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Population dynamics of the Common Loon (*Gavia immer*) associated with mercury-contaminated waters in northwestern Ontario

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Contents

Abstract

Acknowledgements

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Common Loons on lakes of the Wabigoon–English River system, northwestern Ontario, were adversely affected by unnatural, unpredictable water-level fluctuations and turbidity, and by mercury contamination. Extensive, man-induced water-level changes resulted in increased desertion and predation of clutches. Increasing turbidity resulted primarily in a decrease in the number of potential territories occupied. A strong negative correlation existed between the successful use of territories by breeding loons and mercury contamination. Results suggest that one can expect reductions in egg laying, and in nest and territorial fidelity at mercury concentrations ranging from 0.3 to 0.4 ppm in prey and from 2 to 3 ppm in adult loon brain and loon eggs. The effects of acid precipitation on the availability of mercury to loons through the food chain are discussed.

Introduction

This paper centres on the population dynamics of loons subjected to mercury contamination and/or unnatural water-level fluctuations and turbidity.

The restricted positioning of the loon's nest leaves it susceptible to flooding when water levels rise and more susceptible to predation when levels decline. Loons evolved in holarctic habitats offering numerous nesting lakes subject to the natural rhythm of annual water-level changes. This natural rhythm results in high water levels during the spring thaw, followed by gradually declining levels throughout the nesting season. Precipitation during this period seldom raises levels enough to flood nests and the lack of it seldom leaves nests stranded far from water. However, the manipulation of water levels for hydro-electric power or reservoir impoundment disrupts the natural rhythm and exaggerates the range of fluctuation. Extensive changes in levels and flow rates, as well as industrial effluent, contribute to deterioration of the aquatic environment, including increased turbidity.

Studies on mercury contamination in the Wabigoon and English River systems have suggested that fish-eating birds in general (Fimreite *et al.* 1971, Vermeer and Armstrong 1972), and the Common Loon (*Gavia immer*) in particular may be adversely affected by high levels of methylmercury accumulated from their diet (Fimreite and Reynolds 1973). Fimreite (1974) observed relatively few adult loons and noted the lack of juvenile loons in lakes of the Wabigoon drainage downstream from Dryden, compared to other nearby lakes. High levels of methylmercury were also found in bottom sediment (Armstrong *et al.* 1972), in tissues of aquatic invertebrates (Hamilton 1972), and in various fish species (Bligh 1970; Lockhart *et al.* 1972, 1973; Scott 1974; Bishop and Neary 1976) taken from the Wabigoon River system downstream from Dryden and from the English River system downstream from Maynard Falls.

The chlor-alkali plant at Dryden was considered to be the main source of waterborne mercury contamination in the Wabigoon and English River systems (Bligh 1970), with levels of methylmercury reaching 21.95 ppm (Fimreite and Reynolds 1973) in fish from Clay Lake, some 85 km downstream, and 5.25 ppm in those from Tetu Lake, 320 km downstream near the Ontario–Manitoba border. Levels of mercury in liver tissue of loons from Ball Lake reached 90.5 ppm and averaged 51.9 ppm in 1971 (Fimreite 1974).

Although the amount of mercury effluent entering the Wabigoon River from the chlor-alkali plant at Dryden was, supposedly, reduced in early 1970 from 95 g to 3 g per tonne of chlorine produced (plant capacity of 11 000 – 12 000 tonnes of chlorine per year), levels of mercury in the biota sampled downstream up to 1972 indicated that mercury was not being eliminated from the system by natural means as quickly as first thought (Armstrong and Hamilton 1973). According to Fimreite and Reynolds (1973), this may have been due in part to the oligotrophic conditions in the aquatic environments of the area, a view supported by studies in Sweden (Jernelov *et al.* 1975), and in the United States (D'Itri *et al.* 1971, Kleinert and Degurse 1972).

High levels of mercury were not only found in those parts of the Wabigoon and English River systems directly affected by effluent from the chlor-alkali plant at Dryden but also in other lakes in the study area. Those lakes are on the Wabigoon River upstream from the dam at Dryden and on the English River upstream from Maynard Falls. Other lakes in the area that are entirely independent of the Wabigoon and English Rivers are also affected. These elevated levels of mercury are reflected in the fish sampled (see Bishop and Neary 1976). Sources of mercury in lakes not subject to waterborne contamination from the Dryden Plant are not known but may be natural, airborne, or both (Fimreite and Reynolds 1973). High levels of naturally occurring mercury associated with mineral deposits, particularly greenstone belts, are common in northwestern Ontario (Jonasson and Boyle 1972, Allan *et al.* 1974). Jernelov *et al.* (1975), Madsen (1981), and Brosset (1982) discuss the probable broad (global) atmospheric dispersion of mercury from natural and industrial sources. Whether the source is natural or industrial, originates locally or from global atmospheric distribution, the availability of mercury to the aquatic food chain is increased by acid precipitation. The relatively low numbers of fish-eating birds observed along those parts of the river system containing potentially hazardous levels of mercury contaminants suggest a possible link between these two factors.

Study area and methods

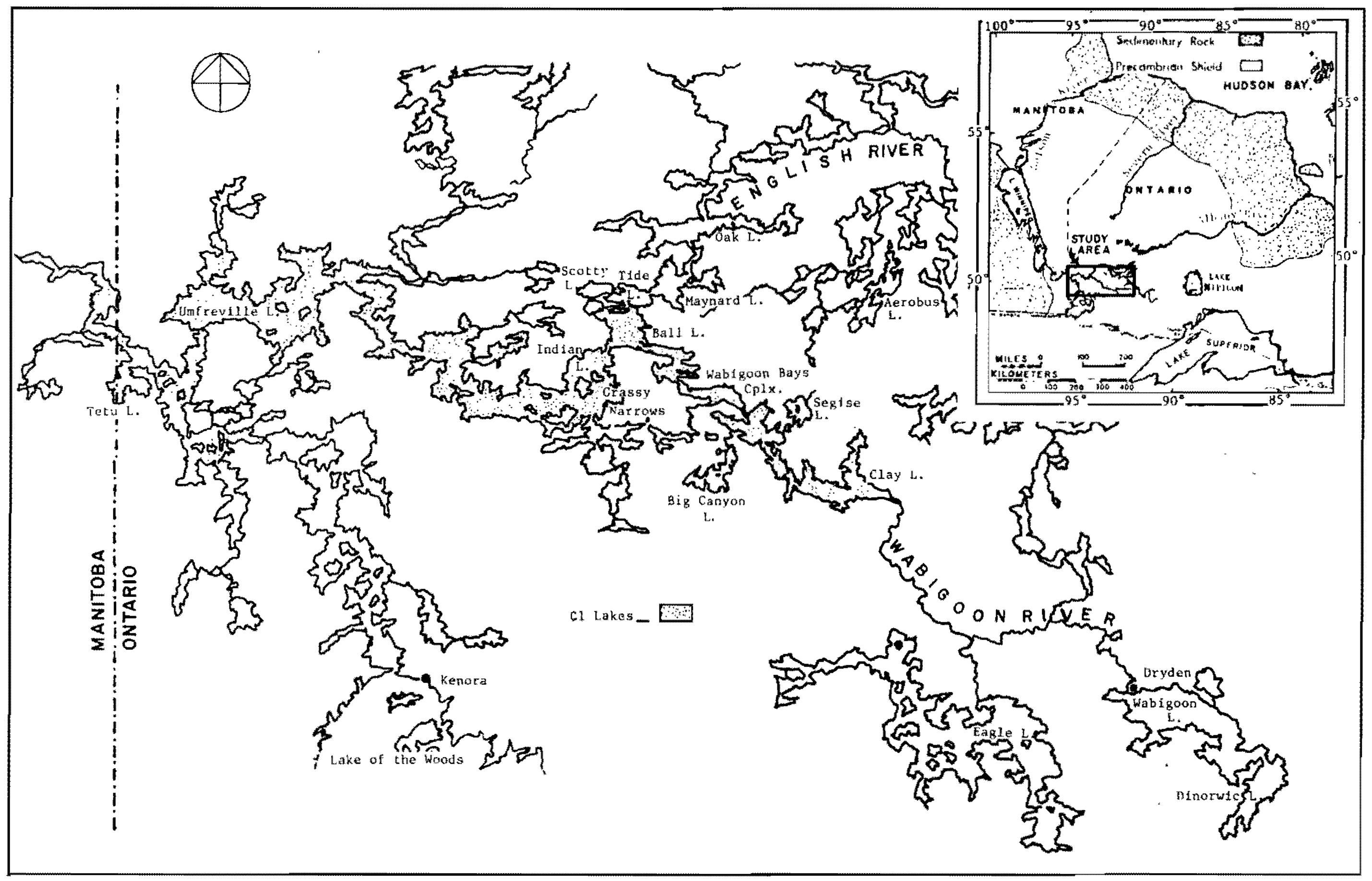
The study area encompassed approximately 50 000 km² centred on the drainage basin of the Wabigoon–English River system (Fig. 1). I selected 34 lakes, containing a total of 222 potential territories, and divided them into four classes (C) as follows:
C1 consisted of 6 lakes (54 potential territories) downstream from the source and directly in the path of waterborne mercury from the Wabigoon River at Dryden. Aquatic invertebrates, fish, and fish-eating birds in these lakes contained high levels of methylmercury.
C2 consisted of 6 lakes (17 potential territories) on or adjacent to the Wabigoon–English River system, out of the flow of waterborne mercury but directly accessible to fish from C1. In all cases streams flowed from lakes of C2 downstream into areas of higher mercury contamination.
C3 consisted of 10 lakes (97 potential territories) on the contaminated river system, but upstream from the source of mercury contamination on the Wabigoon River and upstream from Maynard Falls on the English River. There is no known access for either waterborne mercury or contaminated fish from C1 or 2 into C3.
C4 consisted of 12 lakes (54 potential territories) adjacent to but independent of the contaminated river systems, and acted as a control.

1. Determination of potential loon territories

I studied selected lakes on 1:250 000 topographic maps (Dep. of Mines and Technical Surveys, Ottawa) and marked the location of all potential loon territories. Preliminary selection of a potential territory by use of maps was based on the size and shape of lakes and the number, location, size, and shape of islands, bays, and marshes. I determined the area of each lake with an Ott No. 16 compensating polar planimeter. Territory size and habitat features considered important to loons are based on previous (Barr 1973) and current studies (Barr, in prep.) which are basically consistent with the findings of other researchers for the Common Loon (Munro 1945, Olson and Marshall 1952, McIntyre 1975, Yonge 1981) and for other loon species (Lindberg 1968, Lehtonen 1970, Dunker 1974).

I then surveyed each lake by canoe or motorboat. During the initial survey I recorded, for each potential territory, the presence and location of small islands and islets not shown on the maps, physical nature of the shoreline, marginal vegetation, and type and extent of marshes and shoals. Gillnets, seines, and minnow traps were used to confirm the presence of suitable prey.

Figure 1
Study area



2. Selection criteria

1. Only lakes larger than 40 ha were considered.
Note: Although loons did nest on lakes as small as 6 ha, the average territory size was about 75 ha (n = 442, present study; Barr 1973). Loons established territories less frequently on lakes smaller than 40 ha. Less than 50% of lakes 20 ha in area were occupied by territorial pairs and there was a continuous sharp decline in use of even smaller lakes. As territory size was compressed due to the proximity of nesting facilities of adjacent nesting pairs or absolute lake size, adult loons frequently fed on neutral water outside their territory in larger lakes or in lakes adjacent to the smaller nesting lakes. In the latter case, reproductive success is less likely to reflect the toxicant level in the food resource of the nest lake.
2. Each potential territory had to include at least one island or floating bog marsh with individual bog islets and have shelter from wind-induced wave action for nest site and brooding.
Note: Most Common Loons nest on structures (islands, bog islets, logs, hummocks) off the mainland shore. Less than 2% of all Common Loon nests I observed have been on the mainland.
3. Fish had to be present, of a size suitable as food for loon chicks from hatching through fledging (this includes fry [1–2 g] up to 200 g).
Note: Although the Common Loon has reportedly nested and reared chicks on fishless lakes (Munroe 1945), the author has observed the following:
i) Lakes with no fish, although occasionally frequented by loons, have had no breeding pairs establish nests.
ii) Loons stopped nesting on lakes from which fish were eliminated by poisoning and did not maintain territories or resume nesting until fish populations were renewed several years later.
iii) When poisoning occurred in lakes, loons gorged for several days on easily caught, dying fish and expressed territorial behaviour, including posturing and calling. After fish were eliminated loons left these lakes.
iv) Loons nested more frequently on marginally small lakes when the fish population was augmented.
4. A surplus population of adult loons, present singly or in groups, had to be available for replacement in territories. These loons regularly occupy neutral areas of larger lakes or lakes lacking suitable nesting facilities.
Note:
i) A member of a territorial pair, either sex, collected from an established territory during the spring, was always replaced within 2 weeks and several were replaced within a day of collection. Hence a potential territory in a region of prime habitat was assumed to be vacant for reasons other than a lack of available loons.
ii) Of 442 potential territories selected, using the method and criteria outlined, over 90% of those territories unaffected by turbid water, unnatural water-level fluctuations, waterborne contaminants, or frequent human disturbance were occupied. More than 95% of this 90% had occupants during all survey years.

An area on a lake was confirmed as a potential territory after the initial on-site survey if it met the criteria as outlined.

I surveyed lakes at approximately 2-week intervals from May through October in 1974 and 1975, and from May to July in 1976 to record the presence and behaviour of loons, the establishment of new territories, and the modification or breakdown of established territories. Reproductive success of each pair was followed from nesting through fledging of chicks.

Various combinations of water-level fluctuations and turbidity affected individual loon territories in all study classes; therefore the territory is used as the basic unit against which each variable is compared.

Success was based on the degree to which a potential territory supported loons and was measured according to the following categories: not occupied by a territorial pair; occupied briefly in spring, then deserted; occupied through mid-July but no nest attempted; nest(s) built; clutch incubated; chicks hatched; chicks fledged. To be considered occupied a territory must be defended by a pair of loons until mid-July. The sum of the categories reached in a potential territory, as a percentage of the total attainable, determined the ability of that territory to support loons. Similarly, the sum of the scores for territories, as a percentage of the total score possible, determined the success of territories in each lake and in each class of water level, turbidity, and lake.

3. Turbidity measurements

Turbidity in each potential territory was measured by Secchi disks at least once in spring, summer, and fall in 1974 and 1975 and in spring 1976.

Feeding efficiency of loons is reduced as visibility in water drops below 1.5 m (Barr 1973), so results were compared between territories experiencing disk readings <1.5 m and those with readings >1.5 m. No territory changed from one category to the other.

4. Water-level fluctuations

I checked water levels on each survey by using reference marks on vertical rock faces, calibrated wooden stakes, and metal rules. In addition, archival records were obtained for a number of monitoring stations associated with dam sites along the Wabigoon–English River system. These data, recorded daily for periods ranging from 27 to 54 years, at five locations along the English River (Site 1, 49°50′N, 91°30′W; Site 2, 50°05′N, 91°35′W; Site 3, 50°10′N, 92°12′W; Site 4, 50°20′N, 92°20′W; Site 5, 50°40′N, 93°10′W), were analysed to determine the seasonal and annual changes effected by flow control through various dam sites and were compared to lakes subjected only to natural water-level changes.

5. Human disturbance

Human disturbance was assessed by establishing a cumulative score for each potential territory. Factors were allotted for human presence, depending on its distance from each potential nesting area within a territory:

within	50 m	150 m	300 m
factor	3	2	1

Each relevant factor was multiplied by the number of cottages and, on each survey until August, by the number of watercraft. Watercraft in a territory were divided into two categories, transient and lingering. Lingering watercraft were multiplied by (factor + 2), to account for increased disturbance expected from prolonged human activity near nesting areas. Most watercraft in the study area contained fishermen who concentrated much of their effort from or near islands. The sum of the combined scores was divided by the number of potential nesting areas for each territory. The score for each lake consisted of the sum of the scores for each territory divided by the number of territories in the lake.

6. Specimen collection and analysis

Fish of a size normally consumed by loons (10–250 g, see Barr 1973, Alexander 1976) were caught in gill nets (1½" stretched mesh, both cotton and monofilament) and in minnow traps. Crayfish (*Orconectes* sp.) were also sampled from several lakes. Use of a variety of prey species allowed comparison of mercury levels in each and compensated for the lack of one or more species from certain lakes. Yellow perch (*Perca flavescens*) was used as the target species where present, because of its prevalence in lakes of the study area and in the diet of loons (see Barr 1973).

I recorded the date, lake from which collected, and fork length for each fish. All members of each species collected from a single location were wrapped separately in aluminum foil, packaged together in a plastic bag, and frozen for transport to the Freshwater Institute in Winnipeg for analysis. Each entire fish was analysed separately for total mercury by the method of Hendzel and Jamieson (1976).

Loon eggs were collected only from deserted nests in 1974 and 1975 to avoid affecting the reproductive success. Analysis of these eggs gave a preliminary estimate of relative mercury levels from each study class. In 1976, 38 adult loons (23 ♂, 15 ♀), 11 chicks (5 ♂, 6 ♀) and 34 eggs were systematically collected from selected territories in the study area. Adult loons were shot, using B.B. or #2 magnum shot.

Immediately after collecting, each bird was weighed, measured, and skinned. Tissue samples of pectoral muscle, liver, brain, gonads, and fat were taken for toxic chemical analyses. Each tissue was labelled (waterproof laundry marker) and wrapped separately in aluminum foil. All samples from each specimen were combined in individual plastic (Whirl-Pak) bags identified by specimen number with waterproof felt marker pen. Each egg and tissue sample was analysed separately for total and methylmercury.

Loon material from 1974 and 1975 was analysed by the Ontario Research Foundation and material from 1976 by the Toxic Chemicals Division, Canadian Wildlife Service. Tissue samples were homogenized, with the addition of half their weight of 0.1 *N* sulfuric acid, and stored in closed polyethylene cups in a freezer until analysed. At the time of analysis, two subsamples of 0.1–5 g were weighed into disposable plastic cups. One subsample was analysed for total mercury, and the other for inorganic mercury, by flameless atomic absorption spectrophotometry, using selective reducing agents (Fisheries and Environment Canada 1977). Methylmercury levels were calculated by difference between the total and inorganic mercury determinations, which is reliable as long as the percentage of methylmercury is high. This situation obtained for all tissues except adult liver, which frequently contained an amount of methylmercury not statistically significant from zero. Thus only the total mercury values were used from the analyses of adult liver samples. The results for all samples collected in the present study, as well as those of other authors referred to, are expressed on a wet weight basis.

Results

1. Water level and turbidity

Annual water-level fluctuations ranged from < 1 m in control lakes to > 3 m in some study lakes. Typically, in control lakes water levels reached highest peaks in late May or early June, depending on the time of spring break-up, the extent of snow cover, prevailing spring temperatures, and precipitation. Peaking time and levels also depended on a lake's size and its isolation from or position along a river system, but the pattern was consistent from year to year; levels had peaked or were declining by early June. After spring thaw the change in water level never exceeded 0.6 m and seldom exceeded 0.3 m throughout the nesting season. Although local rainfall caused some fluctuations, loons accommodated when necessary by adding nest material and no nests were flooded. Because changes in water level were small, the distance of nest from water did not change appreciably (< 1 m) throughout incubation. Similarly, the exposure of nests on bog islets and their distance from water remained virtually unchanged.

The situation described for control lakes did not prevail in those study lakes affected by dams along the Wabigoon and English River systems. Mean seasonal changes in water levels of Wabigoon and other lakes upstream from the small dam on the Wabigoon River at Dryden ranged from 0.7 to 1.0 m during the present study. Levels frequently fluctuated from 2.5 to 3 m in other lakes along the Wabigoon–English River system affected by larger hydro-electric power dams. During the present study, lakes influenced by such dams were characterized by large water-level fluctuations during the nesting season, exceeding 3 m in 1974. Fluctuations were unpredictable within seasons and from year to year, with levels differing almost 4 m during the same period of 1974 and 1976 at Ball Lake. The greatest fluctuations occurred during spring, as in the control lakes, but the fluctuations were much greater and frequent increases in levels occurred during June and July.

Water levels were exceptionally high in 1974, reaching 1.5 m above usual spring flood levels in lakes of both the Wabigoon and English River systems. A combination of dam control on the English River through Lac Seul, and on the Wabigoon River at Dryden and Wainwright Falls, plus heavy rains in June caused the level to increase a further 30–40 cm by mid-June. High water levels persisted through the first week in July, then dropped rapidly (1.75 m in 5 days) in the Wabigoon system and gradually in the English system. Water levels continued to decline along both systems.

Table 1
Frequency distribution of the annual maximum and minimum water level, expressed as a percentage of the total number of years recorded at five sites*

	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Site 1 (52)†												
Max.	2	0	0	0	21.2	36.5	23.1	0	5.8	9.6	1.9	0
Min.	3.9	1.9	30.8	44.2	0	0	0	0	7.7	9.7	1.9	0
Range‡ (2.51)												
Site 2 (53)												
Max.	0	0	0	0	47.2	37.7	3.8	0	3.8	5.7	1.9	0
Min.	0	3.8	30.2	22.6	0	0	0	0	22.6	18.9	1.9	0
Range (2.83)												
Site 3 (27)												
Max.	0	0	0	0	0	11.1	37.0	7.4	22.2	11.1	7.4	3.7
Min.	0	0	11.1	77.8	0	0	0	0	0	0	3.7	7.4
Range (5.95)												
Site 4 (54)												
Max.	1.9	0	0	0	0	0	29.6	18.5	14.8	9.3	11.1	0
Min.	0	0	14.8	77.8	3.7	0	0	0	0	0	1.9	1.9
Range (5.48)												
Site 5 (40)												
Max.	2.5	0	0	0	0	7.5	35.0	22.5	15.0	10.0	5.0	2.5
Min.	0	2.5	7.5	72.5	10.0	0	0	2.5	0	0	2.5	2.5
Range (5.44)												

*Compiled from archival data, daily measurements. See Methods for coordinates.
†Number of years of daily records.
‡Range between the maximum and minimum water level recorded at each monitoring site.

Flood levels crested 1.5 m lower in 1975 than in 1974, were considered typical of the systems since construction of the large dams (pers. commun. with natives, local residents, and lodge owners), and approximated levels obtained from archival data (Tables 1 and 2; Fig. 2). Water levels from spring thaw through July 1976 were lower than in 1975. The range of change within each of the three study seasons was similar (2.5–3 m), being slightly less in the Wabigoon than the English River and less during 1975 and 1976 than in 1974.

Most potential territories in all study lakes contained one or more islands with possible nesting sites. In 1974, the exceptionally high water levels, persisting throughout the nesting season, completely flooded small islands and eliminated many previously used nest sites, at the same time rendering new potential sites available. A few pairs had nested in these sites by early June, but five were flooded by rising water in mid-June. Rising levels in June and July inhibited other loons from nesting.

The high water resulted in increased turbidity by exposing clay and peat soil to continuous erosion and caused much woodland debris to become flotsam. When water levels declined, tangled debris and exposed muddy shores further eliminated potential nest sites. In addition, extensive blooms of green algal slime developed along the shorelines of islands and prevented loons from ready access to the shores. As water levels declined, this strong-smelling slime hung from the branches of trees and shrubs and lay strewn along the shoreline, further inhibiting loons.

Declines in water levels in 1974, 1975, and 1976 resulted in nest desertion and increased predation when loons were unable to climb to nests (Fig. 3) or were forced to traverse long stretches (sometimes exceeding 8 m) of exposed rocky shore. The change in nest-to-water distance was significantly greater (χ^2: $P = 0.005$) for predated ($n = 68$) than for successfully hatched clutches ($n = 65$).

Archival data showed that water-level fluctuations occurring during the present study fitted the pattern at the five sites monitored for periods of 27–54 years. Annual water-level maximums were as likely to occur during June or July as in May (ANOVA $F = 0.01$), and in fact occurred most frequently in July at three of five sites and at only one site in May (Table 1).

The range of levels from May through July varied in excess of 1.5 m from the mean maximum level at three of five sites during all 3 months (Fig. 2); the change in water level from minimum to maximum exceeded 1.5 m at all sites in all months except May at Site 2.

Loons occupied approximately 15% more of those potential territories with water-level fluctuations < 1.5 m than of those experiencing greater fluctuations. The greatest reduction in occupancy occurred in those territories with turbid water. Thus, at $P = 0.005$, significantly fewer potential territories were occupied where clarity < 1.5 m prevailed, whereas there was no significant reduction in those subjected only to water-level fluctuations > 1.5 m. Based on all potential territories, those with relatively clear water and slight fluctuations averaged 1.5 times greater success than territories with large water-level fluctuations.

Once occupied, success increased most for territories experiencing turbid conditions, and remained lowest in territories affected by both excessive turbidity and water-level fluctuations (Table 3). Excluding territories affected by turbidity, territories with smallest fluctuations were more successful than those experiencing fluctuations exceeding 1.5 m.

Excluding all territories subject to mercury contamination (Table 3), the following results prevailed (significant at $P = 0.005$, χ^2):

Table 2
Maximum increases (I) and decreases (D) in waterlevels* during May, June, and July, at five sites along the Wabigoon–English River system

	Site									
	1		2		3		4		5	
	I	D	I	D	I	D	I	D	I	D
May	2.2	0	2.6	0.8	5.3	0	4.7	0.1	5.0	0.2
June	2.0	1.8	2.0	2.4	5.4	0	4.5	4.0	4.9	0
July	1.2	1.5	0.8	2.0	5.3	1.5	4.0	4.6	4.5	4.9

*Measurements in metres.

Figure 2
Range of variations for the monthly high water level recorded every year for May, June, and July at five sites along the Wabigoon–English River system

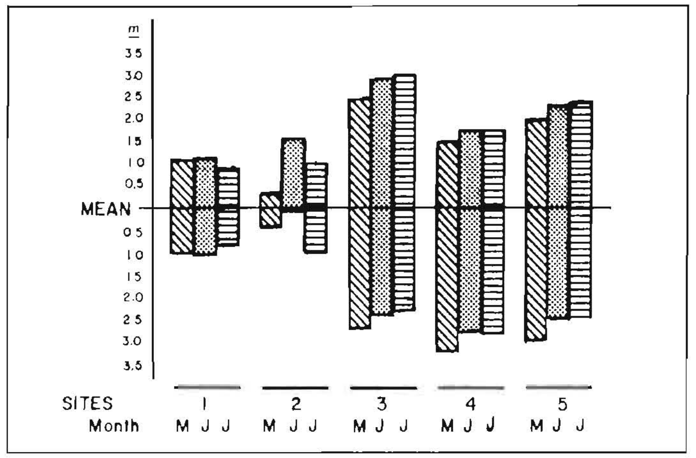


Figure 3
Three days earlier, this loon's nest was 17 cm above water level

1. More loons deserted territories and fewer pairs nested where the combined effects of water-level fluctuations > 1.5 m and water clarity < 1.5 m prevailed.

2. Nesting was carried out by a lower percentage of those pairs occupying territories where water-level fluctuations > 1.5 m and water clarity < 1.5 m prevailed.

Where water-level fluctuations were < 1.5 m there was no significant difference in the rate of desertion, nor in the percentage of pairs that nested, between loons occupying territories where clarity was < 1.5 m compared to > 1.5 m.

Excluding all territories experiencing water-level fluctuations > 1.5 m and clarity < 1.5 m, there was no significant difference in the percentage of territorial pairs that nested.

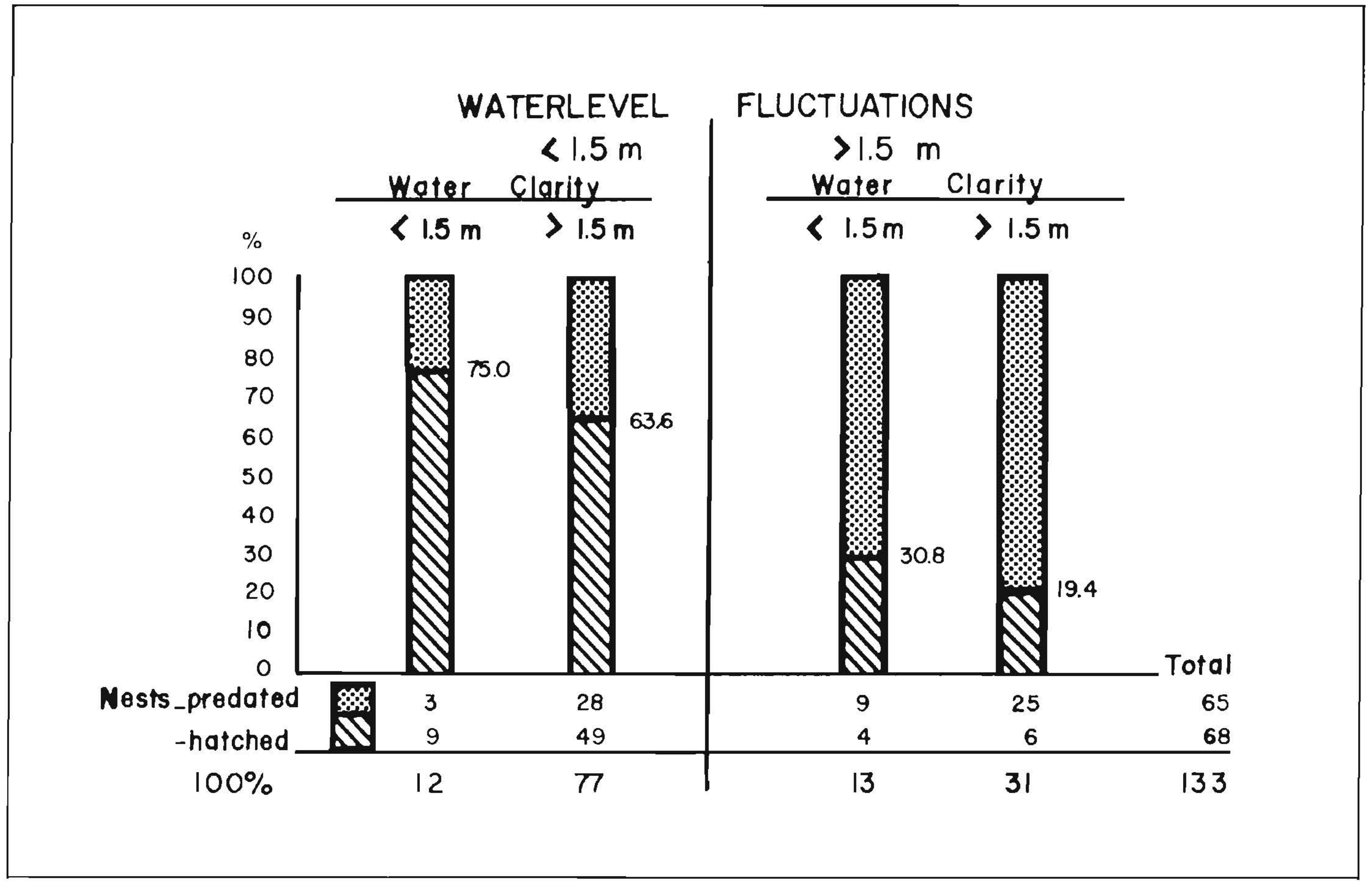
Clutches hatched in 33% more of those territories experiencing water-level fluctuations < 1.5 m than in territories with larger fluctuations (significant at $P = 0.005$). In a comparison between the distributions of hatched and predated clutches between 1974 and 1976, over 72% of hatched clutches occurred where water clarity was > 1.5 m and fluctuations were < 1.5 m. The lowest percentage of hatched clutches occurred where the effects of both turbidity and large water-level fluctuations were operative (significant at $P = 0.005$). Excluding turbid areas and flooded nests, over 80% of all other nests established where fluctuations were > 1.5 m were predated. Only 36% of similar nests were predated in territories unaffected by unnatural water-level fluctuations (Fig. 4). As a result, the predation rate on loon clutches was significantly greater ($P = 0.005$) in territories affected by unnatural fluctuations > 1.5 m than in territories where reduced clarity < 1.5 m alone prevailed.

Table 3
Effects of water-level fluctuations and turbidity on the occupation and success of loon territories*

	Water-level fluctuations <1.5 m		Water-level fluctuations >1.5 m	
	Water clarity		Water clarity	
	<1.5 m	>1.5 m	<1.5 m	>1.5 m
Territories				
Potential n =	48.0	59.0	20.0	18.0
Occupied n =	15.0	55.0	7.0	14.0
% occupied =	31.3	93.2	35.0	77.8
Success† based on				
a. All potential territories	18.3	50.1	7.5	33.0
b. Only occupied territories	62.1	52.8	26.0	45.0
c. Territories where clutches hatched as % of territories where clutches were laid	n = 38 territories		n = 8 territories	
	57.9		25.0	

*Only territories free from mercury contamination.
†See Methods.

Figure 4
Percentage of nests predated or hatching under four combinations of water-level fluctuations and turbidity



2. Human disturbance

Human disturbance was significantly less ($P = 0.05$) in C1 than in all other classes and there was no significant difference among C2, 3 and 4, indicating that human disturbance was not an important factor in the low success of loons in C1 lakes. The decreases in fishing, officially discouraged in mercury-laden waters, and other recreational use (cottages, canoeing, swimming, waterskiing), undoubtedly discouraged by turbid water, would account for some of the lower human disturbance in C1 waters.

3. Mercury

3.1. Use of potential territories by loons

Potential territories were occupied throughout the breeding season in 4 of 94 possible incidents (one incident = one potential territory X in one season) in lakes along a 160 km reach of river downstream from the source of waterborne mercury (Fig. 5). Only one nest was built on lakes along this reach of the Wabigoon River between 1974 and 1976 and no chick hatched. Strong negative correlation between success of territories and mercury levels ($r = 0.97$) was most apparent on the same reach.

Mated pairs defended a higher percentage of potential territories in lakes more than 160 km downstream from the source of mercury contamination but many of these pairs deserted territories by the end of June. Loons nested in only 2 of 11 potential territories on Ball Lake and, although they nested for 11 of the 27 possible incidents and in 7 of the 9 potential territories on Indian Lake, most nests were predated and only one clutch successfully hatched between 1974 and 1976.

Loons appeared to nest as readily on lakes in the lower reaches of C1 as they did in C2 lakes and even in C3 lakes affected by similar conditions of water level and turbidity. In those territories in C2 and C3 not affected by water level and turbidity conditions common to C1, the percentage of territories occupied approximated that of the control group (C4). Although there was little difference in the proportion of potential territories occupied in these C2 (compared to C4) lakes, a higher proportion of loons on C2 lakes deserted and a lower proportion nested, both significant at $P = 0.005$. There was no significant difference between the performance of loons on C3 territories (those comparable to the C2 territories) and of loons on C4 lakes.

3.2. Reproductive success of loons

Comparing the reproductive success of loons that initiated clutches in C1, 2, and 3 lakes to that in C4 (Table 4), a higher percentage of clutches hatched in territories of C2 and C3 lakes that experienced seasonal water-level changes < 1.5 m than in territories subject to level changes equal to or greater than territories in lakes of C1. The hatching success of C3 territories that did not experience extensive water-level changes compares favourably with hatching success in C4 lakes. The smaller increase in success of C2 clutches suggested that some factor other than extensive water-level changes or reduced water clarity may be operative.

The proximity of water with high levels of mercury contamination and its easy accessibility to adult loons suggests a connection.

The following trend existed from C1 to C4 in order: 0.08, 0.13, 0.51, 0.72 chicks fledged per territorial pair, 1974 and 1975 combined. Among the four lake classes, there was no significant difference in the ratio chicks fledged/chicks hatched.

The degree to which potential territories of the study lakes supported loons is shown in Fig. 5 and Table 4. The results for C4 are comparable to results for similar lakes in eastern Ontario (Barr, unpubl.).

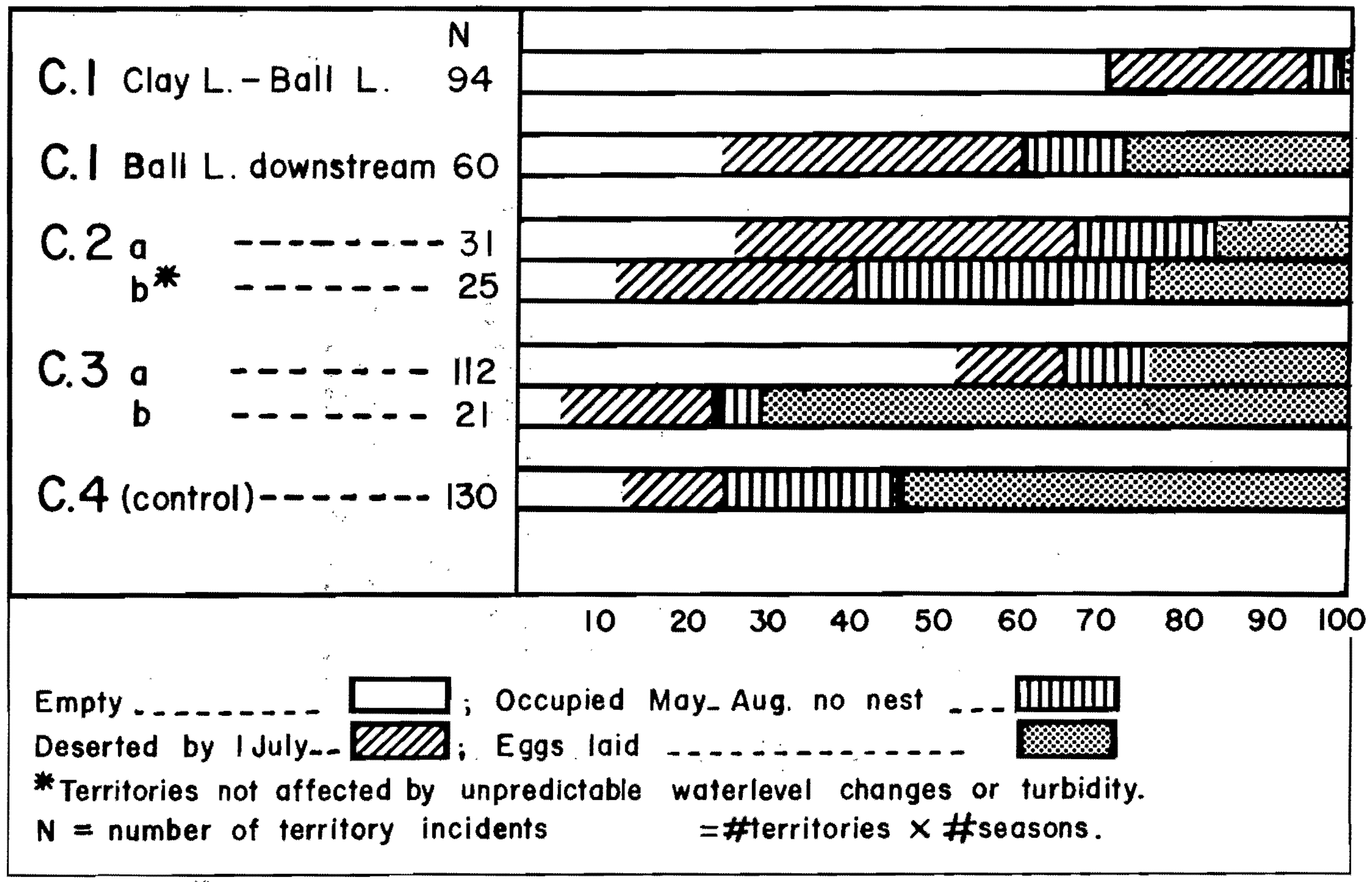


Figure 5
The percentage success of potential territories in supporting loons to the stage of egg laying

Table 4
Loons that initiated clutches*, hatched, or fledged chicks in four lake classes

		Study lake classes			
		C1	C2	C3	C4
Number of pairs with clutches		9	9	37	36
Number of pairs with clutches that hatched	(a)	2	3	17	23
	(%)	22	33	46	64
	(b)†		2	11	
	(%)		40	73	
Number of pairs with clutches that fledged		2	3	16	21
	(%)	22	33	43	58
Clutches fledged/clutches hatched	(%)	100	100	94	91
Chicks fledged/chicks hatched		3/4	3/4	25/30	33/38
	(%)	75	75	83	87

*Data based on 1974 and 1975 combined.
†Territories in C2 and C3 not affected by unpredictable water level changes and turbidity.

3.3. Mercury in prey

Fish species collected included yellow perch, yellow pickerel (*Stizostedion vitreum*), sauger (*Stizostedion canadense*), mooneye (*Hiodon tergisus*), northern pike (*Esox lucius*), cisco (*Coregonus artedii*), whitefish (*Coregonus clupeaformis*) and sucker (*Catostomus commersoni*) (see Methods). Crayfish occurred in 21 (69%) and fish remains in only 11 (36%) of 31 loon stomachs containing food. Crayfish remains occurred more frequently in loons collected from turbid lakes. This was more than twice the frequency in which they occurred in loons collected from clear lakes during a previous study (Barr 1973) which had shown that loons experienced difficulty catching an adequate diet of fish as turbidity increased.

At $P = 0.005$, when data from all prey fish species were combined, the following results were obtained:

1. In C1 lakes the level of mercury in prey fish decreased significantly from each test lake complex to the next

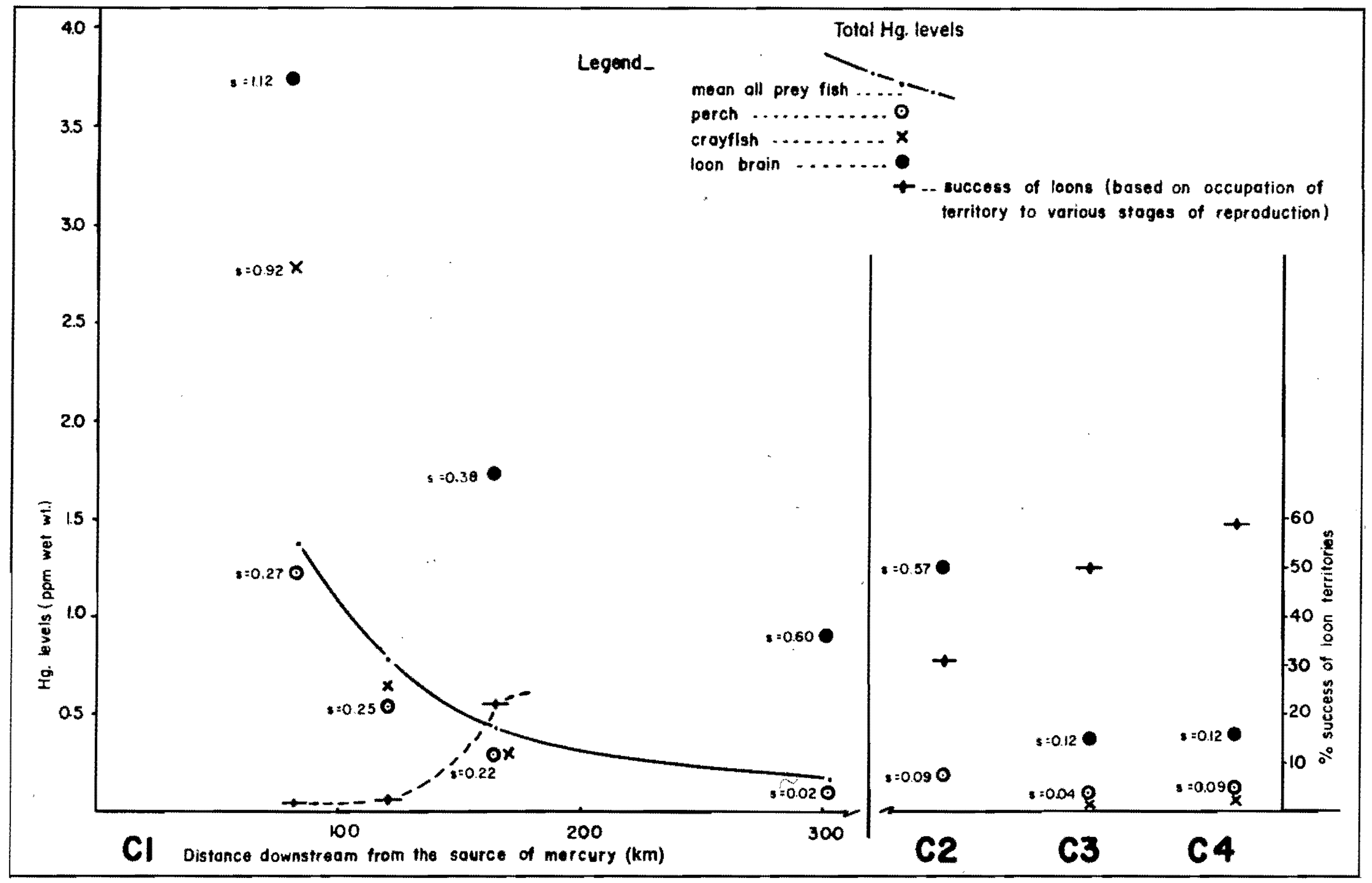


Figure 6
Mercury levels in loons and prey species, and success of loons in four study lake classes

downstream: Clay Lake > Wabigoon Bay Complex > Ball–Indian Lake Complex > Tetu Lake (see Fig. 1).

2. Mercury levels in fish from Tetu Lake (the C1 lake farthest downstream) and from C2 lakes were significantly higher than those in fish from C4 lakes.

In addition, mercury levels in fish from Ball-Indian Lake complex were significantly higher than in those from C2 lakes (at $P = 0.05$), while levels in fish from C2 lakes were significantly higher than those from Tetu Lake (at $P = 0.01$). There was no significant difference in mercury levels in prey fish from C3 and C4 lakes.

When perch alone were considered the following results were significant at $P = 0.005$.

1. Mercury levels in perch from Clay Lake were higher than in perch from the Wabigoon Bay Complex.

2. Mercury levels in perch from Ball–Indian Lake Complex were higher than in perch from Tetu Lake or C2, 3, and 4 lakes.

3. Mercury levels in perch from C2 lakes were higher than those from C4 lakes.

In addition, mercury levels in perch from the Wabigoon Bay Complex were significantly higher than in perch from Ball–Indian Lake Complex (at $P = 0.01$). Levels in perch from C2 lakes were generally higher in those from the Tetu Lake region of C1, but not significantly so. Mercury levels in perch from C3 and C4 lakes were not significantly different from each other.

Where perch and other species of similar sizes were collected, results (Fig. 6), suggested that pike, pickerel, sauger, and mooneye would probably have mercury levels higher than perch, but levels in cisco, whitefish, and sucker would be equal or lower.

Mercury levels in crayfish showed a trend similar to that in fish, declining as distance increased downstream from Clay Lake to Indian Lake. Mercury levels in crayfish from C1 were significantly higher than those in crayfish from C3 and C4 lakes ($P < 0.05$, Student *t*-test). Crayfish from highly contaminated waters contained relatively higher levels of mercury than perch from the same waters (Table 5). The opposite was true in areas of lesser contamination and in lakes affected

Table 5
Mercury residues in fish, by study lake class

Study lake class / Species	*n*	Body wt (g) $\bar{x}$	Length (mm) $\bar{x}$	Length (mm) SD	Hg residue (ppm wet wt) $\bar{x}$	Hg residue SD	Hg residue Range
C1							
Clay Lake							
Perch	8	73	166	30.9	1.20	0.27	0.77–1.53
Pike	2	124	258	43.1	2.12	0.52	1.75–2.49
Crayfish *a**	5	20	81	5.5	2.75	0.92	2.28–5.16
b					3.59	0.19	
Wabigoon Bay Complex							
Perch	19	46	141	20.1	0.47	0.20	0.15–0.93
Pickerel	5	97	206	40.8	1.51	0.56	0.75–2.08
Cisco	2	103	185	49.5	0.60	0.23	0.43–0.76
Crayfish *a*	4	15	78	10.4	0.75	0.56	0.38–1.58
b					1.18	0.74	0.49–2.06
Ball–Indian Lake Complex							
Perch	15	60	164	23.0	0.29	0.23	0.10–0.36
Pickerel	4	126	234	22.9	0.62	0.08	0.56–0.74
Sauger	4	—	224	43.8	0.47	0.20	0.24–0.70
Pike	5	160	283	21.9	0.67	0.62	0.58–0.73
Mooneye	5		198	23.9	0.46	0.10	0.31–0.55
Crayfish *a*	3	18	75	5.0	0.26	0.17	0.13–0.45
b					0.50	0.27	0.36–0.82
Tetu Lake							
Perch	24	53	144	16.9	0.09	0.24	0.04–0.14
Pickerel	6	85	205	17.6	0.38	0.06	0.30–0.45
C2							
Perch	36	69	160	37.7	0.17	0.09	0.05–0.35
Pickerel	20	91	211	27.4	0.53	0.38	0.16–1.20
Pike	8	173	262	46.3	0.16	0.12	0.04–0.37
Mooneye	6	79	194	33.0	0.53	0.49	0.12–1.23
C3							
Perch	35	112	189	28.7	0.08	0.03	0.02–0.18
Pickerel	21	95	199	50.5	0.15	0.03	0.08–0.22
Sauger	1	136	250	—	0.16	—	—
Pike	5	186	307	49.6	0.09	0.03	0.07–0.13
Mooneye	6	—	172	27.0	0.05	0.01	0.03–0.05
Cisco	8	89	181	41.0	0.05	0.02	0.03–0.06
Whitefish	6	105	202	9.8	0.09	0.02	0.07–0.10
Crayfish	2	13	70	5.0	0.02	0.00	—
C4							
Perch	64	59	158	24.7	0.11	0.08	0.03–0.53
Pickerel	6	75	190	22.4	0.07	0.02	0.05–0.09
Pike	2	228	315	22.6	0.22	0.17	0.10–0.34
Sucker	3	166	230	5.0	0.07	0.05	0.02–0.10
Crayfish	8	12	73	7.8	0.03	0.01	0.02–0.05

*a — homegenized, whole crayfish; b — tail muscle tissue only.

Table 6
Mercury levels (ppm wet wt) in loon tissues and eggs from northwestern Ontario

	Study lake class 1*	2	3	4
A. Tissue				
Liver —				
Adult *n* =	5	4	12	10
Total mercury	29.73 ± 12.37	16.65 ± 10.86	5.10 ± 3.20	8.81 ± 4.63
Methylmercury	1.53 ± 2.10	1.09 ± 2.18	1.04 ± 0.71	0.20 ± 0.40
% Methylmercury	8.85 ± 12.26	7.47 ± 14.94	27.14 ± 21.89	4.08 ± 8.86
Chick *n* =	1	0	6	4
Total mercury	1.28	—	0.91 ± 0.37	0.83 ± 0.30
Methylmercury	0.97	—	0.84 ± 0.35	0.71 ± 0.22
% Methylmercury	75.78	—	91.71 ± 3.46	86.99 ± 5.46
Muscle —				
Adult				
Total mercury	4.57 ± 1.56	3.41 ± 2.01	1.22 ± 0.46	1.20 ± 0.64
Methylmercury	2.32 ± 1.49	1.59 ± 0.70	1.04 ± 0.40	0.85 ± 0.49
% Methylmercury	49.73 ± 26.15	60.39 ± 31.67	85.56 ± 5.40	73.36 ± 26.90
Chick				
Total mercury	0.89	—	0.38 ± 0.19	0.42 ± 0.13
Methylmercury	0.80	—	0.33 ± 0.17	0.30 ± 0.06
% Methylmercury	89.89	—	84.87 ± 10.40	82.32 ± 10.90
Brain —				
Adult				
Total mercury	1.49 ± 0.58	1.15 ± 0.57	0.42 ± 0.12	0.43 ± 0.12
Methylmercury	0.76 ± 0.50	0.50 ± 0.27	0.39 ± 0.11	0.33 ± 0.06
% Methylmercury	52.91 ± 29.20	51.95 ± 26.66	91.69 ± 4.80	79.69 ± 12.70
Chick				
Total mercury	0.78	—	0.30 ± 0.12	0.37 ± 0.14
Methylmercury	0.75	—	0.30	0.37 ± 0.13
% Methylmercury	96.15	—	100.0	99.06 ± 1.89
B. Eggs *n* =	5	6	10	13
Total mercury	1.39 ± 0.55	0.72 ± 0.23	0.54 ± 0.09	0.59 ± 0.10
Methylmercury	1.34 ± 0.53	0.71 ± 0.22	0.53 ± 0.10	0.58 ± 0.10
% Methylmercury	96.98 ± 0.51	98.65 ± 1.12	96.67 ± 3.16	98.72 ± 2.19

*Breeding adults only, from Ball L. downstream in C1 lakes.

Table 7
Mercury (ppm) in selected tissues of adult loons ($n = 37$) and chicks ($n = 10$)

	Liver $\bar{x}$	Liver SD	Liver range	Muscle $\bar{x}$	Muscle SD	Muscle range	Brain $\bar{x}$	Brain SD	Brain range
Adults									
Total mercury	12.95	11.67	(1.64–47.71)	2.33	2.07	(0.16–6.87)	0.86	0.89	(0.31–4.61)
Methylmercury	11.67	2.40	(0.00–10.20)	1.65	1.60	(0.15–6.59)	0.65	0.79	(0.22–4.27)
Chicks									
Total mercury	0.91	0.33	(0.35–1.47)	0.44	0.22	(0.14–0.89)	0.37	0.18	(0.14–0.78)
Methylmercury	0.80	0.29	(1.36–0.32)	0.37	0.20	(0.09–0.80)	0.37	0.17	(0.14–0.75)
% Methylmercury									
Adults	16.75	21.42		77.68	17.81		81.50	18.05	
Chicks	88.55	6.18		84.61	9.57		99.31	1.54	

Table 8
The correlation (*r*) between total mercury and methylmercury for liver, muscle, and brain tissues and the correlations among these tissues for total mercury and methylmercury for adults and chicks

	Liver	Muscle	Brain
Adults	$r = 0.23$	$r = 0.84$*	$r = 0.98$*
Chicks	$r = 0.82$*	$r = 0.98$*	$r = 0.99$*
	Liver vs. muscle	**Liver vs. brain**	**Muscle vs. brain**
Adults			
Total mercury	$r = 0.69$	$r = 0.58$	$r = 0.90$*
Methylmercury	$r = 0.65$	$r = 0.46$	$r = 0.90$*
Chicks			
Total mercury	$r = 0.78$*	$r = 0.78$*	$r = 0.94$*
Methylmercury	$r = 0.63$	$r = 0.61$	$r = 0.95$*

*Significant at $P = 0.05$.

only by natural mercury deposits. In similar boreal lakes in eastern Ontario, affected only by natural mercury deposits, crayfish (n = 25) from five lakes averaged 0.09 ppm total mercury, or 43% of that in perch from the same lakes.

3.4. Mercury in loons

Levels of mercury residue in loon tissue and eggs declined as the distance increased downstream on the Wabigoon River from the source of industrial mercury contamination at Dryden (Fig. 6, Table 6).

Both total and methylmercury levels were significantly higher (χ^2, P = 0.05) in brains of adult loons from the Clay Lake region of C1 lakes (80–140 km downstream from the source of waterborne mercury) than in those from C1 lakes farther downstream or from C2 lakes.

Mercury levels in brains of nesting loons from C1 lakes 150–320 km downstream in the path of waterborne mercury and from C2 lakes, although not significantly different from each other, were significantly higher (ANOVA, F = 0.01) than in loons from C3 and C4 lakes (Table 6), which were not significantly different from each other.

The concentration of total mercury residue in loon tissues decreased in the sequence liver > muscle > brain but the percentage of methylmercury increased from liver < muscle < brain (Table 7). The correlation (r) between total and methylmercury within tissue of both adults and chicks increased from liver < muscle < brain, but the correlation among tissues, for both total and methylmercury levels, was stronger between muscle and brain than between liver and either muscle or brain (Table 8).

Almost 100% of the mercury transferred from adult loons through eggs to chicks was organic (Table 6), with no net loss of methylmercury in chick tissue to suggest effective demethylation by the developing embryo. Levels of methylmercury in eggs and in the brain of newly hatched chicks frequently exceeded levels in the female parent's brain. The correlation (r = 0.94) between total mercury levels in the brain of nesting females and their eggs was significant (P = 0.005). There was no signficant difference between the ratios (chick brain/egg) from C1, C3, and C4 lakes.

Adult male loons generally contained higher levels of mercury than did their mates or other females from the same lake class, although the difference was not significant at P = 0.05. This was consistently the case for both total and methylmercury in muscle and brain. Methylmercury levels in liver were often too low for reliable assessment.

Adult male loons from C1 lakes weighed significantly less ($\bar{x}$ = 4.23 kg), at P = 0.05, than those from C3 and C4 lakes, whose weights were similar ($\bar{x}$ = 4.62 kg), (although males from C4 tended to be heaviest). The weights of males from C2 ($\bar{x}$ = 4.27 kg) were similar to those from C1 lakes. There were no significant differences in weight among females collected from the different lake classes.

Discussion

1. Effects of water-level fluctuations

The strong negative correlation between the successful use of potential loon territories and mercury levels prevailed for a considerable distance downstream from the source of industrial mercury contamination. But the decrease in territory establishment and nesting success, resulting from turbidity and unpredictable water-level fluctuations, obscured effects that mercury contamination might have on loons more than 160 km downstream from the source of industrial mercury in C1 and C2 lakes.

The natural water-level fluctuations occurring in the control lakes did not flood any nests. Under natural conditions, rising water caused by precipitation after spring run-off does occasionally exceed the ability of loons to compensate by adding nest material (Barr, unpubl.). However, the pattern from spring thaw through the nesting season is relatively consistent each year. After spring floods subside, changes are gradual and increases seldom more than a few centimetres. This is important because a rise of 15 cm may be sufficient to flood a nest constructed on a solid substrate at water's edge.

Loons waited for specific nest sites to become available as water receded. Thus the time of nest initiation varied, depending on the time and speed of spring thaw, precipitation, and type of nest site selected. The repeated use of territories and successful nest sites suggests strong territory and site fidelity by resident pairs and is supported by banding and marking results (McIntyre 1974; Yonge, pers. commun.).

As water-level fluctuations increase in range and become unpredictable in occurrence the availability of specific nest sites is less certain. Even if a specific site is available at the appropriate time for nesting there is increased risk that it will be flooded, or become too difficult for the loons to reach from water.

Loons select nest sites that are free from wave action, have immediate access to sufficient water for submerged approach or departure, have some concealment and seem free from mainland predators and disturbance (Olson and Marshall 1952, McIntyre 1975, Yonge 1981). As the range in water-level changes increases, bog marshes supply these features more reliably than do islands. Although loons will wait for previously successful island nest sites when the seasonal rhythm of water-levels is consistent, unpredictable timing, increases in the range and frequency of changes, and percentage of changes involving rising levels disrupt island nest sites, although floating bog sites remain unchanged. However, when the range in fluctuations exceeds the adaptive capacity of the bog marsh, the marsh is destroyed, leaving islands as the only potential nest sites. Water-level changes that destroy the bog marshes also eliminate the shoreline vegetation and topsoil of islands. As a result, wide bands of bare rock separate sheltered nest sites from water. Nests established when water was high and adjacent to vegetation become more vulnerable to predation. This is accentuated by increasing disturbance from human activities such as fishing, which is often concentrated around islands.

Loons appear reluctant to establish nests when the distance from water to some concealment (vegetation, tree root, rock) is much more than 1 m. Over 90% of all nests were built within 1 m of the shoreline. The original distance from nest to water had been increased by at least 1 m for 26 (40%) of 65 predated nests. On one lake alone, five of eight pairs had nested when high water reached island vegetation. Subsequently, receding water rendered all islands inaccessible in two territories and resulted in predation of the five established nests. One renest was attempted but was deserted as the water continued to recede.

Established territories dependent on a single island nest area would be most severely affected when water levels are first manipulated by means of a dam. With strong affinities for territory and nest, loons are likely to return in succeeding years to territories that no longer offer a nest site each year, or offer ones that, though initially available, are more likely to be flooded, deserted, or predated (Fig. 4) than under natural conditions. Eventual turnover in the loon population would result in replacement birds having insufficient opportunity to form and reinforce attachment to territory or nest.

According to local Ojibwa natives, after the first dams were built along the Wabigoon–English River system, water levels fluctuated much less than now, shoreline vegetation and bog marshes persisted, loons were plentiful and many chicks were still seen annually in the lakes. Manipulation of water through more and larger dams has now destroyed most of the nesting habitat and caused decreases in productivity, stability, and use of potential territories. Destruction of marginal vegetation by impounding large lakes in Norway has apparently prevented Arctic Loons (*Gavia arctica*) from nesting (Dunker 1974).

2. Effects of turbidity

Fluctuating water levels erode shorelines and contribute to turbidity in the river drainage basin, which contains numerous deposits of lacustrine clay (Zoltai 1961). Even when changes are moderate, an increased mean water level can expose extensive areas to erosion for many years. A small dam built at Dryden in 1910 raised the level of Wabigoon Lake, a large (10 760 ha), shallow body of water. Through the years, wave action has eroded much of the shoreline clay and visibility in the water remains low, particularly in the main body of the lake. Although there are 42 potential territories with nesting areas, loons consistently occupy and are successful only in secluded shallow bays with bog marshes. Loons do not nest on or even maintain territories around the numerous islands in the main body of the lake.

In previous experiments (Barr 1973) hand-reared loons required supplemental feeding of approximately 50% of daily diet when water clarity was reduced below 1 m, and McIntyre (1975) found loons nested on turbid lakes in Minnesota only when such lakes were shallow (< 3 m). Loons caught in gill nets on Wabigoon Lake are always enmeshed near the surface float line (pers. commun., G. Adam, commercial fisherman). In clear lakes loons are most frequently tangled in nets at considerable depths. It is possible that steeper shorelines and deeper water around islands in the main body of the lake, combined with poor light penetration, diminish the size of feeding areas and efficiency of capture below the threshold necessary to raise chicks. Consistently successful reproduction in the large shallow bays of Wabigoon Lake and the use of island nest sites in adjacent interconnected lakes experiencing the same water-level changes but better light penetration support this explanation.

If necessary, adult loons can range far within a large lake, or fly to other lakes to feed. Chicks are restricted to the natal territory until they fledge at 11 weeks. Loons are visual hunters, form prey images and are excited by concentrations of prey (Barr 1973). It is possible that frequent sighting of adequate food for small chicks as well as the presence of suitable nesting habitat stimulates breeding or nesting behaviour. Autopsies on 293 loons, during the present and previous studies (Barr 1973, Frank *et al.* 1983), indicate that adults arrive on the breeding grounds in spring with considerable fat reserves. Most if not all lakes in the study area are oligotrophic and productivity in a number of nearby lakes was found to be extremely low (Armstrong and Shindler 1971). Gill netting during the present study suggested that prey species were less numerous than in oligotrophic lakes sampled in eastern Ontario (Barr 1973). The fact that crayfish were found more frequently in loons collected from turbid lakes suggests that, with a combination of decreasing visibility and productivity in lakes, loons become more dependent on crayfish, a food source not suitable for a young chick whose gizzard can not readily break up the chitenous exoskeleton. Loons may be incubating within a week of arrival in spring if nesting habitat is suitable, and most would be on nests several weeks before fat reserves appear depleted. Therefore if the availability of prey species influences the reproductive cycle, prey suitable for young chicks appears to be the most likely and most advantageous stimulus to have evolved.

Light penetration is limited in many lakes of the study area by humus staining, typical of bog and muskeg lakes, and further reduced periodically by plankton blooms and pollen. These natural phenomena do not reduce clarity below 1.5 m and do not seem to deter successful reproduction by loons. The addition of industrial effluent, combined with the turbidity induced by fluctuating water levels, reduces light penetration, resulting in Secchi disk readings of less than 1.5 m in parts of all lakes exposed to these actions. For years, effluent and residues from pulp and paper mills on both the Wabigoon and English Rivers have exceeded the river's natural capacity to flush and assimilate. Effluent from the Dryden Paper Company mill (later known as Reed Paper) alone contained an average of 32 000 kg per day of suspended solids in 1968 (OWRC 1970). This mill, in operation since 1913 (German 1969), is not unique. Its effluent had suppressed dissolved oxygen, eliminated fish life for 60 km downstream (OWRC 1970), and contributed to increased turbidity for over 350 km. Beyond 60 km downstream from Dryden, the Wabigoon River is aerated by several sets of rapids and falls. Normal levels of oxygen are restored below High Falls and Quibell Falls. This 20 km stretch of river contained some fish, although no game fish, until just before Clay Lake (German 1969). The variety of fish species available to loons in Clay Lake is similar to that in other lakes of the study area, although Beamish (pers. commun.) noted that some size classes were poorly represented.

The water was considerably clearer in the past. Older natives and local guides (pers. commun.) insist that it was much cleaner when they were young. A written account (Dewdney and Arbuckle 1975: 207) mentions the "crystal clear" water of the Wabigoon River in 1937. In spring 1976, when the mill was inoperative during a strike, the foam and odour disappeared from the rapids for 65 km downstream from the source and Secchi disk readings in some parts of Clay Lake, 85 km downstream, increased as much as 1 m.

3. Mercury: its availability to, and accumulation in, loons

When only lakes experiencing natural water-level changes are considered, the smaller increase (Table 4) in the percentage of clutches hatched in C2 lakes than in C3 lakes suggests that some factor other than water-level changes is suppressing nesting success. No C1 lake is free from unpredictable water-level changes induced by flow rates through dams. C2 lakes are clustered about C1 lakes in the region of the Ball–Indian Lake Complex. Mercury levels in prey fish from some C2 lakes approached levels in fish from adjacent C1 lakes and were higher than in fish from C1 lakes farthest from the source of waterborne mercury. Access between C1 and C2 lakes for prey species, other fish, and other members of the food chain may partly account for this phenomenon.

The observed ranges of mercury levels in prey species from different parts of the same lake suggest that the movements of crayfish and the smaller prey fish populations are local. Hence mercury levels in the prey of a specific territory would be reflected in the resident loons, because mated loons spend most of their time in the established territory until mid-July and longer if chicks are raised.

As contamination of a lake increases, waterborne mercury will selectively affect residents in territories most exposed to current through the lake. When loons abandon a territory, they usually forage in the more exposed, neutral parts of a lake and in the larger connecting rivers, feeding predominantly on prey that probably contain the highest concentrations of mercury. During the present study, most loons that abandoned territories in lakes with high mercury contamination soon left the lake, instead of forming the social groups so characteristic of non-nesting loons on larger lakes of the breeding grounds.

Historically, the principal breeding ground of the Common Loon has coincided with wooded lakes of the Precambrian Canadian Shield and the mountainous Cordillera regions along the west coast of North America. The Cordillera and the southerly side of the Canadian Shield, which extends in a great arc from the eastern seaboard to the latitude of Great Bear Lake, are also regions of mercury-rich sphalerite, particularly in Proterozoic volcanogenic deposits (Jonasson and Sangster 1974). Regions possessing the richest and most accessible mercury deposits include the Hanson Lake – Flin Flon volcanic belt of northern Saskatchewan and Manitoba, the vast greenstone belt outcroppings of northwestern Ontario, and the Sudbury basin deposits which include the Algonquin Highlands. The naturally high levels of mercury in these regions are reflected in the ecosystems of numerous lakes. Yet researchers in these three areas (Barr 1973, Yonge 1981, present study) have found that, in lakes relatively free of man's activities or effluents, loons aggressively defend most potential territories and produce the number of viable eggs and chicks considered normal to this species in prime habitat. However, continuing broad atmospheric dispersal of acidic emissions is resulting in acid stress to, and increased mercury concentrations in, the vast number of poorly buffered lakes of this summer range. Suns *et al.* (1980) found that, in Precambrian lakes of Muskoka, Ontario, the availability of mercury to fish was strongly correlated with the size of the drainage basins and lake volume. They also demonstrated that acid stress accelerated mercury uptake in young yellow perch.

Johnels *et al.* (1969) point out that naturally occurring mercury levels in fish from uncontaminated but extremely acidic or oligotrophic lakes may be more than twice as high as the suggested maximum background level (0.2 ppm) for lakes in general. This view was supported by D'Itri *et al.* (1971), who compared rainbow trout from an oligotrophic and an eutrophic lake. Miller and Akagi (1979) found that the amount of methylmercury in the water column doubled when pH decreased by two units over organic sediment. Consequently, chronic exposure to elevated levels of mercury through the food resource may become a far more widespread, if less acute, hazard than that associated with waterborne industrial effluent. Acid precipitation poses an indirect threat to the loon in addition to augmenting the availability of mercury. Increased acidity may result in widespread depletion or elimination of the food resources (Beamish 1974, 1976; Beamish *et al.* 1975; Scheider *et al.* 1979), particularly for loon chicks, even before the toxic effects of mercury directly disrupt reproductive efforts of adult loons.

The physiological stresses of migration and moult on birds are well documented. In loons, these stresses occur sequentially and, if aggravated by some degree of incapacitation due to mercury toxicity, may leave the loon more susceptible to secondary infection. Hartung and Dinman (1972) suggested that fish subjected to sublethal mercury poisoning had lowered resistance to infection by diseases or parasites. Preliminary investigations into the die-off of more than 2500 loons in the Gulf of Mexico during the winter of 1983 (Graham 1984) found elevated levels of mercury and pathological signs of mercury toxicity associated with abnormally high infestations of internal parasites, particularly microphallid trematodes.

Nesting success was lowest for those loons initiating clutches in C1 lakes (Table 4), being less than half that of C3 birds under conditions apparently similar except for exposure to mercury. The consistently high fledging success of loon chicks from all lake classes implies that the mercury level in C1 loon eggs sampled is too low (Table 6) to cause mortality once chicks have successfully hatched.

Loon chicks have high energy requirements and growth is rapid (Barr 1973). Thus it appears likely that mercury levels in the smaller prey fish on which chicks would be fed, especially during the first few weeks after hatching, would be diluted rather than increased in loon tissues. However, with a combination of increased prey size and decreasing growth rate by the time the chick fledges, mercury level in the brain could conceivably surpass that at hatching.

Loons feed intensively before migrating (McIntyre and Barr 1983). It is therefore possible for young loons to attain high concentrations of mercury before leaving the natal lake when 12–16 weeks old. Such levels could be further amplified if time was spent before migration on even more highly contaminated lakes nearby, such as Clay Lake. Assuming that a loon chick consumes approximately 50 kg of food and attains a weight of about 3 kg between hatching and migration (Barr 1973; the values used here are slightly less than I found in 1973, as loons in northwestern Ontario were smaller than those in Eastern Ontario), a mercury level of 0.5 ppm in available prey would result in the juvenile ingesting about 25 mg of mercury prior to migration. Most of this would be methylmercury, according to this and previous studies (Uthe 1971, Zitko *et al.* 1971, Westoo 1973).

Although the biological half-life of mercury is not well documented for birds, it seems relatively short (Wright *et al.* 1974). For methylmercury it is at least 5 weeks for some species (Swensson and Ulfvarson 1968), and about 12 weeks in Mallard drakes (Stickel 1973, unpubl. rep. in White and Stickel 1975). Juvenile loons do not return to the breeding grounds until at least their third spring, a period encompassing two complete and one partial moult. Hence, juveniles migrating with a high body burden of mercury from a natal lake would have a good chance of reducing mercury levels if, when returning to the breeding grounds, they select lakes free of mercury contamination. Adults would also benefit from wintering in areas with low background levels of mercury. Loons undergo a complete moult, including renewal of primary feathers, by late winter, before migrating to the breeding grounds. Growing feathers, particularly primaries, are known to concentrate mercury. Compared to breast muscle, mercury levels in primary feathers were up to 12 times as high in adults and 22 times as high in juvenile Pintail ducks (Vermeer and Armstrong 1972). In both adult and juvenile loons, whether healthy or emaciated, both back and belly feathers contained approximately 5–6 times the levels in breast muscle (Frank *et al.* 1983). Berg *et al.* (1966) divided by seven to estimate the mercury levels in muscle from known levels in feathers. Thus, individual loons, if wintering on relatively mercury-free waters, should arrive on the breeding grounds with internal mercury levels lower than at any other time of year. Loons tend to return to familiar summer territories, hence any mercury contaminant reduced by moulting will quickly be replenished and further amplified if the bird returns to mercury-contaminated waters. However, one cannot dismiss the possibility of mercury contamination on the wintering grounds.

4. Sensitivity to mercury poisoning

Birds exhibit a wide range of sensitivity to mercury, depending on species, exposure time, toxicant level, age, and physiological demands (Borg *et al.* 1970, Stoewsand *et al.* 1974, Finley *et al.* 1979). Loons with mercury levels in various tissues equal to or exceeding those in other birds showed similar symptoms. In loons the level of mercury was, occasionally, tenfold higher in liver than in brain tissue. Fimreite (1971) observed a significant decrease in hatchability of pheasant eggs with methylmercury levels of 0.5–1.5 ppm from hens containing 3–13.7 ppm in liver tissues. The hens, though apparently healthy, suffered from spinal nerve demyelination. The survival of the chicks that hatched was not reduced by the presence of methylmercury. Finley and Stendell (1978) found that Black Duck (*Anas subrubripes*) ducklings died from approximately 3–7 ppm methylmercury in the brain. Thus earlier stages of life appear most sensitive to mercury poisoning, although long-term exposure is eventually lethal at lower levels than is short-term exposure, even in older birds (Platonow and Funnell 1971, Evans and Kostyniak 1972).

5. Correlation of mercury in prey and reproduction in loons

Mercury levels in prey species were high enough to inhibit reproductive activities of loons in some territories of lakes in the lower reaches of C1. Upstream from Ball Lake only one egg was laid (which did not hatch) from 1974 to 1976. The highest total mercury level (2.21 ppm) of sampled eggs came from one of the only two territories on Ball Lake where loons laid eggs. Mercury levels in fish sampled from this territory were unexpectedly low for Ball Lake (perch 0.15 ppm, Table 5) (see Fimreite and Reynolds 1973) relative to its position along the Wabigoon River, and considerably lower than levels in perch collected at other locations in Ball Lake (Bishop and Neary 1976), even accounting for the difference in size. A chick was successfully reared on the same territory in 1975. The second chick died at hatching with 2.44 ppm total mercury (homogenate, whole chick) and 0.178 mg mercury total body burden. Eggs from this C1 nest and two nests on different C2 lakes were abnormally pigmented (pale ash to grey-green, few or no dark spots). Both nests from C2 lakes were predated and no renesting was attempted. During the present study, abnormally pigmented eggs (pale green to turquoise, with no spots) were found in nests of a Herring Gull (*Larus argentatus*) colony on Clay Lake. Abnormally coloured eggs have been associated with mercury toxicity in other species (Fimreite 1971). Although eggs were laid in 78% of the potential territories on Indian Lake, the next lake downstream from Ball Lake, no nests were initiated during the 3-year study in two occupied territories where perch ($\bar{x}$ length = 161 mm) averaged 0.36 ppm.

Failure to produce eggs appears to be a common manifestation of methylmercury contamination in birds (Ljunggren 1968, Peakall and Lincer 1972, Wright *et al.* 1974). Egg production may decline before embryo residues cause teratogenicity or increased mortality in newly hatched young (Heinz 1974, present study). Mercury levels in some loon eggs from the lower reaches of C1 Lakes (Table 6) may be sufficiently high to reduce hatching success; they exceed levels found to increase embryo mortality in other species (Borg *et al.* 1969, Spann *et al.* 1972). The mean difference in mercury levels of 17% ± 9 (n = 14 pairs) between eggs of the same clutch and a range of 24% in brain levels between siblings suggests that both chicks would not necessarily succumb to mercury toxicity at hatching as residues approached a critical level.

6. Correlation of mercury levels with loon behaviour

There are indications of reduced nest site fidelity in mercury-contaminated birds (Tejning 1967). Such aberrant behaviour, if it occurred in loons, may have been amplified in areas where changing water levels made it more difficult to go from water to nest. Thus reduced attachment to nests might explain the greater nest desertion and predation that resulted in lower success of clutches in C1 and C2 than in similar C3 lakes with little or no mercury contamination.

Adult loons with total mercury concentrations in the brain as low as 2 ppm (Table 6, Fig. 6) may show aberrations in reproductive behaviour, resulting in lowered incubation success and the abandonment of territories. More territories were abandoned after brief periods each spring in C1 and C2 than in other lake classes (Fig. 5). Peregrine Falcons with mercury levels of 42 ppm in primary feathers apparently failed to produce eggs and abandoned their nests (Berg *et al.* 1966). Using the same author's conversion factor this approximates 6 ppm in muscle tissue. The figure is probably high, but still approximates total mercury levels in muscle tissue of loons from the C1 and C2 lakes of the Ball–Indian Lake region. Heinz (1976) showed that, after prolonged exposure to a diet containing 0.5 ppm methylmercury (equal to 0.1 ppm in natural diet), Mallard hens, whose eggs contained an average of 0.86 ppm, exhibited aberrant nesting behaviour.

Exposure time and residual tissue levels carried by loons from one season to the next are important determinants of tissue burdens. Methylmercury concentrates in and is retained longer by dark muscle than by white muscle fibre (Backstrom 1969). Such dark, well irrigated and myoglobin-rich muscle fibre is characteristic of loons. Added to residual tissue loads from previous seasons, mercury levels of 0.35–0.5 ppm in prey may be adequate to elevate residues to levels in adult loons in time to interfere with reproductive behaviour.

Using the mean weight for breeding males (4.4 kg) and females (3.54 kg) from the present study and assuming a food consumption of 20% body weight per day (Barr 1973), male and female loons would ingest approximately 6.2 and 5.0 mg of mercury per week respectively at 1.0 ppm in prey. However, no loons hatched chicks in territories harbouring perch ($\bar{x}$ length = 161 mm) with mean residue levels >0.36 ppm, while only one egg was laid in lakes from which mean mercury levels in perch ($\bar{x}$ length = 141 mm) exceeded 0.4 ppm. The highest total mercury level in brain from mated loons that hatched chicks between 1974 and 1976 occurred on Ball Lake (♂2.06 ppm, ♀1.83 ppm). The male weighed only 3.75 kg and was emaciated, although its other measurements (total length, wingspan, skull width, and length of bill, radius, tarsus, and midtoe) corresponded to those of considerably heavier males ($\bar{x}$ = 4.74 kg, SD = 0.35). The second lightest breeding male also came from Ball Lake. Emaciation and muscle atrophy are symptomatic of heavy metal poisoning (Borg *et al.* 1970), and the tissue may contain elevated mercury levels, although the concentration of mercury does not increase as rapidly as the concentration of organochlorines in emaciated loons (Frank *et al.* 1983).

In addition to eating more, male loons tend to eat larger fish than do females (Barr 1973). Because mercury concentration varies positively with length of fish within species from one location (Scott and Armstrong 1972), the consumption of larger prey may partly account for the generally higher levels of mercury in adult males than females of nesting pairs. But all these females had recently excreted considerable quantities of methylmercury via eggs, and other physiological differences cannot be discounted. In a comparison of 12 unpaired adult loons (7♂, 5♀ from eastern Ontario, Barr, unpubl. data), males (0.81 ppm) had higher, but not significantly so, concentrations of mercury in the brain than females (0.58 ppm). Data for newly hatched loon chicks from the present study are meagre, but the greatest difference (24.4%) for methylmercury concentration in brain occurred between the only male–female sibling pair, residues in the male being higher, although there was less than 2% difference in their weights. Differences in mercury levels in brain between male siblings and between female siblings were 3.4 and 16.3% respectively.

It appears that physiological blockage to egg production and reduced nest attentiveness by female loons occur in lakes where mercury residues, in prey and in eggs, exceed the levels that caused those symptoms recorded in experiments with other species. A lower percentage of loons laid or hatched eggs in such lakes. The present study shows that the male loon of a pair is likely to have mercury concentrations as high, if not higher, than his mate. Male loons normally share incubation duties and aggressively defend large territories. Any reduction in incentive to defend nest or territory could result in lowered reproductive success and breakdown of territories. One might expect some nervous system dysfunctioning to occur in loons chronically exposed to mercury contamination in C1 and C2 lakes. This may express itself in reduced territorial drive, resulting in the high percentage of abandoned territories after brief spring residence, and in abandoned and predated nests during the incubation period.

Clinical signs of mercury poisoning, such as impaired vision and ataxia, have been found in several avian species (Evans and Kostyniak 1972, Hays and Risebrough 1972) at mercury levels lower than those in loons from Ball Lake. Significant behavioural deviations due to methylmercury poisoning have also been observed in the absence of overt clinical signs (Spyker *et al.* 1972). It is reasonable to assume that any impairment of vision or ataxia in a visual hunter such as the loon would reduce its chances of procuring adequate food and its ability to defend a territory. Ataxia and blindness, as well as inappetance, retarded growth, and emaciation, have been observed in fish exposed to mercury (Takeuchi 1966, Ruohtula and Miettinen 1975, Panigrahi and Misra 1978). Large pike, another visual hunter, netted from C1 and C2 lakes during the present study were frequently emaciated. Mercury was even more concentrated in the eye lens than in the kidney or liver of large but emaciated pike from Clay Lake (Lockhart *et al.* 1972). There was also mercury-associated destruction to the retina of Clay Lake pike (Braeckevelt, pers. commun.).

From Ball Lake downstream on the Wabigoon river and in C2 lakes, mercury levels in perch approximated those in crayfish. Crayfish from waters subject to higher levels of waterborne mercury, upstream from Ball Lake, contained higher concentrations of mercury than did small perch. It seems probable that frequent deaths of highly contaminated fish from these waters contribute substantially to the food supply of scavenging crayfish. The high mercury levels reported by Scott and Armstrong (1972) and others for all species of fish present in the Clay Lake to Ball Lake reach of the Wabigoon River exceed lethal levels reported for other freshwater species (McKim *et al.* 1976). The emaciated condition and visual impairment of predacious species such as pike support the hypothesis of mercury-induced mortality.

The C1 waters contaminated by high levels of mercury were also affected by turbid conditions in which loons were found to consume a higher percentage of crayfish than fish. One could expect loons to accumulate mercury more rapidly in such waters than in clear-water lakes of equal contamination where they predominantly eat fish, or in the areas of lower contamination from Ball Lake downstream in C1 and C2 lakes, where the accumulation of mercury appeared to be sufficiently high to inhibit reproductive activities of some loons. The low percentage of birds laying eggs, the high percentage of territories abandoned, and the poor success in incubation by loons in C1 and C2 lakes where survival of chicks, once hatched, equalled that of C3 and C4 lakes, all show that the lowered reproductive success of loons, as mercury contamination increases, is due primarily to failure to produce eggs and to behavioural aberrations in adults.

7. Correlation of mercury with other toxicants

Checks during the present study for toxicants other than mercury indicated generally low levels (0.001 ppm for lindane, heptachlor, aldrin, heptachlor epoxide, and dieldrin in most cases; 0.02 ppm for all of the above chemicals plus DDT metabolites for all species; and 0.04 ppm for PCBs) in all fish tested from C1, C2, and C3 study lakes. In a survey from lakes across Ontario, including the present study area (Frank *et al.* 1983), only a very small percentage of loons contained toxicants at levels found to affect other species adversely. This phenomenon was supported by the observations of Locke and Bagley (1965) and Ohlendorf *et al.* (1982). This evidence shows that high levels of toxicants other than mercury were not derived from local food sources and that only a small percentage of loons in the study area would have accumulated high levels of such toxicants elsewhere. Non-mercury toxicants can be discounted as a major factor in the failure of loons in the Wabigoon–English system subjected to high levels of mercury contamination.

Methylmercury was found to act synergistically with parathion (Dieter and Ludke 1975), although ethylmercury (Ceresan M) in combination with DDE showed no synergism in Japanese Quail (*Coturnix japonica*) and Ring-necked Pheasant (*Phasianus colchicus*) (Kreitzer and Spann 1973). Therefore it is reasonable to assume that the detrimental effects of methylmercury may sometimes be augmented either synergistically or cumulatively, as in the case of organochlorines (Sileo *et al.* 1977).

Mercury appears to be the only toxicant present in prey species at levels sufficiently high to induce the effects found in the loon population on the study lakes. Vermeer *et al.* (1973) reported that mergansers, having eaten more perch and crayfish, contained higher concentrations of mercury than all other ducks tested. Perch in the present study contained levels of mercury only slightly lower than sauger and pickerel, two of the most highly contaminated species. Crayfish are also known to concentrate mercury to very high levels, mostly in the methylated form (Vermeer 1972, Doyle *et al.* 1976). Fish and crayfish apparently excrete mercury very slowly (Miettinen *et al.* 1969, Hamilton 1972, Uthe *et al.* 1972). According to Wood (1972), the half-life for methylmercury in perch is approximately 500 days and in pike 500–700 days, while Lockhart *et al.* (1972) found that pike, transferred from Clay Lake to a mercury-free lake, eliminated only 30% of their mercury contaminant in 1 year. Jarvenpaa *et al.* (1970) found the methylmercury half-life in European pike (*Esox* sp.) to be almost 2 years.

There is little doubt that fish remaining in the contaminated lakes would increase their concentration of mercury for a considerable time after the input of pollution ceased. According to Armstrong and Hamilton (1973), the vast reservoir of mercury in Clay Lake ensures that crayfish affected by these waters will retain elevated levels of mercury for decades. It is reasonable to assume that fish and loons, which feed on both, will be affected equally as long. There was essentially no change in levels of mercury contamination in fish in the Wabigoon–English River system during this study (Bishop and Neary 1976). The persistence and effects of mercury-contaminated sediments from industrial effluents is fully supported by studies on other aquatic systems (Hasselrot 1968, Underdal and Hastein 1971, Kleinert and Degurse 1972, Langley 1973). Hence, no increase in the loon population or its reproductive success in mercury-contaminated lakes of the Wabigoon–English River system can be expected for many years. Because of the unpredictable, extensive water-level changes resulting from dams, even the lakes along this river system that are little contaminated will for the foreseeable future be poor nesting places for loons.

Summary

Unpredictable water-level fluctuations and turbidity resulted in significant decreases in the number of territories established and in the nesting success of loons. Increasing turbidity resulted primarily in a decrease in the number of potential territories occupied. Large, unpredictable water-level changes resulted in increased desertion and predation of clutches. Clutches initiated in territories subject to turbid waters alone hatched as frequently as those in the control group.

There was a strong negative correlation between the successful use of territories by breeding loons and levels of mercury contamination in lakes for 160 km downstream from the source of industrial pollution on the Wabigoon River. The correlation was weaker beyond 160 km downstream, being masked by the deleterious effects of extensive, unpredictable water-level changes and turbidity. However, prey species and loons and their eggs from this area contained levels of mercury contamination high enough to result in reduced egg production, physical and behavioural dysfunction, and increased mortality.

Reductions in egg laying, and in nest site and territorial fidelity were associated with mean mercury concentrations ranging from 0.3 to 0.4 ppm in prey, and from 2 to 3 ppm in adult loon brain and loon eggs. Loons established few territories, laid only one egg, and raised no progeny in waters where mean contamination of small prey species exceeded 0.4 ppm.

The existing amounts of mercury and organic sediment, combined with river currents and both aerobic and anaerobic methylation, ensure that levels of contamination will decline slowly and remain available to loons through the food chain for decades.

The naturally elevated levels of mercury in the vast number of poorly buffered lakes throughout the loons' breeding grounds, including the present study area, are likely to be increased to hazardous levels by persistent, wide-spread acid precipitation.

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