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ACCUMULATION OF MERCURY IN FISH AND MAN FROM RESERVOIRS IN NORTHERN FINLAND

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Abstract. Fishing is of great importance in northern Finland, where large water-control projects have been constructed. Increased Hg content in fish from recently impounded reservoirs has stimulated an investigation of possible accumulation of Hg. Therefore, samples of fish and human hair have been analyzed for Hg content. The concentrations of Hg in fish from man-made lakes were higher than in fish from a background (natural) lake. Fish of prey, burbot *(Lota lota)* and pike *(Esox lucius)* contained more Hg (max 2.0 mg kg^{-1}) than other species of fish and higher values were recorded in the flesh than in the liver. In the Porttipahta reservoir the Hg content of burbot and pike exceeded the Finnish safety limits of 0.5 and 1 mg kg^{-1}. In samples of human hair there was also a clear difference between persons living near man-made lakes (mean 4.9 mg kg^{-1}) and background (mean 1.6 mg kg^{-1}) areas. The highest concentrations (about 30 mg kg^{-1}) were found in hair samples from middle-aged people eating substantial amounts of fish from reservoirs. The concentrations were higher in males than in females probably caused by a higher fish consumption.

1. Introduction

In recent years elevated Hg concentrations have been found in fish from recently impounded reservoirs (Abernathy and Cumbie, 1977; Bodaly and Hecky, 1979; Cox *et al.*, 1979; Meister *et al.*, 1979; Verta, 1982). In northern Finland extensive water control projects have been built. The fishing in the new man-made lakes has become important for the local people. For these reasons it seemed necessary to study the effect of water control on the Hg content in fish and man. Human hair has been widely used as an indicator of Hg exposure and there has in general been a good correlation between the consumption of polluted fish and the Hg content of hair (Sumari *et al.*, 1972; Nuorteva *et al.*, 1975; Harada *et al.*, 1977; Ohtsuka and Suzuki, 1978; Suzuki *et al.*,1979; Phelps *et al.*, 1980).

2. Material and Methods

2.1. Study Areas

Fish and hair samples were obtained from eight areas in northern Finland (Figure 1):

2.1.1. *Lokka*

The ground under this reservoir consisted of 60% open fens, 30% marsh land and 10% forests. The annual mean temperature in the Lokka-Porttipahta area is −1.5 °C (Franssila and Järvi 1974). The filling of the reservoir started in 1967. The maximum allowed

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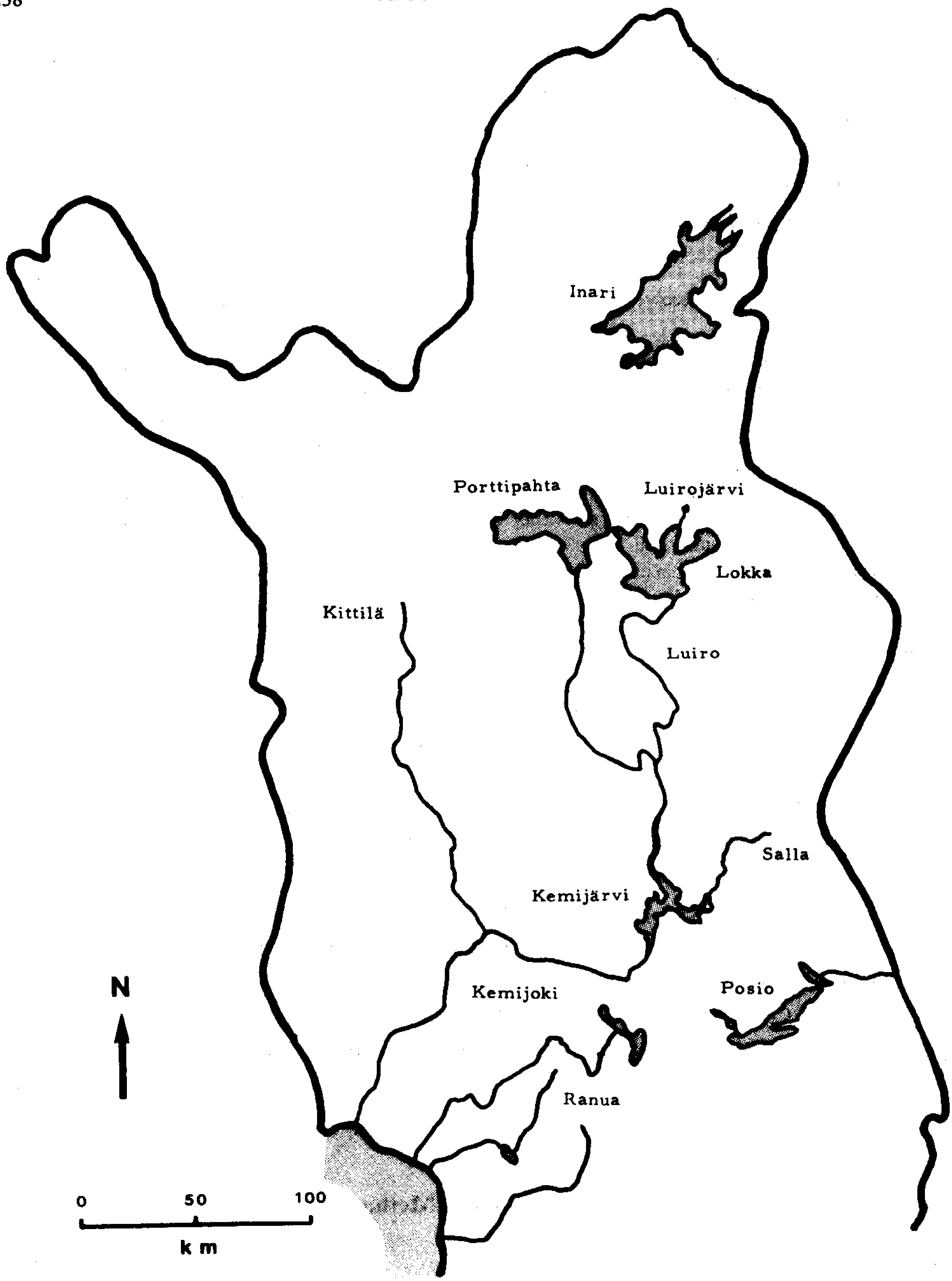

Fig. 1. The study areas.

fluctuation in water level is 5 m and the volume varies from 500 to 2063 × 10^6 m^3. At the minimum water level about 200 km^2 of the bottom are exposed. The water is polyhumic (mean color 130 mg Pt l^{-1}) and slightly eutrophic with O_2 depletion occurring periodically. The pH-value is normally about 6.0 to 6.2 in the winter and about 6.5 to 6.7 in the summer (Heinonen and Airaksinen, 1974).

In the year 1977 the fish catch from Lokka was 183000 kg (Anon., 1979). The most important species in 1979 were (as a percentage of the total fish catch): pike (43%), perch (22%), ide (13%), whitefish (12%) and burbot (6%) (Mutenia, 1981).

2.1.2. *Porttipahta*

About half of the ground under this reservoir consisted of bogs (Nenonen and Nenonen, 1972).

The filling of the reservoir started in 1970. The maximum allowed water level fluctuation is 11 m and the volume is 150 to 1353 × 10^6 m^3. At the minimum water level about 180 km^2 of the bottom are exposed. The water is polyhumic (color about 150 mg Pt l^{-1}) and a little more oligotrophic than in Lokka. Oxygen depletion may occur. The pH-value varies normally between 6.3 and 6.8 being thus somewhat higher than in Lokka (Heinonen and Airaksinen, 1974).

The fish catch in the year 1977 was 85000 kg (Anon., 1979) and the most important fish species in 1979 were: perch (50%), pike (34%) and burbot (12%) (Mutenia, 1981).

2.1.3. *Kemijärvi*

Lake Kemijärvi and the river Kemijoki about 45 km above Kemijärvi are strongly controlled. Kemijärvi receives water from the Lokka and Porttipahta reservoirs. The maximum allowed water level fluctuation is 7 m and the variations in water quality are extensive due to the control and natural factors (Nenonen, 1978).

2.1.4. *Control Areas*

The waters in the Salla, Posio and Ranua areas are unpolluted, oligotrophic and oligohumic lakes and rivers. Hair samples were also obtained from the following areas: Sodankylä, Rovaniemi, Kittilä, and Inari. The background fish samples originate from Luirojärvi, a small unpolluted lake situated above the Lokka reservoir.

2.2. Fish and Hair Samples

Altogether 159 fish samples were obtained from Lokka, Porttipahta, Kemijärvi and Luirojärvi. Samples of the dorsal, axial muscle and, if possible, the liver were taken and the length and weight of the fish were measured.

The people involved in this investigation cut their hair samples according to detailed instructions and sent the samples by mail to the laboratory. They also filled in a questionnare concerning their age, sex, fish eating habits and other possible sources of Hg contamination. A fish consumption index (FCI in the tables) was calculated on the basis of the answers. In this index

0 = no fish consumption,
1 = 1 fish meal a week or less,
2 = 2-4 fish meals a week, and
3 = more than 4 fish meals a week.

Altogether 111 hair samples were obtained. If possible the hair samples were divided in 1.5 cm long segments starting from the scalp.

2.3. Mercury analysis

The samples were digested with 5 ml of concentrated nitric and sulphuric acids (1 : 4) in a water bath (+ 60 °C) and analysed using cold vapor atomic absorption spectrometry (Coleman MAS-50).

3. Results

The total fish consumption was almost the same in all the areas investigated (Table I) and fish consumption was higher for males (mean FCI 2.2) than for females (mean FCI 1.5). However, there were significant differences in the distribution of fish species in the diet in different areas. In Lokka, Porttipahta and Kemijärvi (reservoirs) the people ate more pike and burbot than in the background areas. There was no significant difference in the composition of the fish consumption between males and females.

TABLE I

The total fish comsumption (FCI 0-3 as described in the text) and the percentage distribution of species in the fish diet in 7 areas according to the answers to the questionnare.

Area	FCI	Pike	Burbot	Perch	Whitefish	Other species
Lokka	1.6	32	13	16	28	11
Porttipahta	2.0	24	18	19	30	9
Kemijärvi	2.0	36	20	16	14	14
Salla	1.6	19	11	19	26	25
Posio	2.1	10	0	18	25	47
Ranua	1.9	34	3	35	4	24
Other areas	2.1	20	10	24	23	23

The highest Hg contents in fish were found in burbot and pike from Porttipahta (Table II). In the other reservoir areas, Lokka and Kemijärvi, the concentrations were also higher than in the background lake, Luirojärvi. In most fish species there was less Hg in the liver than in the flesh. In whitefish, however, the relationship was the reversed (Table III).

There were no significant differences in the sex or age distribution of the people from the various areas investigated. In the reservoir areas the Hg content in human hair was three times higher than in the background areas (Table IV). Mercury concentrations exceeding 15 mg kg^{-1} were found only in reservoir areas, where the maximum values exceeded 30 mg kg^{-1}. The Hg concentration in hair was 1.8 times higher in males than in females. The highest values were found in people eating lots of fish from reservoir waters. There was a positive correlation between the total fish consumption and the Hg content in hair in the reservoir areas ($r = 0.343, p < 0.01$) and in the whole material ($r = 0.256, p < 0.01$) but not in the background areas ($r = 0.173$).

TABLE II

Mercury content (mg kg^{-1} fresh weight) in fish flesh from different areas in northern Finland

Area	Species	*n*	Weight, g $\bar{x}$ (range)	Mercury, mg kg^{-1} $\bar{x}$ (range)
Lokka	Pike (Esox lucius)	14	1004 (250–2750)	0.32 (0.09–0.77)
	Perch (Perca fluviatilis)	29	329 (155–770)	0.24 (<0.02–0.48)
	Ide (Leuciscus idus)	7	694 (225–820)	0.15 (0.10–0.20)
Porttipahta	Pike (Esox lucius)	9	1031 (500–1860)	0.50 (0.10–0.83)
	Burbot (Lota lota)	26	922 (350–2100)	0.70 (0.26–2.0)
	Perch (Perca fluviatilis)	1	300	0.32
	Roach (Rutilus rutilus)	2	230 (200–260)	0.32 (0.30–0.33)
	Whitefish (Coregonus lavaretus s.l.)	16	605 (520–680)	0.20 (0.07–0.34)
Kemijärvi	Pike (Esox lucius)	11	1049 (380–2400)	0.38 (0.18–0.75)
	Burbot (Lota lota)	5	2130 (500–4000)	0.30 (0.21–0.40)
	Perch (Perca fluviatilis)	2	160 (150–170)	0.15 (0.12–0.17)
	Ide (Leuciscus idus)	2	270 (270)	0.13 (0.10–0.16)
	Whitefish (Coregonus lavaretus s.l.)	3	217 (170–300)	0.07 (0.06–0.08)
Luirojärvi	Pike (Esox lucius)	1	200	0.04
	Burbot (Lota lota)	11	855 (300–2200)	0.20 (0.10–0.48)
	Roach (Rutilus rutilus)	7	30 (20 –40)	0.20 (0.14–0.24)
	Whitefish (Coregonus lavaretus s.l.)	13	96 (50 –300)	0.05 (0.03–0.08)

TABLE III

Mercury content (mg kg^{-1} fresh weight) in fish liver from different areas in northern Finland

Area	Species	*n*	Weight, g $\bar{x}$ (range)	Mercury, mg kg^{-1} $\bar{x}$ (range)
Lokka	Pike (Esox lucius)	6	933 (250–2750)	0.17 (0.10–0.27)
	Perch (Perca fluviatilis)	12	309 (155–550)	0.16 (0.07–0.42)
	Ide (Leuciscus idus)	1	740	0.07
Porttipahta	Pike (Esox lucius)	9	1031 (500–1860)	0.32 (0.14–0.45)
	Burbot (Lota lota)	24	918 (350–2100)	0.27 (0.12–0.68)
	Perch (Perca fluviatilis)	1	300	0.10
	Roach (Rutilus rutilus)	2	230 (200–260)	0.16 (0.14–0.18)
	Whitefish (Coregonus lavaretus s.l.)	6	591 (520–650)	0.52 (0.22–1.0)
Kemijärvi	Pike (Esox lucius)	5	896 (380–1500)	0.13 (0.10–0.18)
	Burbot (Lota lota)	4	2538 (750–4000)	0.08 (0.04–0.10)
	Perch (Perca fluviatilis)	2	160 (150–170)	0.08 (0.07–0.09)
	Ide (Leuciscus idus)	2	270 (270)	0.05 (0.04–0.06)
	Whitefish (Coregonus lavaretus s.l.)	3	217 (170–300)	0.06 (0.03–0.12)
Luirojärvi	Pike (Esox lucius)	1	200	0.10
	Burbot (Lota lota)	11	855 (300–2200)	0.08 (<0.02–0.16)
	Whitefish (Coregonus lavaretus s.l.)	3	250 (150–300)	0.11 (0.10–0.12)

TABLE IV

Age, fish consumption and hair Hg content of the population in seven north Finnish areas. Fish consumption index (FCI) 0–3 calculated as described in the text.

	n	Age $\bar{x}$	FCI	Hg content (mg kg^{-1} d.w.) $\bar{x}$ (range)
Lokka	19	43	1.6	4.4 (<0.02–27)
males	11	47	1.9	5.6 (0.58–27)
females	8	38	1.1	2.8 (<0.02–11)
Porttipahta	16	45	2.0	5.9 (0.37–35)
males	10	45	2.1	6.4 (0.67–35)
females	6	45	1.8	5.1 (0.37–17)
Kemijärvi	33	49	2.0	4.7 (0.16–32)
males	18	49	2.0	5.2 (0.41–32)
females	15	48	1.9	4.0 (0.16–8.7)
Salla	13	57	1.6	1.9 (<0.02–13)
males	6	57	2.0	1.4 (<0.02–5.0)
females	7	57	1.3	2.4 (<0.02–13)
Posio	12	44	2.1	1.4 (0.26–6.0)
males	5	53	2.2	1.8 (0.43–6.0)
females	7	37	2.0	1.1 (0.26–2.4)
Ranua	9	47	1.9	1.2 (0.15–12)
males	6	49	2.2	1.5 (0.15–12)
females	3	45	1.3	0.72 (0.36–0.94)
Other areas	9	52	2.1	2.0 (0.70–4.6)
males	6	49	2.7	2.2 (0.70–4.6)
females	3	57	1.0	1.6 (0.78–2.7)

The highest Hg concentrations were found in middle-aged people (Figure 2). The variation in Hg contents of the hair segments taken at different distances from the scalp was great and no significant time-dependent trend could be observed.

4. Discussion

The observed Hg concentrations in burbot and pike, particularly from the Porttipahta reservoir, were higher than in fish from unpolluted north Scandinavian lakes (Johnels *et al.*, 1967; Westöö and Rydälv, 1971; Sauvonsaari *et al.* 1979) and they are obviously caused by the construction and water control activities. The even distribution of Hg between muscle and liver indicates that the Hg is methylated (Johnels and Westermarck, 1969; Zelenko and Kosta, 1973; Kosta *et al.*, 1974).

The source of Hg in new impoundments is apparently the inundated soil but it is not completely known how it is introduced to and accumulated in the limnetic foodchains.

In the soil, upward movements of Hg in pellicular water or as dissolved elemental vapor have been noted (Jonasson, 1973) and in Finland the Hg content in the top soil layer is higher (mean 0.10 mg kg^{-1}) than in deeper layers (mean 0.02 mg kg^{-1}) (Soveri,

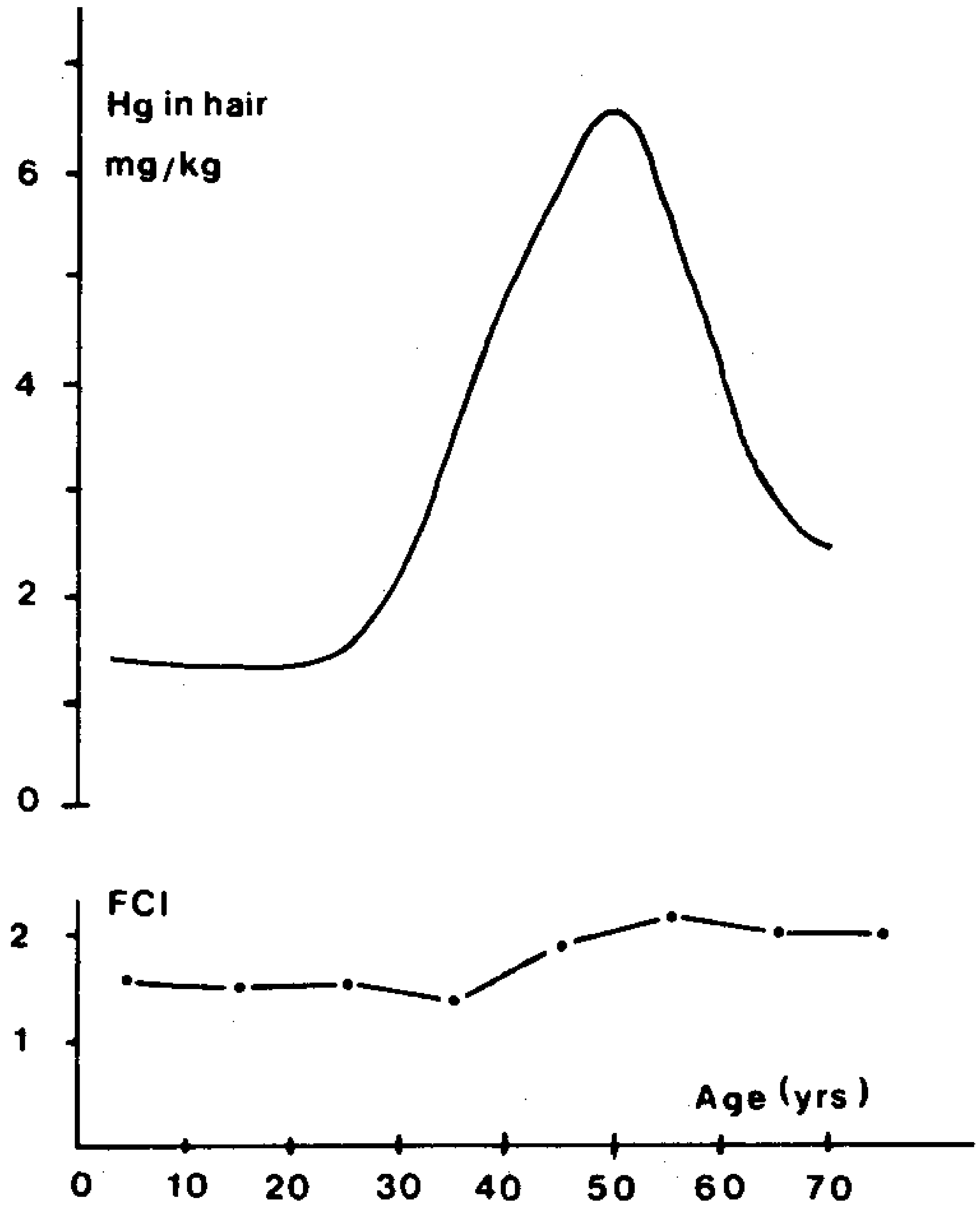

Fig. 2. Mercury content in hair and the fish consumption index (0–3, FCI as described in the text) in different age groups (whole material).

1977). Physical mixing, microbial degradation of humic substances, methylation and gas ebullition may contribute to the mobilization of Hg. Mercury may be very strongly but reversibly bonded to humic acid (Strohal and Huljev, 1974; Miller, 1975; Beneš *et al.*, 1976; Jackson *et al.*, 1980).

The sedimentation rate is very low in Finnish man-made lakes and the original vegetation and bottom structure are only slightly changed after 15 yr of water control (Vogt, 1978). Anaerobic conditions periodically occurring in the reservoir bottom water promotes the formation of insoluble mercuric sulphide, which, however, is converted back to soluble, divalent Hg under aerobic conditions (Fagerström and Jernelöv, 1972). Microbial methylation of Hg may occur both under aerobic and anaerobic conditions (Bisogni and Lawrence, 1975). Meister *et al.*, (1979) considered microbial activity as the main source of Hg release in new impoundments. When sediments are exposed to air the formation of volatile dimethylmercury may be very fast (Jernelöv *et al.*, 1971), but no dimethylmercury seem to be formed under acidic conditions (Beijer and Jernelöv, 1979).

Even if the solubility of Hg decreases with increasing acidity (Schindler *et al.*, 1980), a low pH-value and a low bioproduction will promote an accumulation of Hg in biota (Brosset and Svedung, 1977; Björklund and Norling, 1979; Håkansson, 1980: Jackson *et al.*, 1980) as will a high humus content in the water (Hultberg, 1978). The relatively high fish biomass in the man-made lakes of Lokka and Porttipahta implies a 'dilution' of the Hg circulating in the biota. As the methylation of Hg in new impoundments is fast (Bodaly and Hecky, 1979) and the elimination of Hg from organisms in cold water is slow (Ribeyre *et al.* 1980), the mercury concentrations in fish may stay at a high level. In large specimens of pike the decrease in Hg content after the cessation of Hg pollution may be quite rapid even if no decrease is observed in smaller specimens (Nuorteva *et al.*, 1979).

Cox *et al.* (1979) estimated that the Hg content of fish in man-made lakes should be normal within ca. 5 yr after the impoundment. Since the Lokka and Porttipahta reservoirs are 14 and 11 yr old, respectively, it is obvious that the purification of these watercourses has taken much longer, and there are still quite high Hg concentrations in the fish.

The mobility of Hg in the environment seems to be much greater than formerly assumed. For example, high Hg concentrations have also been found in unpolluted areas in precipitation and freshwater biota (Koirthyohann *et al.*, 1974; Delisle, 1979; Nuorteva and Soveri, 1979; Sherbin, 1979; Ohlin, 1980).

According to Finnish regulations, the Hg content of fish should not exceed 1 mg kg^{-1} wet weight, and if the Hg content is 0.5 to 1 mg kg^{-1}, fish consumption should be restricted to 500 g per week. Burbot and pike weighing 1 kg exceeded the lower limit in Porttipahta while the larger specimens exceeded even the upper limit. Large pike from Lokka exceeded the lower limit. From this reservoir no burbot were obtained for analysis. In Kemijärvi the 0.5 mg kg^{-1} limit was exceeded only by the largest pike and in the background lake, Luirojärvi all the values were low.

A regular intake of Hg constitutes a health risk. Symptoms of methylmercury poisoning (Minamata-disease) may occur when hair Hg levels are 50 mg kg^{-1} or more, but symptoms may still appear when the Hg content in hair has diminished (Harada and Smith, 1975; Igata *et al.*, 1975; Takeuchi and Eto, 1975). According to a Swedish expert committee (Berglund *et al.*, 1970), the Hg levels in hair should not exceed 6 mg kg^{-1}. In the reservoir areas the mean Hg concentration in hair was near this level and the maximum levels exceeded it 5-fold, but no values were at the level, where clinical symptoms appear. In the background areas only two samples of hair exceeded 6 mg kg^{-1}.

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