Heavy-Metal Contamination by Atmospheric Fallout of Several Flin Flon Area Lakes and the Relation to Fish Populations

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High concentrations of zinc and other heavy metals were found in lakes in the immediate vicinity of the Flin Flon smelters. In a study of 31 lakes, 7 had Zn levels above 100 $\mu g/\ell$, 6 had levels between 50 and 100 $\mu g/\ell$, and the remainder had concentrations <50 $\mu g/\ell$. The accuracy and precision of the heavy metal chemical analyses were evaluated using intercomparisons with other laboratories and a standard reference water. A linear relationship was demonstrated between $\log_{10}$ concentration of Zn, Cu, and SO_4^{2-} and $\log_{10}$ distance from the smelter, suggesting atmospheric fallout as the main source of these substances in the lakes. Fishes were more tolerant of these high zinc concentrations than would be expected on the basis of the responses of fish and other aquatic organisms to similar concentrations of zinc in some laboratory toxicity tests.

Key words: heavy metals, zinc, atmospheric fallout, fish toxicity, lake contamination, chemical analysis, Flin Flon, Canada

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Nous avons trouvé de hautes concentrations de zinc et autres métaux lourds dans les lacs situés dans le voisinage immédiat des hauts fourneaux de Flin Flon. Sur 31 lacs étudiés, 7 ont des niveaux de Zn dépassant 100 $\mu g/\ell$ 6 entre 50 et 100 $\mu g/\ell$, et la balance ont des teneurs <50 $\mu g/\ell$. Des comparaisons avec d'autres laboratoires et avec une eau-étalon nous ont permis de vérifier la précision des analyses chimiques de métaux lourds. Nous démontrons une relation linéaire entre le $\log_{10}$ de la teneur en Zn, Cu et SO_4^{2-} et le $\log_{10}$ de la distance du haut fourneau, ce qui donne à croire que la retombée atmosphérique est la principale source de ces substances dans les lacs. Les poissons tolèrent mieux ces hautes teneurs en zinc qu'on s'y attendrait en se basant sur leur réponse et celle d'autres organismes aquatiques à de semblables concentrations de zinc dans certains essais de toxicité en laboratoire.

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THERE are at least two major problems associated with the setting of "safe" limits for metals in the aquatic ecosystem. Firstly, interlaboratory comparison studies on metal analysis, e.g. Uthe et al. (1971), Van Loon (1974), and Lauwerys et al. (1975), have indicated that variability obtained is often so high as to cast doubt on the validity of much of the metal data now in the literature. Secondly, there is very little information concerning the response of fish populations to gradual accumulations of sublethal or chronic concentrations of heavy metals in natural aquatic systems.

The purpose of this work was to examine the response of fishes in natural lake systems to sublethal concentrations of Zn or mixtures of Zn and other metals. A study of the condition of fish populations was undertaken from a selection of lakes with varying Zn and other heavy-metal levels. The area near Flin Flon, Manitoba, was selected because the possibility existed that the lakes, of almost neutral pH in this vicinity, had been contaminated by atmospheric fallout containing heavy metals.

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Materials and Methods

Study Area

Flin Flon, Manitoba, is located on the Manitoba–Saskatchewan border at roughly 55°N, 102°W (Fig. 1). A Cu, Zn, Ag, Au sulfide ore has been mined and smelted at this location since 1930. Production is presently 4172 t/day. Winds in the area (Fig. 2) which intersect the stack gases, blow in a predominantly northwest, southeast direction (Monthly record of meteorological observations in Canada). Atmospheric fallout from stack emissions contains sulfur acids and metal-bearing aerosols. Until recently, stack heights were < 30 m. Now, in an effort to dilute contamination close to the smelter, a tall stack is in operation. Tailings are dumped into Flin Flon Lake (Fig. 1) which is now nearly obliterated. Water drainage occurs from Flin Flon Lake through Ross Lake into the northwest arm of Schist Lake. Cliff Lake, northeast of Flin Flon, is the town water supply.

Sampling and Sample Preservation

A clean Van Dorn water sampler was used to collect $1\text{-}\ell$ water samples at 1 m depth from 31 lakes. One sample was taken near the center of each lake. In Hamell, Cliff, and Ross lakes, samples were taken at up to five locations and at approximately 2-m depth intervals to the bottom. Spring, summer, and fall sampling programs were carried out over the period 1973–74.

All samples for pH were placed in nonacid-washed, high-density, linear polyethylene bottles. Determinations of pH were made at 20°C within 2 h of completion of sampling. A Radiometer Model 53 Specific Ion Meter, calibrated prior to each set of determinations using pH 4 and 7 buffers, was used. Water for heavy metal analysis was stored in acid-washed, high-density, linear polyethylene bottles at 4°C.

"Dissolved" metal concentrations were obtained by filtering a sample immediately after collection through an acid-washed and distilled-water-rinsed 0.45-μm porosity membrane filter. The filtrate was acidified with 3 ml of 1:1 HNO_3 for every 1000 ml of sample as recommended by the EPA (1971).

"Total" metal was determined from an unfiltered sample that was collected and acidified at the site. In the laboratory a suitable volume of the sample was placed in an acid-washed beaker and evaporated to near dryness in the presence of HNO_3. A blank was run with each sample set.

Sulfate, calcium, magnesium, and pH were determined from nonacidified samples according to the procedures of Stainton et al. (1974). Alakalinity was not determined.

Heavy Metal Analyses

A solvent extraction–atomic absorption procedure similar to that of Kinrade and Van Loon (1974) was used. A solution of two chelating agents, 1% ammonium pyrolidine dithiocarbamate (APDC) and 1% diethyl ammonium diethyl dithiocarbamate (DDDC) in water, was employed to extract heavy metals into methylisobutyl ketone (MIBK). An acetate buffer

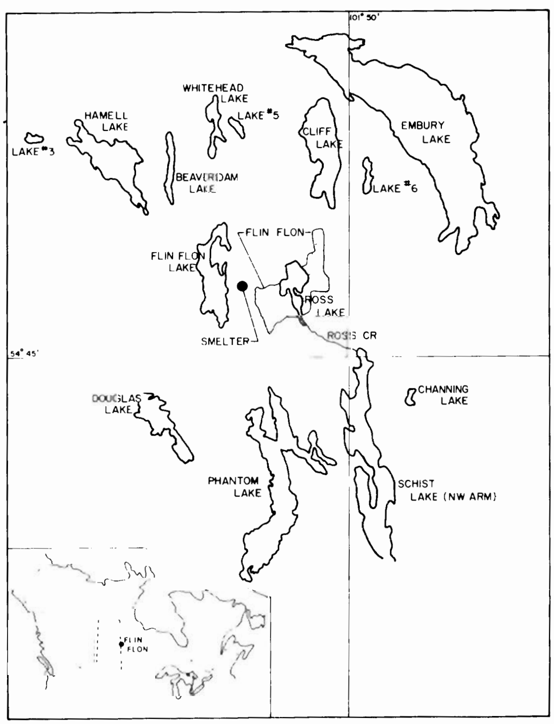

FIG. 1. Flin Flon, Manitoba, area.

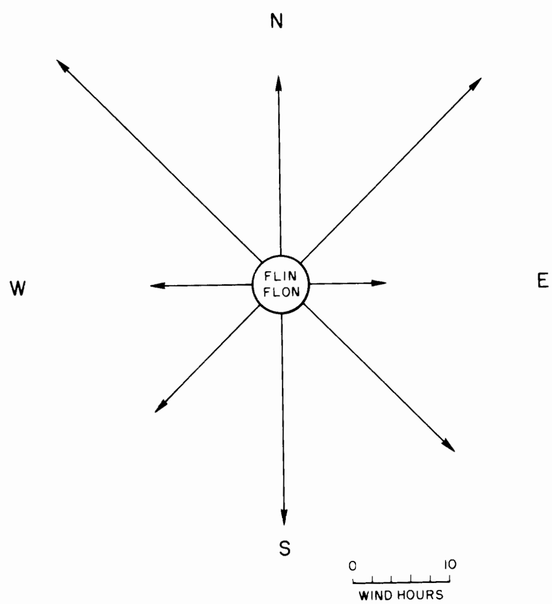

FIG. 2. Summary of winds in the Flin Flon area.

was used. Stock solutions were prepared by dissolving pure metals in acid. Heavy-metal working solutions were prepared fresh each day.

Appropriate volumes of working solutions, samples, blanks and EPA-1 were placed in separatory funnels equipped with Teflon stopcocks. The extraction was done at pH 4. A control sample (EPA-1) was run with every 20 samples. Blanks were included with each sample set. An Instrumentation Laboratories Model 153 equipped with a three-slot burner was used. The spectral lines employed were 324.7 nm Cu, 213.9 nm Zn, 248.3 nm Fe, and 228.8 nm Cd.

Brungs et al. (1976) point out that, currently, toxicity studies should be based on dissolved quantities of metal determined after 0.45-μm filtration. To examine the chemical form of the Zn in Hamell Lake, an unacidified sample was taken in the spring of 1974. Samples of water were analysed before and after filtration through 60-, 5.0-, 0.45-, and 0.2 μm porosity filters. All the samples were acidified after filtration and evaporated in the presence of strong acid. Hamell Lake water, filtered through 0.45-μm filters, was also analyzed by DC differential pulse polarography using a P.A.R. Model 174 polarograph.

Fish Study Method

Eight of the lakes with the highest Zn concentrations, ranging from 50 to 8000 $\mu g/\ell$, were fished with gill nets of stretched-mesh size ranging from 18 to 100 mm. Ross, Hamell, and Cliff lakes were fished with approximately 600 m of gillnet. Embury, Phantom, Whitehead, Douglas, and Lake No. 6 were netted with 50–125 m of the variable-mesh nets. Fish were measured for fork length and weighed, and the condition of the ovaries was noted. Scales were taken from selected samples of fish for age determination.

Chemical Analysis

Because of the lack of acceptable standard reference samples, it is difficult to assess the precision and accuracy of analytical methods for the determination of metals in water. The U.S. Environmental Protection Agency has issued three water–trace standards, designated EPA-1, EPA-2, and EPA-3. EPA-1, one sample with every 20 unknowns, was used as a control throughout this study and was analyzed 10 times.

Recognizing the need to have a further assessment of accuracy, we undertook an interlaboratory comparison of heavy metal analyses with three other laboratories.

In the analysis of water, where micrograms-per-litre levels are being measured, blanks are crucially important. All data reported were corrected for blanks. Samples of lake water, obtained as described above, were analyzed for SO_4^{-2}, Fe, Cu, Cd, Zn, Ca, and Mg. The pH was also determined.

Results and Discussion

Standard deviations obtained from a metal analysis of the EPA-1 water standard show that adequate precision was obtained (Table 1). Acceptable agreement with analyses of other laboratories was obtained for all heavy-metal elements and in all samples except for Cu and Pb in Swedish lake samples (Table 1). The good agreement obtained for these two elements in other sample types, including the EPA-1 standard reference sample, suggests that the results in this study are accurate. Spiking and other "accuracy" tests, involving the addition of metal standard solution to the sample, were not done because of the well-known pitfalls of these approaches.

Of the 31 lakes surveyed, 7 had average Zn concentrations > 100 $\mu g/\ell$, 3 lakes had concentrations ranging from 51 to 100 $\mu g/\ell$, 8 had concentrations ranging from 11 to 50 $\mu g/\ell$, and 12 had concentrations of $\leqslant$ 10 $\mu g/\ell$ (Table 2). Ross Lake had excessive concentrations of almost all chemicals measured. The northwest arm of Schist Lake also contained high concentrations of Cu, Cd, and Zn, similar to concentrations found by other workers (Crowe 1973). Lakes farthest from the smelter had the lowest

TABLE 1. Interlaboratory study of the metal content of freshwaters. Average values are presented, with standard deviations in parentheses.

	Our lab ($\mu g/\ell$)	Other lab(s) ($\mu g/\ell$)
Swedish lakes		
Zn	36	44
	42	48
Cu	2	0.4
	2	0.4
Ni	3	3
	2	2
Pb	4	<0.1
	7	0.1
Fe	93	124
	43	38
Cd	0.3	<0.5
	0.3	<0.5
Tap water		
Pb	4	4
	9	6
	300	330
River water		
Fe	260	300
Zn	18	18
Cu	35	33
Pb	2	1
EPA-1[a]		
Zn	8 (2)	10
Cd	2 (0.5)	1.8
Fe	25 (3)	18
Pb	33 (4)	28
Cu	8 (1)	9

[a]Accepted values.

TABLE 2. Chemical variables (0.45 μm filtered). Values represent four sampling periods. —, indicates no value available; *, receives effluent.

Lake	Distance from smelter (km)	pH	Ca (mg/ℓ)	Mg (mg/ℓ)	SO_4^{2-} (mg/ℓ)	Fe (μg/ℓ)	Cu (μg/ℓ)	Cd (μg/ℓ)	Zn (μg/ℓ)
Ross*	1.8	4.0	210	20	550	1600	450	50	8000
Beaverdam	3.5	7.5	40	6	30	54	23	1	450
Lake 6	5.0	7.9	15	4	15	30	12	0.5	150
Lake 5	5.0	7.7	7	2	10	68	13	0.5	110
Douglas	5.0	8.1	24	4	20	10	8	0.3	60
Cliff	5.3	7.6	16	4	16	10	10	0.4	85
Whitehead	5.3	8.0	16	2	8	100	10	0.5	150
Hamell	5.8	7.8	16	3	13	15	11	0.6	300
Channing	6.3	8.1	35	5	23	10	2	<0.2	25
Phantom	7.3	8.8	18	5	19	20	5	0.3	55
Schist N.W.*	7.5	6.2	30	4	30	20	13	5	1300
Schist Main	—	7.5	15	2	15	8	5	0.2	170
Lake 4	8.0	7.5	10	2	17	50	10	0.6	50
Lake 3	8.0	7.5	12	3	10	100	8	0.4	50
Embury	8.2	7.7	14	4	16	15	10	0.4	50
We	11.0	7.6	13	5	12	50	6	<0.2	15
Wonderland	11.0	7.5	13	5	13	50	6	<0.2	18
Johnson	12.0	7.8	8	2	10	30	3	0.2	10
Little Spruce	12.0	8.3	30	11	33	50	3	<0.2	5
Nesootao	12.5	7.6	—	—	12	26	8	0.2	30
Mosher	15.0	—	—	—	15	43	4	<0.2	17
Scottie	15.0	8.3	6	2	—	5	1	<0.2	2
Bluenose	17.0	8.2	6	3	6	9	2	<0.2	5
Kisseynew	20.0	—	—	—	5	90	1	<0.2	1
Neso	24.0	7.7	8	3	6	40	2	<0.2	1
Twin	30.0	7.9	12	3	6	62	1	<0.2	5
Naosap	30.0	7.6	—	—	6	50	2	<0.2	7
Maskunow	33.0	7.5	6	2	8	200	<1	<0.2	1
Otter	33.5	7.7	10	4	8	150	2	<0.2	4
Maligne	50.0	8.2	14	4	5	22	2	<0.2	1
Winteringham	70.0	7.8	6	2	5	30	<1	<0.2	1

concentrations of heavy metals which were similar to mean concentrations found in 109 relatively unpolluted lakes in northwestern Ontario (Beamish et al. 1976). Other metals, such as Ni, Hg, As, and Pb, were analyzed but values were very low or showed no trend. Of these, in a grossly contaminated lake such as Ross Lake, As, Hg, Ni, and Pb were 5, 6, 30, and 80 μg/ℓ, respectively. This compares with 0.5, 0.8, < 1, and < 1, respectively, for an uncontaminated lake (Van Loon unpublished data).

Fish were surviving in Hamell Lake despite the high concentrations of Zn. To see whether Zn was dissolved or particulate in form, filtration studies were done showing the following results:

Filter size (μm)	Zn (μg/ℓ)
No filtration	Variable ~ 1000
60	350
5	340
0.45	380
0.2	350

Toxicity to fish is dependent on the form of the metal (Brungs et al. 1976). From the text table it can be seen that any metal which passes the 60-μm filter also passes the 0.2-μm filter. Hence, the 350 μg/ℓ Zn in the spring sample of 1974 Hamell Lake water is either very finely divided or soluble. By EPA definition (1971), it is soluble.

Polarographic analysis of Hamell Lake water was accomplished to determine whether the Zn was bound or free. The amount of Zn found is as follows:

Sample treatment	Zn (μg/ℓ)
Acidified	240
Nonacidified	260
Acidified–evaporated	340

Analysis of the acidified–evaporated sample of Hamell Lake water gave 340 μg/ℓ Zn. This agrees well with 350 μg/ℓ Zn obtained for this sample by atomic absorption. A nonacidified sample analyzed by polarography gave 260 μg/ℓ Zn. The one-half wave potential for the Zn reduction in all cases, above, was the same and corresponded to the value obtained from a reduction of Zn in a simple $Zn–HNO_3$ standard solution. These data suggest that up to 260 μg/ℓ Zn is not very strongly complexed by either organic or inorganic species.

Atmospheric Fallout

Ross and Schist lakes receive effluent from the smelter operation. Hence, these lakes were excluded from the calculations to determine the relationship of atmospheric fallout to lake chemistry. There was a strong linear relationship found between $\log_{10}$ Zn, Cu, and SO_4^{-2} and $\log_{10}$ distance from the smelter as follows:

For Zn, $\log y = 3.51 - 2.13 \log x$
$r = -0.90$, $F = 18.9$, significant at $P > 0.05$
For Cu, $\log y = 1.70 - 1.01 \log x$
$r = -0.84$, $F = 19.6$, significant at $P > 0.05$
For SO_4^{-2} $\log y = 1.59 - 0.505 \log x$
$r = -0.74$, $F = 88.0$, significant at $P > 0.05$

No linear relationship was found between Fe, pH, and distance from the smelter.

Fish Study

Hamell Lake — Hamell Lake is a moderately small shallow lake with a surface area of approximately 250 ha and estimated maximum depth of 5 m. Most of the lake ranges from 1 to 2 m deep. Dissolved Zn concentrations in July, September, and October 1973 were similar, ranging from 130 to 160 μg/ℓ. Concentrations in a vertical profile varied by only 5 μg/ℓ in one series of determinations, and concentrations from five stations around the lake varied between 130 and 150 μg/ℓ. In May 1974 three stations around the lake ranged from 260 to 350 μg/ℓ of Zn. Samplings at other times gave values up to 360 μg/ℓ Zn. The value of 300 μg/ℓ given in Table 2 is an average of all determinations. Average values for Cu in 1973 and 1974 were 9 and 15 μg/ℓ, respectively.

Despite these rather high heavy-metal concentrations, the lake supported populations of walleye (*Stizostedion vitreum vitreum*), yellow perch (*Perca flavescens*), northern pike (*Esox lucius*), lake whitefish (*Coregonus clupeaformis*), white sucker (*Catostomus commersoni*), and possibly other species. Among the captured fishes, 8 walleye ranged in age from 4 to 10 yr, northern pike and white suckers included at least the last six year-classes (1973–68), yellow perch varied from young of the year to mature older fish, and 28 lake whitefish were age 3–10 yr. None of the fish, except perhaps the yellow perch, was stunted. The sample size of most species was not large enough to determine if some younger year-classes were absent. However, the presence of young-of-the-year yellow perch, northern pike, and white suckers indicated that at least some of the species had reproduced in the Zn concentrations measured during the study. The capture of young fish is always a problem and the failure to catch young-of-the-year walleye and lake whitefish does not indicate that they were absent. An examination of the ovaries of females did not suggest any abnormal development was occurring. There was little doubt that these species had been able to reproduce, grow, and survive in this lake.

It was not possible to estimate the population size for the various species in Hamell Lake. If the number of species captured per unit length of gillnet set was compared with catches from other nearby lakes (Table 3), then Hamell Lake appears to have smaller densities of some species. However, the size of a gillnet catch can be related to many variables, such as the selection of fishing site, time of year, mesh sizes, experience in handling and setting nets, and physical and chemical properties of the lake. Thus, it was only possible to conclude that fish in Hamell Lake could not be considered to be rare and that the total catch was perhaps below average when compared with other nearby lakes of lower heavy metal content.

Cliff Lake — Cliff Lake has a surface area of approximately 360 ha and a maximum depth of 11 m. The lake is the source of drinking water for the city of Flin Flon and because no power boats are allowed on the lake it is poorly fished. This lake had an average value for Zn of 85 μg/ℓ and a range, over the sampling period, of 70–120 μg/ℓ. Copper averaged 10 μg/ℓ with a range of 9–11 μg/ℓ during the study. Zinc and copper concentrations at a series of five stations, including a vertical series and duplicate samples, ranged from 70 to 88 μg/ℓ and 9 to 11 μg/ℓ, respectively, for a single sampling time.

The lake contained an abundance of fish. At least nine species were present; northern pike, walleye, lake whitefish, white sucker, yellow perch, lake herring (*Coregonus artedii*), burbot (*Lota lota*), trout-perch (*Percopsis omiscomaycus*), and spottail shiners (*Notropis hudsonius*). In general, there was no indication of year-class failure, abnormal growth, or abnormal reproductive impairment in any of the populations. Lake whitefish age 3–8 were common and the population appeared to contain slow- and fast-growing individuals. The occurrence of dwarf or slow-growing and fast-growing forms of whitefish has been described for other populations (Fenderson 1964). Some females were apparently not spawn-

TABLE 3. Comparison of catches among lakes. Catch per unit effort (CPUE) = number of fish divided by total length of gillnet set.

	Hamell Lake		Cliff Lake		Phantom Lake		Embury Lake	
Species	No.	CUPE	No.	CUPE	No.	CUPE	No.	CUPE
Walleye	8	.003	63	.025	—	—	—	—
Yellow perch	53	.002	155	.061	611	.873	14	.018
Northern pike	56	.023	45	.018	6	.009	9	.011
White sucker	53	.023	130	.051	15	.021	7	.009
Lake whitefish	29	.012	34	.013	—	—	14	.018
Other fishes	0	—	13	.004	48	.083	12	.015

ing each year. The failure of females from more northern populations to spawn each year has also been described for other populations of lake whitefish (Kennedy 1953). All northern pike age-classes from 2 to 9 were captured. Walleye were also large and ranged in age from 2 to 9 yr. Young-of-the-year yellow perch and lake herring up to age 6 were taken, as were all age-classes of immature white sucker. Mature white suckers older than 4 yr were not aged.

Other lakes — Lakes listed in this category were fished with less effort. Maximum depths are indicated when available.

Ross Lake was one of the smaller lakes fished (Fig. 1) but was a deeper lake with a maximum depth of approximately 9 m. Unlike other lakes fished that received heavy metals from atmospheric fallout, Ross Lake received toxicants directly from wastes entering from the inlet waters. Because of the extremely high concentrations of toxicants in the lake (Table 2), fish were unable to survive. However, the response of fish to the toxicant concentrations was interesting because of the accidental and intentional movement of some species into the high toxicant levels.

Local residents have reported that in the spring, white suckers move up the outlet of Ross Lake from the northwest arm of Schist Lake prior to spawning. In 1974, 99 white suckers, 11 lake herring, 4 northern pike, 2 walleye, and 1 lake whitefish were captured and tagged in this stream 500 m upstream of Schist Lake as part of a study being conducted by geologists from the Hudson's Bay Mining and Smelting Company (W. W. Fraser personal communication). In 1975, 24 northern pike and 132 white suckers were tagged. Flooding conditions in the creek apparently prevented the capture of all upstream migrants. Tagged and untagged white suckers were subsequently captured in Ross Lake. During the tagging period, toxicant concentrations (in micrograms per litre) averaged as follows: Ca, 210 in 1974 and 230 in 1975; Zn, 3550 in 1974 and 4970 in 1975; Fe, 690 in 1975; Pb, 120 in 1975; Cd, 50 in 1975; and Mn, 210 in 1975. The pH of the water was 6.3 in 1974 and 7.0 in 1975 (W. W. Fraser personal communication).

Gillnetting in the lake during the summer and fall in 1973 and 1974 resulted in the capture of 10 yellow perch and 1 northern pike. It is possible for fish to enter Ross Lake from other lakes and it is most probable that fish captured in the gill nets were migrants from other lakes and would either pass through or die in the lake. While this movement into the lake appeared accidental, the movement of white suckers up the inlet in the spring into such high heavy-metal concentrations was deliberate.

Embury Lake with Zn concentrations of 30–60 $\mu g/\ell$ is a moderately large deep lake (Fig. 1) with a maximum depth of 45 m. The lake contained lake trout (*Salvelinus namaycus*), burbot, white sucker, lake whitefish, yellow perch, northern pike, lake herring, and probably other smaller, less abundant species. Phantom Lake contains many shallow areas $<$ 2 m but also contained a deeper area with a maximum depth of 10 m. The lake samples had Zn concentrations varying from 40 to 90 $\mu g/\ell$. Northern pike, lake herring, white sucker, and a large population of yellow perch were found in this lake. Douglas Lake, with Zn concentrations of 25–75 $\mu g/\ell$, contained yellow perch, northern pike, and white sucker. In an unnamed lake with a Zn concentration of 150 $\mu g/\ell$, identified as Lake No. 6 in this study, 14 pike and 1 white sucker were captured. Douglas Lake and Lake No. 6 were shallow lakes. No maximum depth estimate was available for these lakes.

Discussion

Source of Heavy Metals in the Lakes

Elevated levels of heavy metals in lakes in an area such as Flin Flon can be caused by atmospheric fallout, liquid effluent discharge, and leaching of metal bearing minerals. Drainage from the Flin Flon smelter is southward into Ross and Schist lakes. Of the lakes listed in Table 2, these latter are the only ones that could have been contaminated by liquid effluent from the smelter.

Koo and Mossman (1975) report economic ore bodies and "barren" sulfide deposits (combined Cu–Zn values < 0.05%) are relatively common in the Flin Flon area. If the metal content of the water is resulting from leaching of metaliferous minerals, one would expect lakes with high Zn concentrations to be found scattered throughout the area. This is not the case. Many of the lakes, particularly those farthest from the smelter, have metal values similar to those of 109 relatively unpolluted lakes in northwestern Ontario (Beamish et al. 1976). The lakes with low metal content are those farthest from the smelter.

For the lakes other than Ross and Schist, a linear relationship was demonstrated between $\log_{10}$ Zn, Cu, and SO_4^{2-} concentrations and $\log_{10}$ distance from the smelter. This, coupled with the other conclusions reached above, suggests that the source of these substances is atmospheric fallout.

Effects of Heavy Metals on Fish

The problem of relating laboratory and field observations is well known (Brungs et al. 1976). It is difficult to determine the effect of above-normal but nonlethal concentrations of heavy metals. In particular it is difficult, on the basis of laboratory studies, to assess the effects of Zn concentrations in the 50–300 $\mu g/\ell$ range found in a number of the study lakes. Workers involved in the field of fish toxicology are generally careful not to try to predict what would happen under field conditions on the basis of laboratory tests. As a result, the problem of assessing the hazards of toxicants to fish populations is often passed on to the managers of an aquatic resource. This obviously is a very difficult task, as many problems must be considered, such as differing response among species, difference in water chemistry, difficulties in the analysis of toxicants in natural waters, and difference in the conditions of exposure as well as possible differences between the response of individual fish compared with the response of the populations.

In this present study, it was found that fish populations in lakes containing up to 90 $\mu g/\ell$ Zn and approximately 10 $\mu g/\ell$ Cu were not noticeably adversely affected by these heavy-metal concentrations. Fish in these lakes did not display abnormal growth, poor year-class strength, or unusually low abundance.

The response of fishes in Hamell Lake was more difficult to assess. A continued examination of this lake up to the fall of 1976 showed that mean annual concentrations of Zn remained at approximately 300 $\mu g/\ell$ (McFarlane and Franzine unpublished data). In 1976, concentrations as high as 1000 $\mu g/\ell$ were observed but these concentrations were found in the surface waters for only a short time in the early spring. During 1976 yellow perch and northern pike populations remained moderately abundant and continued to spawn; however, catches of white sucker, walleye, and lake whitefish were greatly reduced and spawning of white suckers appeared to be partially impaired.

Laboratory studies of the effects of Zn or Zn metal mixtures on fishes and other aquatic organisms have shown that harmful effects occur over the range of about 30–200 $\mu g/\ell$ (Brungs 1969; Biesinger and Christensen 1972; Eaton 1973). For example, fathead minnows (*Pimephales promelas*) exposed to approximate trimetal mixtures ranging from 40 to 300 $\mu g/\ell$ Zn, 7 to 30 $\mu g/\ell$ Cu, and 7 to 60 $\mu g/\ell$ Cd showed reduced spawnings and severe effects on reproductive performance beginning at a trimetal concentration of approximately 27 $\mu g/\ell$ Zn, 5 $\mu g/\ell$ Cu, and 4 $\mu g/\ell$ Cd (Eaton 1973). Much of the reproductive impairment was attributed to the presence of Zn. Our observations did not reveal any adverse effects on a variety of fish populations subjected to Zn and Cu concentrations of approximately 90 and 10 $\mu g/\ell$, respectively. Some long-term adverse effects occurred for some species that were subjected to Zn concentrations in the approximate range of 200–1000 $\mu g/\ell$ over a period of at least 4 yr. We cannot say that there has been no effect on the individual fishes and indeed, in Hamell Lake, adverse effects were apparent. However, many populations were surviving in high concentrations of Zn and, except where noted, if major changes were occurring in recruitment, growth, and survival of fishes or species composition in the lakes studied, then these changes were occurring over a time span of many years.

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