10). For example, $CaCO_3$ equivalents for Ca and Mg in Tioga pit were 128 and 92 mg-$CaCO_3$/l respectively, totaling 220 mg/l. Mean total hardness measured in Tioga pit was 221 mg-$CaCO_3$/l. Total alkalinity in the mine pit lakes ranged from 77-439 mg-$CaCO_3$/l with an overall mean epilimnetic value of 132 mg/l. In comparison, median total alkalinity for natural lakes in northeast Minnesota is 75 mg/l. Phenolphthalein alkalinities were only 0-13 mg-$CaCO_3$/l.

Fertility

Total and ortho phosphate levels in the lakes were indicative of low fertility. Mean total phosphate in epilimnetic waters was less than 0.02 mg/l in every lake except Pennington (Table 8). Pennington Lake may be receiving nutrient contamination through seepage from adjacent Armour #2 Lake, which contains secondary sewage effluent from the city of Crosby. Mean epilimnetic ortho phosphate concentration for each study lake was less than 0.01 mg/l.

Table 10. Concentrations (mg/l) of various metal and inorganic constituents of mine pit water determined by flame photometry.

Parameter	Embarrass	Forsyth	Gilbert	Kinney	Miners	St.James	Stubler	Tioga
Al	.08	.32	.10	< .05	.10	.09	.15	.10
B	.03	.02	.02	.01	.03	.01	.01	.05
Ca	49.42	33.94	47.93	29.64	89.86	71.17	23.41	51.41
Cd	< .01	< .01	< .01	< .01	< .01	< .01	< .01	< .01
Cr	< .01	< .01	< .01	< .01	< .01	< .01	< .01	< .01
Cu	.01	< .01	.02	.01	.01	< .01	< .01	< .01
Fe	< .01	6.02	< .01	.01	1.52	< .01	.03	< .01
K	.70	.62	2.88	3.43	1.22	2.30	< .37	2.09
Mg	20.96	17.25	28.72	19.22	26.75	44.34	12.80	22.08
Mn	< .01	22.49	< .01	.25	4.30	.02	.13	< .01
Na	4.60	3.87	7.75	7.68	12.80	10.09	14.50	6.36
Ni	< .03	< .03	< .03	< .03	< .03	< .03	< .03	< .03
P	< .27	< .27	< .27	< .27	< .27	< .27	< .27	< .27
Pb	< .11	< .11	< .11	< .11	< .11	< .11	< .11	< .11
Zn	.08	.06	.08	.08	.10	.05	.05	.06

Mine pit lakes were fertile with respect to inorganic nitrogen but organic nitrogen concentrations were typical for northeast Minnesota. Mean epilimnetic nitrate + nitrite concentrations for each lake were 0.03-2.05 mg-N/l whereas nitrate + nitrite levels in northeast Minnesota are usually less than 0.01 mg/l. Ammonia concentrations were less than 0.02 mg/l in all samples. Mean epilimnetic total Kjeldahl nitrogen concentrations were 0.4-0.7 mg-N/l compared to a median of 0.5 mg/l for northeast Minnesota.

Indices of Productivity and Trophic Status

Algal biomass, as measured by the indicator chlorophyll a, was highest in July (Table 7) and slightly greater than might be expected in lakes that are typically managed for trout. Mean chlorophyll a concentrations in July were 2.4 micrograms/l in epilimnetic samples and 3.5 micrograms/lin metalimnetic samples. Median summer chlorophyll a for northeast Minnesota is 5 micrograms/l and 1-2 micrograms/l is typical for trout lakes.

The morphoedaphic index (MEI) is a method for calculating potential fish yields of lakes based on the relationship between fish production, mean depth and amounts of dissolved solids. MEIs, calculated for the four mine pit lakes which had adequate hydrographic maps, ranged from 2.8-4.7. In comparison, MEIs for nine trout lakes in Ontario ranged from 2-10 (Ryder et al. 1974). Ryder et al. (1974) also related MEIs to angling yields in the trout lakes. Using that relationship, angling yields in our mine pit lakes were predicted to be 0.3-0.6 kg/ha/yr. Estimates of potential fish yields in our mine pit lakes based on MEIs (Ryder 1965) were 2.8-4.3 kg/ha/yr.

Carlson's trophic status indices are numerical rankings of a lake's trophic condition on a scale of 0-100 with 0 representing hypotrophy, 50 representing mesotrophy and 100 indicating hypertrophy. Carlson's indices calculated for the mine pit lakes classified them as intermediate between oligotrophy and mesotrophy. Means for indices based on total phosphorus, chlorophyll a and secchi disc transparency were 34-39 but index values ranged from 20-49.

Colonizing Macroinvertebrates

Both density and species diversity of invertebrates colonizing artificial substrates were low, especially below the littoral zone. Invertebrate densities ranged from 0-2452 organisms/m^2. Highest densities in Gilbert and St. James lakes were found on baskets of substrates at depths less than 5 m but these shallow baskets only contained up to 57 organisms and 9 taxonomic groups (Table 11). Baskets of substrates below 5 m contained only 0-3 individual organisms and 0-1 taxonomic group. Chironomidae was the only group found below 5 m in both St. James and Gilbert lakes. Artificial substrates were not retrieved from Huntington and Kinney lakes because of vandalism.

Benthos

No differences among lakes were seen in densities of benthos species common to the four sampled lakes.

Table 11. Mean densities (organisms/m^2) of invertebrate taxa sampled with artificial substrates suspended at various depths in St. James and Gilbert lakes. Depths (m) were estimated using sonar. One organism per substrate equals a density of 43.1 organisms/m2.

	Mean density					
	St. James			Gilbert		
Taxonomic group	3m	8m	21m	5m	9m	24m
Platyhelminthes						
Turbellaria	0	0	0	43.1	0	0
Arthropoda						
Crustacea						
Amphipoda						
Hyallela axteca	0	0	0	129.3	0	0
Insecta						
Ephemeroptera						
Heptageniidae						
Stenonema spp.	43.1	0	0	1120.7	0	0
Caenidae						
Caenis spp.	0	0	0	172.4	0	0
Ephemeridae						
Ephemera spp.	0	0	0	43.1	0	0
Trichoptera						
Polycentropodidae						
Polycentropus larvae	43.1	0	0	301.7	0	0
pupae	43.1	0	0	0	0	0
Nyctiophylax spp.	43.1	0	0	215.5	0	0
Odonata						
Coenagrionidae						
Enallagma spp.	0	0	0	43.1	0	0
Diptera						
Chironomidae larvae	301.7	129.3	43.1	387.9	43.1	0
pupae	43.1	0	0	0	0	0
Totals	517.2	129.3	43.1	2451.8	43.1	0

Chironomidae was the most important taxon in each lake except Huntington where numbers of oligochaetes surpassed numbers of chironomids (Table 12). Chironomidae and Ephemera spp. were the only two groups present in samples from every lake. No differences in densities of these two groups were found between lakes (H=3.59-5.97; k=4(3,3,4,3); P=0.11-0.31). Shannon diversity indices ranged from 0-2.5 (Table 13) with 9-14 taxa found in each lake. Totals of mean densities in our samples ranged from 605-3,755 organisms/m^2 (Table 9). Numbers of taxa and total densities of invertebrates in benthos samples were directly related (R^2=0.86; F=12.7; d.f.=2,2; P=.07). Patchy distributions of invertebrates were indicated by sample variances which greatly exceeded means (Elliot 1977).

Zooplankton

Mean total zooplankton density for each pit in each sampling period varied from 0.5-11.0 organisms/l with differences in zooplankton standing stocks being related to physical and chemical characteristics of the pits. The average total zooplankton density across all lakes and all sampling periods was 3.2 organisms/l (SE=0.5) with a majority of samples containing less than 5 organisms/l (Tables 14-18). Gilbert and St. James lakes consistently produced less zooplankton than Kinney and Huntington. Average zooplankton densities were negatively related to maximum depths in the pits (R^2=0.92; F=22.9; d.f.=2,2; P=0.04) but positively related to average Kjeldahl nitrogen

Table 12. Mean densities (organisms/m2) of benthic taxa in ponar samples from St. James, Gilbert, Kinney and Huntington lakes on 11 August 1987.

Taxonomic group	Mean density (and standard deviation)			
	St. James	Gilbert	Kinney	Huntington
Porifera		58 (100)		
Coelenterata				
Hydridae		29 (50)		
Platyhelminthes				
Turbellaria		101 (174)	11 (22)	
Annelida				
Oligochaeta		129 (155)	108 (75)	1667 (1408)
Haplotaxida		532 (921)		
Arthropoda				
Crustacea				
Cladocera				
Daphnia spp.	29 (50)			29 (50)
Amphipoda				
Hyallela azteca		862 (1241)	11 (22)	417 (362)
Insecta				
Emphemeroptera				14 (25)
Heptageniidae				
Stenonema spp.		29 (50)	54 (54)	
Baetidae		43 (75)		
Caenidae				
Caenis spp.	43 (75)			
Ephemeridae				
Ephemera spp.	14 (25)	460 (398)	151 (114)	43 (43)
Hexagenia spp.	14 (25)	118 (209)		

Table 12. (Continued)

Taxonomic group	Mean density (and standard deviation) St. James	Gilbert	Kinney	Huntington
Odonata				
Coenagrionidae				
Ischnura or *Anamolagrion* spp.		43 (75)		
Gomphidae				
Gomphus spp.	14 (25)			14 (25)
Macromiidae				
Macromia spp.				14 (25)
Hemiptera				
Corixidae			11 (22)	
Trichoptera				
Polycentropodidae	14 (25)			
Polycentropus spp.		58 (66)		
Nyctiophylax spp.		29 (25)		14 (25)
Leptoceridae			11 (22)	
Phryganiidae pupae	14 (25)			
Coleoptera				
Staphyliridae			11 (22)	
Diptera				
pupae	29 (25)			86 (114)
Chironomidae	560 (540)	1264 (1028)	237 (174)	1236 (527)
Ceratopogonidae				14 (25)
Probezzia spp.	14 (25)			
Mollusca				
Gastropoda				14 (25)
Pelecypoda				
Sphaeriidae	14 (25)			58 (66)
Totals	759	3755	605	3620

Table 13. Shannon diversity indices, standard errors of the diversity indices and means of the indices for ponar samples taken 11 August 1987 from St. James, Gilbert, Kinney and Huntington lakes.

Lake	Replicate	Diversity	S.E.	Mean index
St. James	1	0	0	
	2	1.82	0.34	
	3	0.66	0.27	
				0.83
Gilbert	1	1.93	0.11	
	2	1.67	0.33	
	3	2.51	0.96	
				2.04
Kinney	1	1.98	0.26	
	2	1.76	0.20	
	3	2.14	0.31	
	4	1.84	0.25	
				1.93
Huntington	1	0.96	0.09	
	2	1.77	0.18	
	3	2.27	0.16	
				1.66

concentrations (R^2=0.83; F=9.9; d.f.=2,2; P=0.09) and chlorophyll a concentrations (R^2=0.65; F=3.8; d.f.=2,2; P=0.20). Average total phosphorus concentrations showed no relationship to zooplankton densities (R^2=0.24; F=0.6; d.f.=2,2; P=0.60).

Three taxa dominated the zooplankton communities though some seasonal changes in relative abundance of these taxa were observed. Calanoida, Cyclopidae and *Daphnia* spp. contributed 78-99% of the total densities of zooplankton

Table 14. Mean densities (organisms/l) of zooplankton taxa for three replicate tows taken May 3-6, 1987 from St. James, Gilbert, Kinney and Huntington lakes.

Taxon	Mean density (and standard deviation)			
	St. James	Gilbert	Kinney	Huntington
Daphnia pulex	0.021(0.011)	0.053(0.007)	0.002(0.003)	0
Daphnia spp.	0.177(0.032)	0.514(0.067)	0.154(0.032)	0.725(0.102)
Bosmina spp.	0.009(0.001)	0	0.006(0.006)	0.409(0.153)
Cladocera imm.[a]	0.027(0.016)	0.199(0.022)	0.004(0.007)	0.005(0.009)
Cyclopidae	0.221(0.035)	0.648(0.426)	5.491(1.496)	2.289(0.879)
Calanoida	0.032(0.017)	0.083(0.046)	0.161(0.019)	0.199(0.075)
Copepoda imm.[a]	0.001(0.001)	0	0.028(0.025)	0.004(0.006)
Total	0.488	1.497	5.846	3.631

[a] immature.

Table 15. Mean densities (organisms/l) of zooplankton taxa for three replicate tows taken June 16-22, 1987 from St. James, Gilbert, Kinney and Huntington lakes.

	Mean density (and standard deviation)			
Taxon	St. James	Gilbert	Kinney	Huntington
Daphnia pulex	0.154(0.045)	0.140(0.074)	0.058(0.024)	0
Daphnia spp.	1.704(0.117)	0.654(0.099)	4.855(0.411)	1.342(0.071)
Bosmina spp.	0.248(0.098)	0	0.087(0.042)	0.037(0.016)
Cladocera imm.[a]	0.143(0.029)	0.099(0.035)	0.234(0.010)	0.020(0.008)
Cyclopidae	0.821(0.182)	0.303(0.113)	4.705(2.000)	1.864(0.118)
Calanoida	0.239(0.064)	0.253(0.120)	1.005(0.221)	0.558(0.116)
Copepoda imm.[a]	0.003(0.003)	0.002(0.003)	0.053(0.052)	0.009(0.000)
Totals	3.312	1.451	10.997	3.830

[a] immature.

Table 16. Mean densities (organisms/l) of zooplankton taxa for three replicate tows taken August 11-14, 1987 from St. James, Gilbert, Kinney and Huntington lakes.

	Mean density (and standard deviation)			
Taxon	St. James	Gilbert	Kinney	Huntington
Daphnia pulex	0.124(0.096)	0.185(0.018)	0.047(0.020)	0.002(0.003)
Daphnia spp.	1.627(0.209)	0.759(0.170)	2.919(0.369)	1.004(0.234)
Bosmina spp.	0.023(0.021)	0.028(0.019)	0.301(0.020)	0.045(0.005)
Cladocera imm.[a]	0.049(0.019)	0.073(0.007)	0.114(0.068)	0.025(0.015)
Cyclopidae	0.391(0.109)	0.483(0.059)	0.726(0.047)	2.574(0.258)
Calanoida	0.206(0.041)	0.648(0.108)	0.606(0.106)	1.542(0.087)
Copepoda imm.[a]	0.004(0.003)	0.046(0.054)	0.007(0.007)	0.003(0.003)
Totals	2.424	2.222	4.720	5.195

[a] immature.

Table 17. Mean densities (organisms/l) of zooplankton taxa for three replicate tows taken September 28-October 2, 1987 from St. James, Gilbert, Kinney and Huntington lakes.

	Mean density (and standard deviation)			
Taxon	St. James	Gilbert	Kinney	Huntington
Daphnia pulex	0.135(0.092)	0.111(0.057)	0.134(0.087)	0.002(0.003)
Daphnia spp.	1.060(0.011)	0.574(0.059)	0.938(0.212)	0.600(0.103)
Bosmina spp.	0.204(0.053)	0.019(0.005)	0.192(0.068)	0.366(0.017)
Cladocera imm.[a]	0.051(0.026)	0.014(0.013)	0.034(0.006)	0.016(0.014)
Cyclopidae	0.195(0.059)	0.268(0.011)	0.527(0.090)	3.513(0.301)
Calanoida	0.098(0.096)	0.378(0.057)	0.469(0.054)	1.258(0.128)
Copepoda imm.[a]	0	0.017(0.007)	0.002(0.004)	0.014(0.020)
Totals	1.743	1.381	2.296	5.769

[a] immature.

Table 18. Mean densities (organisms/l) of zooplankton taxa for three replicate tows taken January 1-11, 1988 from St. James, Gilbert, Kinney and Huntington lakes.

	Mean density (and standard deviation)			
Taxon	St. James	Gilbert	Kinney	Huntington
Daphnia pulex	0.008(0.003)	0.018(0.010)	0.077(0.002)	0
Daphnia spp.	0.252(0.113)	0.261(0.107)	0.062(0.028)	0.077(0.013)
Bosmina spp.	0.041(0.026)	0.208(0.064)	0.013(0.013)	0.312(0.108)
Cladocera imm.[a]	0.002(0.003)	0.012(0.013)	0.062(0.030)	0.003(0.003)
Cyclopidae	0.106(0.057)	0.947(0.104)	1.131(0.443)	0.743(0.345)
Calanoida	0.186(0.107)	0.434(0.152)	0.497(0.252)	2.067(0.817)
Copepoda imm.[a]	0	0.002(0.003)	0	0
Chydorus spp.	0	0.002(0.003)	0	0
Totals	0.595	1.884	1.842	3.202

[a] immature.

measured (Figures 2-5). Daphnia spp. were most abundant in the species composition in Gilbert, Kinney and St. James lakes when water temperatures were warmest. Copepods were more important than Daphnia spp. in Huntington Lake; Cyclopidae was the most abundant taxon in Huntington Lake except in January when Calanoida became dominant.

Discussion

Stratification and Water Chemistry

Chemical and thermal stratification reduced the total volume of water available to fish in midsummer but did not affect D.O. in depths where preferred temperatures for trout were found. Except for the smallest lake, Stubler, depths of preferred temperatures for rainbow trout, lake trout and splake were well-oxygenated. Rainbow trout tend to concentrate at levels between 15.6-21.1 C (Becker 1983). Lake trout prefer 10 C water temperatures and seldom remain in water warmer than 18.3 C. Splake prefer water temperatures of 10-12.8 C.

With some notable exceptions, water quality in the mine pit lakes met standards proposed for trout and salmon culture (Piper et al. 1982) and criteria for aquatic life adopted by the Minnesota Pollution Control Agency (MPCA 1986). Boron, chromium, nickel, nitrate, nitrite and pH measurements were all within suggested ranges for aquaculture (Tables 9-10). Iron concentrations in Forsyth and Miners lakes and copper concentrations in Gilbert and St. James lakes were higher than the recommended standards.

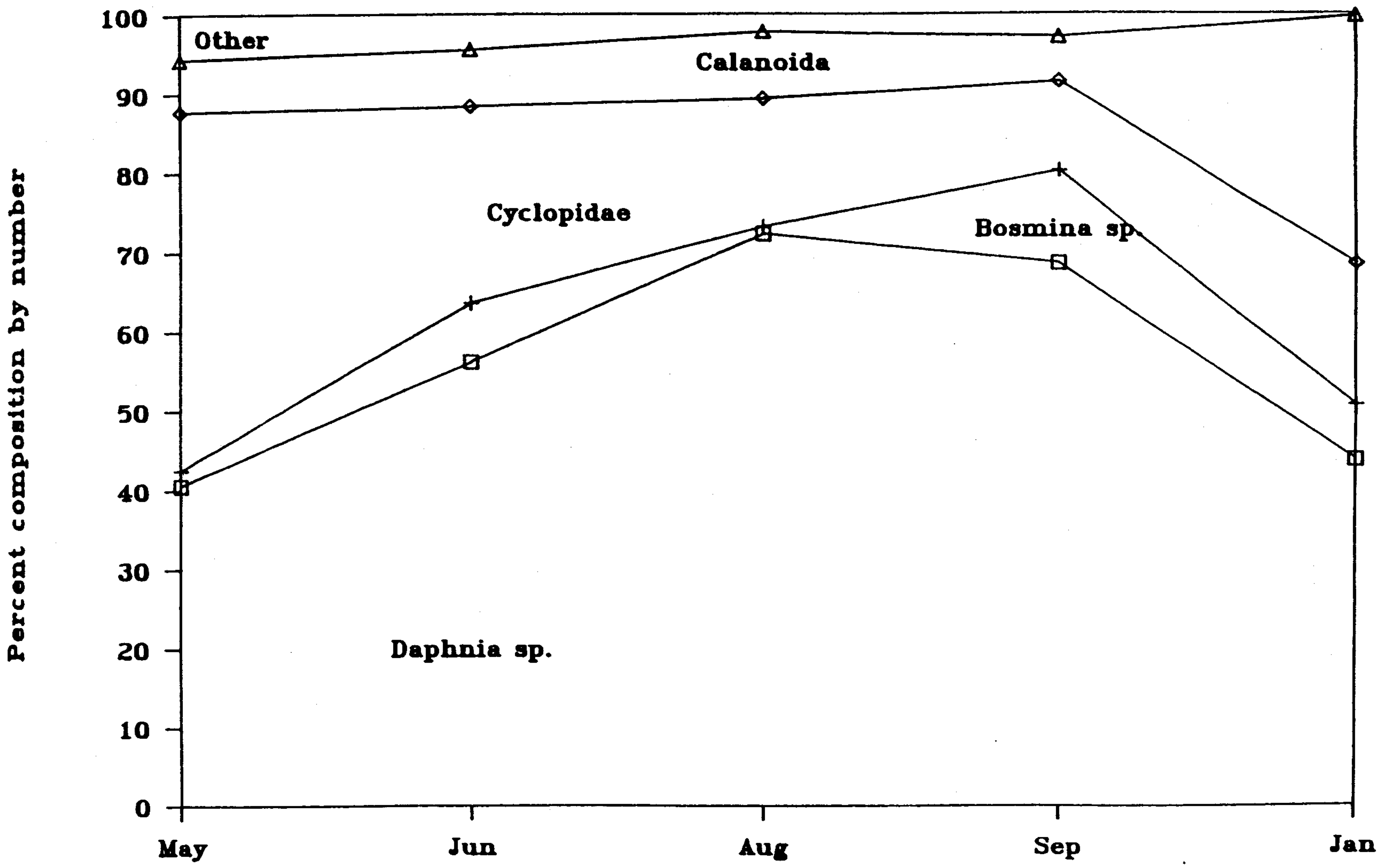

Figure 2. Zooplankton species composition in St. James mine pit lake for 4 May, 17 June, 11 August, 28 September 1987 and 16 January 1988.

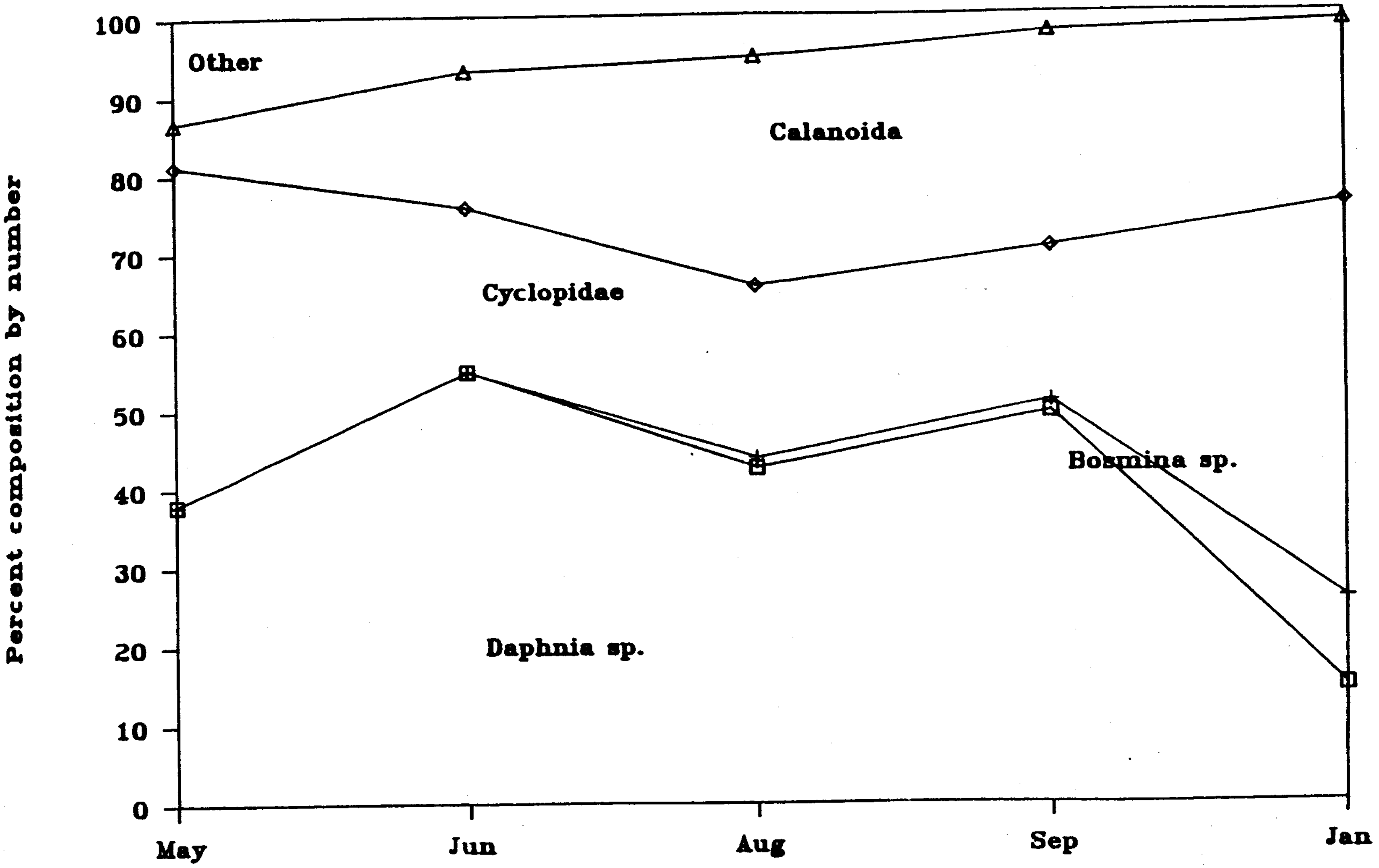

Figure 3. Zooplankton species composition in Gilbert mine pit lake for 5 May, 18 June, 12 August, 29 September 1987 and 16 January 1988.

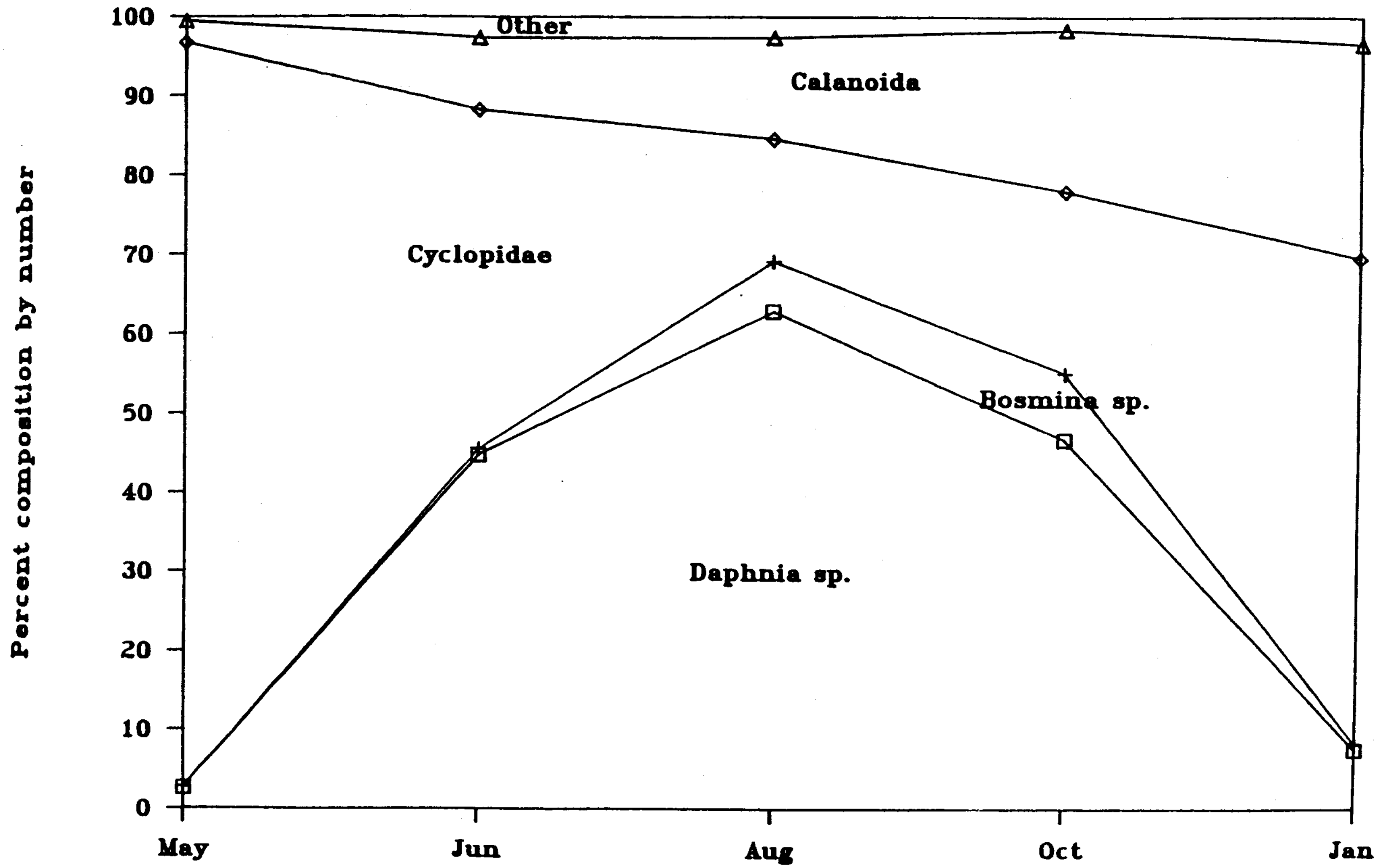

Figure 4. Zooplankton species composition in Kinney mine pit lake for 6 May, 16 June, 13 August, 2 October 1987 and 16 January 1988.

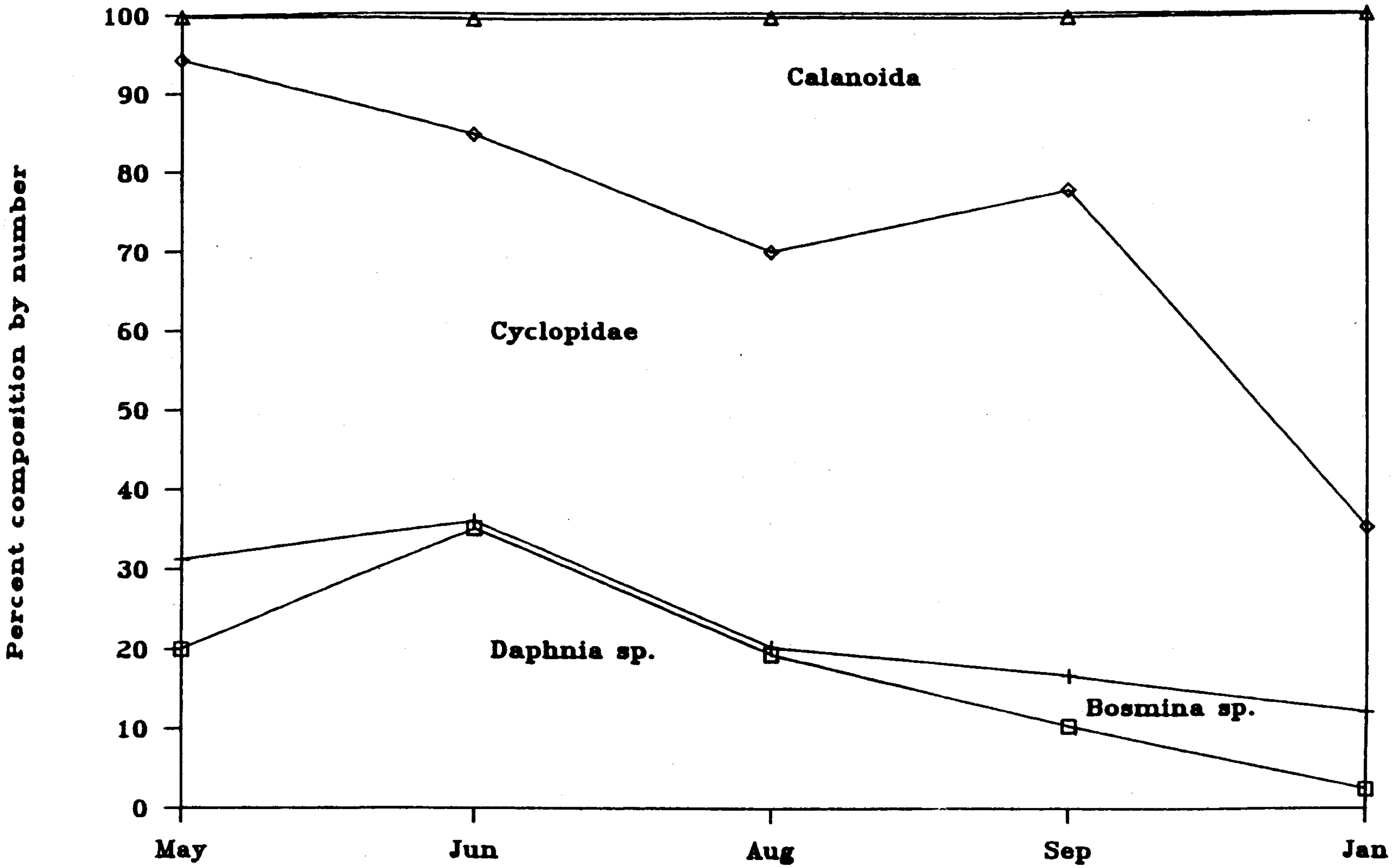

Figure 5. Zooplankton species composition in Huntington mine pit lake for 3 May, 22 June, 14 August, 30 September 1987 and 11 January 1988.

Manganese and zinc concentrations in all hypolimnetic samples were higher than the water quality criteria but epilimnetic samples taken from Embarrass, Gilbert, Mott and St.James lakes in August 1986 (Mark Heywood, MNDNR, personal communication) were below the criteria.

High sulfate concentrations may originate from metallic sulfide deposits such as pyrite (FeS_2) associated with iron ore. Pyrites contribute to high sulfate concentrations in surface mine lakes (Jones et al. 1985) and mine drainage (APHA 1975). Pyrites are oxidized to yield sulfates when exposed to weathering and aerated water (Hem 1975). In several water samples from the mine pit lakes we studied, sulfate levels were greater than the 250 mg/l which, if present in drinking water, induces catharsis in humans (Lind 1979). The St. James pit, which contained high sulfate levels in April, is used by the city of Aurora as a water supply source.

High sulfate levels in the mine lakes may indirectly affect fish by limiting their movements and by affecting aquatic plants. High sulfate concentrations apparently pose no risk to fish (Moyle 1956) but the reduced form of sulfate, hydrogen sulfide, is toxic in very low concentrations (Piper et al. 1982) and may restrict excursions by fish into the hypolimnion of lakes where the gas is present. Hydrogen sulfide smell, detected in some of our hypolimnetic samples, becomes noticeable at concentrations of less than one microgram/l (APHA 1975).

Moyle (1956) noted a relationship between sulfate concentrations and the distribution of various species of aquatic plants in Minnesota. Several plant species are limited in their distribution to waters with sulfate levels greater than 50 mg/l, but others do not appear to be tolerant of high sulfate conditions. For example, wild rice (Zizania aquatica) does not thrive in water where sulfate concentrations exceed 10 mg/l.

Alkalinity is mainly a function of carbonate, bicarbonate and hydroxyl ion content and relative amounts of each can be estimated from the relationship between total and phenolphthalein alkalinities (APHA 1975). Phenolphthalein alkalinities were substantially less than half the measured total alkalinity values. Therefore, alkalinity in the mine lakes was predominantly in the form of bicarbonate alkalinity. Borates, phosphates and silicates may also contribute to alkalinity if present (APHA 1975) but boron and phosphate concentrations were low in mine lake water samples. Silicates were not measured.

Phosphorus was the nutrient limiting primary production in mine pit lakes. Total nitrogen to total phosphorus ratios during July exceeded the range of 14-17 when phosphorus becomes the element present in the lowest concentration relative to demand by algae and plants. Ortho phosphorus concentrations in the epilimnion and metalimnion were low in July while measurable nitrate concentrations were observed in all lakes except Tioga.

Invertebrate Communities

Compared to more productive waters, benthos and colonizing invertebrate densities and species diversity in the mine pit lakes were low. Total mean density of benthos sampled in Lake St. Clair was 9,464 organisms/m^2 from 55 taxa taken with a standard Ponar grab (Hudson et al. 1986). Density of invertebrates colonizing artificial substrates in mid summer were compared to densities in the Upper Mississippi and Ohio rivers. Basket samplers in Pool 13 of the Upper Mississippi River contained an average of 20,029 organisms/m^2 and 12 taxonomic groups (Hall 1982). Mason et al. (1973) found 160-822 organisms and 7-20 taxa on basket samplers in the Ohio River near Cincinnati.

Benthos densities in the mine pit lakes were more comparable to densities found in relatively sterile water and to other waters associated with surface mining. Hamilton (1971) found early May benthos densities of 236-3,556/m^2 (samples sieved through 400-600 micron mesh) in 15 Canadian Shield lakes with low amounts of nutrients and dissolved solids. Surface coal mine lakes in Illinois and Missouri contained 274-4,321 organisms/m^2 and 7-51 taxa in Ponar samples (Jones et al. 1985). Somewhat higher densities, 5,222-7,840 organisms/m^2, were found in two ponds receiving coal mine drainage in Colorado (Canton and Ward 1981). Previous sampling in some of our mine pit lakes with an Eckman dredge (MNDNR internal report) yielded densities of 356-5,022 organisms/m^2 and 5-10 taxa per sample. The low numbers and small sizes of invertebrates that we observed may be due to some combination of the young age and low productive capacity of the pits as well as heavy predation by stocked trout.

Shannon-Weaver diversity indices for benthos samples were low compared to natural lakes but may change as the mine pit lakes age. Shannon diversity indices in natural lakes typically range from 3-4 but can be less than one in stressed environments. Jones et al. (1985) found diversity indices for benthos ranged from 0.6-4.2 in surface coal mine lakes in Illinois and Missouri. Jones et al. also found a positive correlation between the age of mine lakes and the number of benthic taxa they sampled. Ponds receiving coal mine drainage in Colorado had diversity indices for benthos ranging from 2.5-3.0 (Canton and Ward 1981).

Zooplankton densities were lower than or similar to densities measured in oligotrophic natural lakes. Balcer (1988) reported mean concentrations of copepods and cladocerans which totalled 19.6 organisms/l in western Lake Superior. Watson and Wilson (1978) reported crustacean densities ranging from 0.4-5.2 organisms/l for tows with 64 micron mesh nets from various depths in a lake-wide survey of Lake Superior. Whiteside et al. (1985) found total densities of 35.3-69.0 organisms/l during 1979-1981 using vertical tows with 64 micron mesh nets in the more mesotrophic Lake Itasca, Minnesota. In comparing our density estimates with others, it should be noted that our estimates could be biased if the organisms in our study lakes occupied only a portion of the water column we sampled.

Zooplankton densities in the mine pit lakes were similar to densities found in four northeast Minnesota trout lakes where growth of rainbow and lake trout varied from very slow to very fast (Jodene Hirsch, MNDNR, personal communication 1988). Hirsch found 5-8 organisms/l for samples taken in July with an 80 micron mesh Wisconsin net towed vertically. Thus trout growth may depend, at least in part, on food resources other than plankton. Another trout lake in northeast Minnesota, Thrush Lake, sampled with an 80 micron mesh net during May through October, 1986 and 1988, had zooplankton densities (excluding rotifers) ranging from 14.2-56.2 organisms/l (Marilyn Danks, MNDNR, personal communication, 1989).

Excluding rotifers which were not vulnerable to the mesh size we used, zooplankton concentrations were also similar to other surface mine lakes. Two ponds at a coal mine in Colorado had 6-36 organisms/l as sampled with a 64 micron mesh plankton net (Canton and Ward 1981). Tews (1986) recorded mean seasonal densities of 3-13 organisms/l from a coal sediment pond in Montana. Three other iron mine pit lakes in northeast Minnesota, sampled with an 80 micron mesh net, contained 3-24 organisms/l (Margaret Rattei, Barr Engineering Co., personal communication 1988).

Productivity

Evidence that the mine pit lakes are relatively unproductive was obtained from measurements of phosphorus, the morphoedaphic index, and from the low abundance of benthos and colonizing invertebrates. MEIs were low because the deep, steep-sided nature of the pits was reflected in mean depths used to calculate the MEIs. The steep-sided nature of the pits restricts distribution of rooted macrophytes, and the invertebrates and fish which use macrophytes to a small area.

This study also provided evidence that mine pit lakes have the potential to become more productive if additional phosphorus becomes available as they age. Evidence consisted of high levels of nitrates and dissolved materials in the water, chlorophyll *a* measurements, and Carlson's trophic status indices which were higher than expected. Nitrate levels in this study were more similar to levels encountered in agricultural areas of Minnesota than to levels in northeast Minnesota. High amounts of dissolved materials were apparent in measurements of water hardness, total dissolved solids, and conductivity even though these measurements varied substantially among lakes. July chlorophyll *a* concentrations were frequently higher than typical summer concentrations for trout lakes in northeast Minnesota (1-2 micrograms/l). Carlson's indices indicated that mine pit lakes often tended toward mesotrophy.

Management Implications

Physical, chemical and biological characteristics of the mine pit lakes in northeast Minnesota vary enough that it is difficult to make generalizations applicable to all pit lakes. Characteristics of these lakes may also change as the lakes age. Therefore, discretion should be used in applying generalizations to individual lakes.

High levels of copper, iron, manganese and zinc measured in some of our water samples suggest that further investigation of heavy metals in mine pit lakes is warranted. In the future, a graphite furnace method should be used instead of flame photometry for heavy metal analyses. Detection limits for cadmium, copper, lead and zinc using flame photometry were near or above the Minnesota Pollution Control Agency criteria for aquatic life. The graphite furnace method can achieve detection limits necessary for comparison with criteria for aquatic life (Jim Strudell, MPCA, personal communication, 1987). Sediment or fish tissue samples, however, may be more useful than water samples for evaluating the potential accumulation of metals or other toxic chemicals in fish.

An effort should be made to document trout growth rates in mine pit lakes. The apparent low productive capacity of lakes in the Mesabi and Vermilion ranges may be resulting in slow growth of trout. Fisheries personnel in Ely and Grand Rapids have made personal observations of emaciated lake trout and rainbow trout in the lakes. In contrast, rainbow trout stocked in lakes in the Cuyuna range may be exhibiting better growth than trout in the other ranges but there is no supporting growth rate work to confirm these observations. Marking of stocked fish may be a useful tool for evaluating growth.

Stocking rates based on long term productive potential, as measured by the MEI, would not support recent levels of angler use in the mine pit lakes. Mine pit fisheries have been structured around high stocking rates and rapid harvests of fish. That fish are harvested heavily was demonstrated by a dramatic decline in trout numbers observed in Pennington Lake during 1987 using sonar (Tim Brastrup, MNDNR, personal communication, 1988). The number of sonar targets declined rapidly after the spring stocking until very few targets were observed by late fall. Changing management objectives to allow longer-term fish growth or production would require scaling down stocking rates if claims of poor growth are substantiated. Lower stocking rates would likely cause a decrease in angler use of the lakes compared to the use received when the IRRRB was stocking large numbers of catchable-sized trout.

Introductions of prey organisms (either forage fish or large-bodied invertebrates) are not likely to be useful in mine pit lakes where rainbow trout fisheries are being established since planktivorous or insectivorous fish or invertebrates may compete directly with rainbow trout. Crustaceans, especially Daphnia spp., and insects are important food items for rainbow trout (Becker 1983). Introduction of redside shiners (*Richardsonius balteatus*) reduced both growth rates and survival of rainbow trout in two British Columbia lakes (Johannes and Larkin 1961). Redside shiners competed with rainbow trout for amphipods and presumably also for *Daphnia* spp. Introductions of invertebrates such as crayfish have had unpredictable effects on trout. Crayfish were introduced into a lake in Minnesota where they were heavily used as a food resource by stocked rainbow trout (Johnson 1978) but rainbow trout exhibited a decline in growth after crayfish were introduced into a Utah reservoir (Hepworth and Duffield 1987). Crayfish altered the food web and reduced energy transfer to the trout. Because of unpredictable or potentially adverse effects in lakes managed for rainbow trout, any introductions of new forage species should be evaluated by closely monitoring trout growth.

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