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Heavy metals in perch (*Perca fluviatilis*) from the Kostomuksha region (North-western Karelia, Russia)

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The Kostomuksha mining plant (KMP, Republic of Karelia, Russia), which is an important producer of iron pellets, is situated in the upper part of the Kenti–Kento lake–river system. In this water system, Lake Kostomuksha drains its waters through a chain of small lakes into the larger Lake Kuito and on to the White Sea. Effluents from the mining plant have been deposited in Lake Kostomuksha since 1982. For this study, samples of perch (*Perca fluviatilis*) were obtained from three metal-contaminated lakes with different pollutant concentrations downstream from Lake Kostomuksha. The concentrations of heavy metals (Hg, Cd, Cu, Zn, Ni and Cr) in fish liver and muscle were analysed. Concentrations of Hg, Ni and Cr (1.13, 0.09 and 0.08 $\mu g\ g^{-1}$ dry weight, respectively) in fish liver from the studied lakes were higher than those in the control lake, Kamennoe (0.43, < 0.001, < 0.001 $\mu g\ g^{-1}$), which is not directly influenced by the KMP. In the uppermost lake, Poppalijärvi, the concentration of Hg in perch muscle and liver was > 1.0 $\mu g\ g^{-1}$ dry weight. Compared to the control lake, the electron microscope study of liver tissue from perch in this lake showed an increase in the distance between hepatocytes, a decrease in the number of nuclear pores and the smallest mitochondria of all the lakes studied.

Introduction

The role of metals in the physiology of aquatic organisms may be twofold. On the one hand, many heavy metals are activators of enzyme reactions and are thus essential for the viability of organisms (Randall *et al*. 1997). On the other hand, heavy metals may accumulate in organs and tissues mainly by interaction with macromolecules (Weber *et al*. 1992). Consequently, this may lead to various alterations in the organism that contribute to genetic modifications (Linnik and Nabivanets 1986).

The main factors that influence metal toxicity in an aquatic environment include the following: temperature, oxygen content, pH, Ca concentration and the amounts of organic ligands (Tessier 1994), which regulate the concentration of heavy metal ions in water. The formation of ligand and protein complexes transform metal ions to harmless forms that are suitable for penetration, transportation and accumulation of metals in aquatic organisms. Sensitivity to metals decreases with increasing pH and Ca concentrations, thus making the organisms more tolerant to polluted waters. Interactions between various heavy metals and their effects on aquatic organisms have been widely studied (Wang 1987, Downs *et al.* 1998).

Worldwide, the mercury levels in fish exceed now the pre-industrial level of 0.15 mg kg^{-1} wet weight (Downs *et al.* 1998). In fish, mercury is concentrated mainly in the form of methylmercury; and fish, being at the highest trophic level, accumulate maximal concentrations of mercury in their organs. Internationally, the highest permissible limits for Hg in fish have been set at 0.3–1.0 mg kg^{-1} wet weight (Downs *et al.* 1998). In the studies conducted in Wisconsin, USA (Watras *et al*. 1994), the Experimental Lakes Area (ELA), Canada, and Lake Gårdsjön, southern Sweden (Håkanson 1990, Downs *et al.* 1998) three important sources of MeHg have been identified in aquatic systems: precipitation, in-lake methylation and runoff from wetlands.

The majority of aquatic organisms absorb metals from solutions that wash over the surface of their gills and skin. In addition, many animals obtain these metals from food. At the cellular level, metal intake depends on the concentration across cell membranes. The mechanism of metal transport through the cell membrane is very effective (Tessier 1994) and has several stages: accumulation of ligand with metals on the cell surface, transfer through the cell membranes by ligand-carrier, and removal of metal ions from inside the cell by proteins.

Tolerance is an important mechanism by which an organism reacts to an adverse environment. According to Wang (1987), mechanisms that might be responsible for tolerance include decreased uptake, increased excretion, redistribution of metals to less sensitive target sites, and induced synthesis of metallothionein for proteinaceous metal chelation. The metallothioneins are a group of vertebrate and invertebrate proteins that bind heavy metals and may be involved in zinc homeostasis and resistance to heavy-metal toxicity.

The objectives of this investigation were to study metal levels in perch liver and muscle in successive lakes downstream from the Kostomuksha mining plant and to determine possible changes in the structure of fish liver in response to heavy metals.

Study area

The fish for this study were sampled from Poppalijärvi, Koivas and Kento, lakes in the upper district of the Kenti–Kento lake–river system. This area is downstream from Lake Kostomuksha, the waste water depository of the large Kostomuksha mining plant (KMP) owned by the JSC Karelsky Okatysh Company in the north-west part of the Republic of Karelia (64°41´N, 30°50´E; Fig. 1, Lake Kostomuksha is marked as a depository). The KMP extracts iron ore and produces iron pellets for the smelting industry and for further processing in metallurgical enterprises. Since 1982, waste waters from the ore separation process and the mining pits have been collected into the dammed basin for slag water sedimentation.

Lake Kamennoe, which was used as a control, lies ca. 30 km south–west of Lake Kostomuksha, and belongs to a different river basin but is considered to have been similar to Lake Kostomuksha before the latter was used as a waste depository. Some limnological characteristics of the lakes are given in Table 1.

The entire territory is a part of the Baltic or Scandinavian Shield area, which consists of ancient Precambrian silicate rocks overlain by a thin cover of loose glacial deposits. The area was deglaciated only ca. 8 000 years ago, and the resulting variable topography explains the large number of small lakes that are so typical for the region. The area is characterised by long winters and short

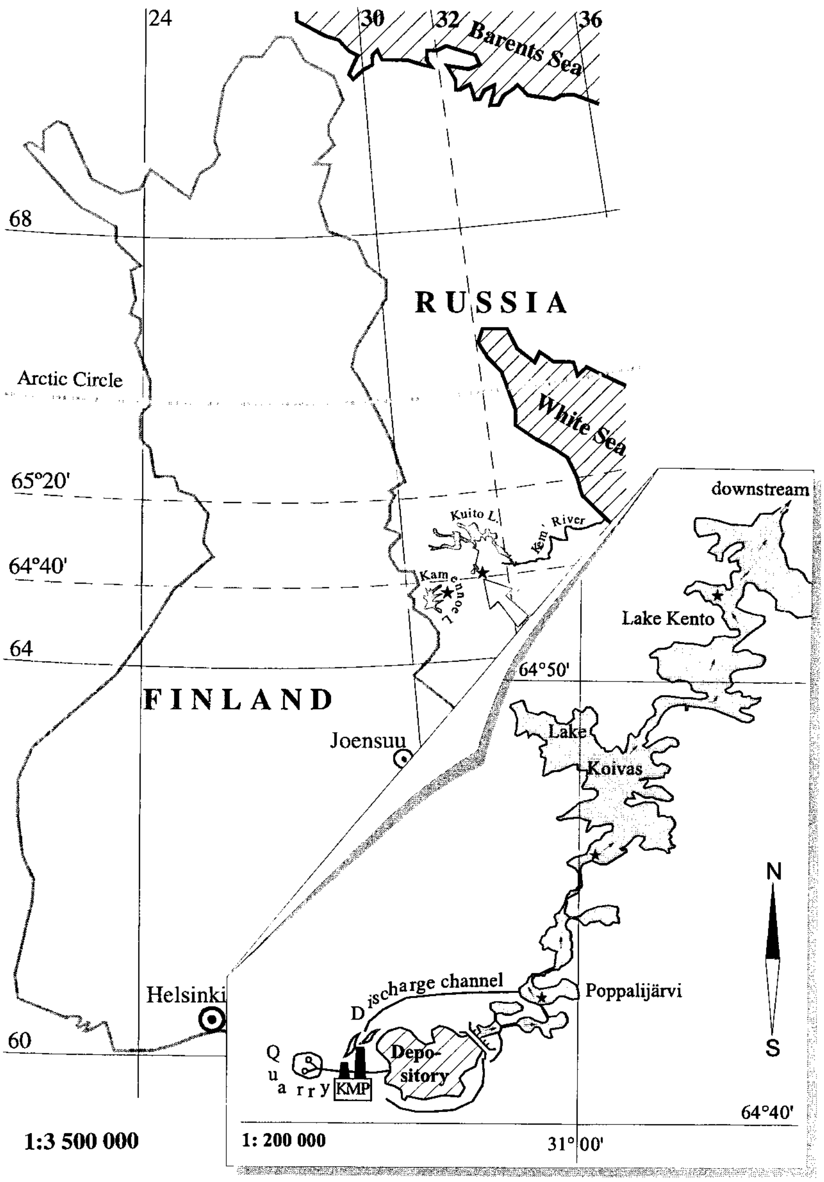

Fig. 1. Location of the sampling sites (V) in the Republic of Karelia, Russia. KMP stands for Kostomuksha mining plant.

cold summers with the predominant westerly winds influencing the local climate. It is part of the widespread northern coniferous zone, the taiga. In a detailed analysis of vegetation zones, Ahti *et al.* (1968) defined the region west and south of the White Sea as being a part of the middle-boreal zone with some oceanic influence. The vegetation is typical for taiga in Russian Karelia: forests cover 66% and wetlands (marsh or peat bog vegetation) 22%–25% of this area, with Scots pine (86%) and spruce (13%) predominating (Startchev 1985). The annual temperature of the lake water ranges from +0 °C to +16 °C.

The environmental effects of KMP include air pollution by SO_2 and dust, and waste water emissions. Atmospheric deposition of metals (As, Cr, Fe, Pb, Ni, V) in the near surroundings of KMP is also obvious (Rühling and Steinnes 1998). Since 1982, all the waste waters from KMP have been deposited in Lake Kostomuksha and due to silting, overfilling and leaking of this basin, the surface waters downstream from this lake have suffered from heavy metal contamination (Morozov 1998). The depository has been reported to have periods of direct overflow during spring floods; overfilling is also thought to increase the risk for breakdown of the depository wall. Furthermore, metals in the waste water have been reported to cause reduction and modification of the algal flora, thus resulting in low productivity in Poppalijärvi (Kaloogin 1991). Further studies include those of Krupnova (1995), Smirnov (1995) and Zekina (1995) concerning the effects of heavy metals on the biochemistry (bile acids, enzymatic activities, peptides) of pike and trout in the Kenti River system, and that of Vlasova (1998) on zooplankton productivity.

In the lower part of the Kenti–Kento River an increase in the mineral content of the water was shown in the high conductivity values, as well as in the alteration of the natural ratio of K^+:Na^+ from 0.3–0.4 to 6.3. The annual concentration of K^+ in Poppalijärvi was 60 mg l^{-1} and that of Na^+ was 6.0 mg l^{-1}. At present, due the discharge channel (Fig. 1) which has worked since 1994, the K^+:Na^+ ratio in Poppalijärvi is ca. 10. Owing to the high mineral content, the buffering capacity of the water has increased (Table 1).

In general, the low quality of the water in this area is caused by the presence of metals, nutrients, ammonium, sulphates and chlorides (Morozov 1998, Virtanen and Markkanen 1999).

Table 1. Some limnological characteristics of the study lakes. The data is from Current State of Water Objects in the Republic of Karelia. Results of monitoring in 1992–1997. Petrozavodsk 1998. * = data on 15–16.03.1994 (Kainuu Regional Environment Centre, Finland). ** = data from Ahvenjärvi, upstream from Poppalijärvi. *** = data on March 1996 (Kainuu Regional Environment Centre, Finland).

	Kenti River system				Control
	Depository (Kostomuksha)	Poppalijärvi	Koivas	Kento	Kamennoe
Drainage basin area (km^2)	68.4	128	356	676.6	652.9
Surface area (km^2)	–	1.65	22.00	27.1	95.5
(Drainage basin area)/(lake surface area)	–	119.2	19.3	25	6.9
Maximum Depth (m)	≈ 25	10.7	≈ 23	23.5	28.7
Mean Depth (m)	–	4.3	4.1	3.8	7.9
pH	8.2–8.4	7.6–8.2	6.8	6.6	6.4–7.0
Color, Pt mg^{-1}	10	50	50	60	25
COD Mn mg l^{-1}	2.4	6.5	10.4	7.8	6.2
TOC mg l^{-1}	2.5	6.2	8.6	7.2	6.1
Phosphorus total (µg l^{-1})	12	8	6	7	7
Phosphorus min./total (µg l^{-1})	L5/11–14	L5/5–8	L5/5–8	L2/5–8	L5/5–8
Nitrogen (total) (µg l^{-1})	2800	2200	860	270	220–350
Phosphorus/nitrogen	0.0036	0.0036	0.0093	0.026	0.0228
Na^+ mg l^{-1}	21.3	6.0	2.9	2.05	1.2
K^+ mg l^{-1}	125	60	27	13	0.4
Li^+ µg l^{-1}	58	25	10.0	7	0.2–0.6
SO_4^{2-}	102	56	23.2	23.2***	1.8–2.2
Alkalinity, mmol l^{-1}	3.1	1.24	0.44	–	0.07
Cl^-	7.1	3.7	1.6	1.5***	0.8
Ca^{2+}	21.9**	34.9	4.89	6.2***	1.6
Zn µg l^{-1}*	2.00**	0.63**	0.54	0.45***	5
Cu µg l^{-1}*	1.68**	0.49**	0.29	0.33***	1
Ni µg l^{-1}*	2.68**	3.03**	0.40	0.40***	< 1.0
Cr µg l^{-1}*	8.77**	8.3**	1.51	0.20***	< 1.0
Cd µg l^{-1}*	0.04**	< 0.03**	< 0.03	< 0.03***	< 0.03
Σ ions (mineral content)	480	240	120	68	11.2

Material and methods

All the perch (*Perca fluviatilis*) analysed in this study were caught with a fishing rod on 21–26 July 1997 and 1998 (Kento). The fish were measured for fork length (AC), weighed and the livers and muscle samples (2–3 g of skeletal muscle from the left side) were dissected and put into polyethylene vials that had been cleaned in 10% HNO_3 for 5 hours and then washed thoroughly with distilled water. Samples for analyses of heavy metals were collected according to the recommendations given by Seiler (1986).

After 2 days, the samples were dried at 105 °C for 12 hours in the biochemistry laboratory at Petrozavodsk State University. The dry samples were kept in the same vials at +4 °C until they were analysed ca. 6 months later.

The dry samples were digested in a microwave digestion unit (Milestone 1200 mega) in a mixture of 8 ml of HNO_3 and 2 ml H_2O_2. Cadmium, chromium and nickel were measured by a graphite furnace AAS (Hitachi 2-9000). Copper and zinc were measured by a flame AAS and mercury concentrations by a gold-film mercury analyzer (Jerome Inst. Corp. Model S-11) in the laboratory of the Department of Biology, University of Joensuu.

For histological study, immediately after dissection samples of fish liver were fixed in 2% glutaraldehyde in a 0.1 M sodium cacodylate buffer and postfixed in 2% OsO_4 in 0.1% sodium cacodylate buffer at pH 7.2 for 2 hours. After dehydration, pieces of liver were embedded in Epon. For light microscopy, thick sections (1 µm) were obtained with a LKB 2188 ultramicrotome and stained with toluidine blue. For electron microscopy, thin sections were cut with a diamond knife, stained with uranyl acetate and lead citrate, and examined with a Zeiss 900 electron microscope. Samples were prepared and analyzed in the laboratory of the Department of Biology, University of Joensuu.

Thirty liver cells were measured from each individual. To show the variation among the cells of each fish and the variation among individual fish, arithmetic means with standard deviations were calculated. The cells were measured on the monitor screen of an electron microscope. Each investigated structure was copied onto a transparency. The monitor zooming factor was estimated to be 33.3.

Because the concentrations of heavy metals were not normally distributed, statistical comparisons were based on medians and nonparametric tests, the Kruskal-Wallis test, the Tukey-Kramer test (Zar 1999) and on log-transformed data in the principal component analysis (PCA). All concentrations of heavy metals (µg g^{-1}) are expressed on the basis of dry weight. The SPSS and JMP IN computer programs were used for statistical analyses.

Results

The perch from the Kenti–Kento lake–river system (Poppalijärvi, Koivas and Kento lakes) did not differ significantly in length (median 160–170 mm; n =10–19), whereas those from the control Lake Kamennoe had a median length of 120 mm (n = 15).

The concentrations of most metals did not differ significantly among the four populations (Tables 2 and 3), and the highest or lowest values of different metals were not characteristic to any particular population. The concentrations of heavy metals in the liver and muscle of perch in all the samples from all four lakes were used in a principal component analysis among the populations (PCA, log-transformed data, Fig. 2). The first principal component (PC1), which explains 42% of the total variation in the liver and 40% in the muscles, indicates the general amount of heavy metals. The second principal component (PC2), which explains 23% and 21% of the variation in the liver and muscle, respectively, divides the material into those with high levels of Hg, Ni, Cr, and those with high Cd, Cu and Zn.

The first two components clearly separate the populations from each other (Fig. 2). The liver and muscle of perch in Poppalijärvi differed from those in the other lakes by having high concentrations of heavy metals, especially mercury. The mercury concentrations in both the liver and the muscle samples clearly decreased downstream from the wastewater depository (Table 3). In the control lake, the Hg level was significantly lower than in Poppalijärvi. Muscle and liver from the other lakes had Hg levels equal to those of the control lake.

Both cadmium and copper concentrations appeared to be the same (within the error range) in all the lakes sampled along the Kenti–Kento system. However, the cadmium and copper burdens in liver and copper burdens in muscle were higher in the control lake.

The zinc level in the liver was the same in all the lakes of the lake–river system and in muscle it had the highest concentration in Lake Kento. In the control lake, the Zn burden was lower both in liver and in muscle.

Among the fish studied nickel and chromium did not differ significantly. Nevertheless, in Poppalijärvi in both muscle and liver tissues the median concentrations of these metals were higher than in all other lakes.

Some ultrastructural characteristics of the liver tissue are given in Table 4. The size of the hepatocytes as well as the size of their nuclei seemed to increase downstream from the waste deposit pond. The same increase was also seen in the size of the mitochondria and in the recurrence of nuclear pores. The maximum distance between hepatocytes was found in Poppalijärvi and this index gradually decreased downstream.

Liver cells of perch from Poppalijärvi contained a large number of glycogen inclusions, the mitochondria were dense and a clear osmiophilic effect was seen on the matrix (Fig. 3). In Lake Koivas similar osmiophilic structures were present in the mitochondria (Fig. 4).

A certain type of dense granules was found in the mitochondria of perch in Poppalijärvi (Fig. 3) and in Lake Koivas, the second lake of Kenti-Kento system. In lakes Kento and Kamennoe, on the other hand, these granules were not observed in the mitochondria (Fig. 5).

Table 2. The significant correlations between metals in our material for perch liver and muscle as used in the PCA.

Element of the correlation matrix (liver)	Correlation	Significance (P <)	Element of the correlation matrix (muscles)	Correlation	Significance (P <)
Cd, Zn	0.30	0.015	Cd, Zn	0.54	0.0001
Cu, Zn	0.30	0.015	Cu, Zn	0.21	0.060
Hg, Ni	0.41	0.001	Hg, Cd	–0.25	0.033
Hg, Cr	0.18	0.099	Cu, Cr	–0.31	0.012
Cd, Cu	0.52	0.0001			

Table 3. Heavy metal concentrations (medians of µg g^{-1} dry weight) in perch liver and muscle in the lakes of the Kostomuksha area. The lakes are ordered by increasing distance from the metal source; the control lake from another river basin is in the last column. Values with no common letter (superscript) differ at $P < 0.05$ level.

	Poppalijärvi		Koivas		Kento		Kamennoe*		*P*	
Metal	Liver	Muscles	Liver	Muscles	Liver	Muscles	Liver	Muscles	Liver	Muscles
Hg	1.13^{a}	1.45^{a}	0.57^{b}	0.68^{b}	0.42^{b}	0.49^{b}	0.43^{b}	0.84^{b}	**	***
Cd	1.76^{b}	0.01	1.90^{b}	0.01	1.73^{b}	0.02	2.34^{a}	0.01	**	ns
Cu	9.66^{b}	0.87^{b}	12.68^{b}	0.63^{b}	9.38^{b}	0.95^{b}	16.97^{a}	1.49^{a}	***	*
Zn	115.26^{b}	25.54^{a}	119.32^{b}	23.58^{b}	116.96^{b}	27.30^{a}	103.66^{a}	21.37^{b}	o	***
Ni	0.09	0.04	< 0.001		< 0.001	0.01	< 0.001		ns	
Cr	0.08	0.05	0.004	0.07	< 0.001		< 0.001		ns	
n	10		10		19		15			

Discussion

According to these results, obtained by using Lake Kamennoe as a control, KMP apparently has not significant effect on copper, zinc or cadmium concentrations in fish tissues. Mercury concentrations are, however, clearly higher in fish from Poppalijärvi, which is influenced most by the plant. Chromium and nickel levels are also higher in Poppalijärvi.

According to the PCA, however, the heavy metal concentrations in fish differ markedly among the lakes. PC axis two divides the lakes according to the influence of the plant, with the control lake, Kamennoe, clearly differing from the others. With the exception of Hg, the metal concentrations in muscle were lower than those in liver, which agrees with the results of Allen-Gill *et al.* (1997) for four Arctic lakes in Alaska.

Metals such as cadmium, copper or zinc may either be bound to cysteine-rich proteins (e.g., metallothionein) or be incorporated into nonlabile pools. The metallothionein contents have increased in molluscs (*Lymnaea stagnalis* L. and *Sphaerium* sp.) in Poppalijärvi (Regerand 1995). This fact, our histological results and the results on heavy metal concentrations in perch indicate the toxic effects of metals on aquatic biota in Poppalijärvi.

In the most polluted Poppalijärvi, the mercury

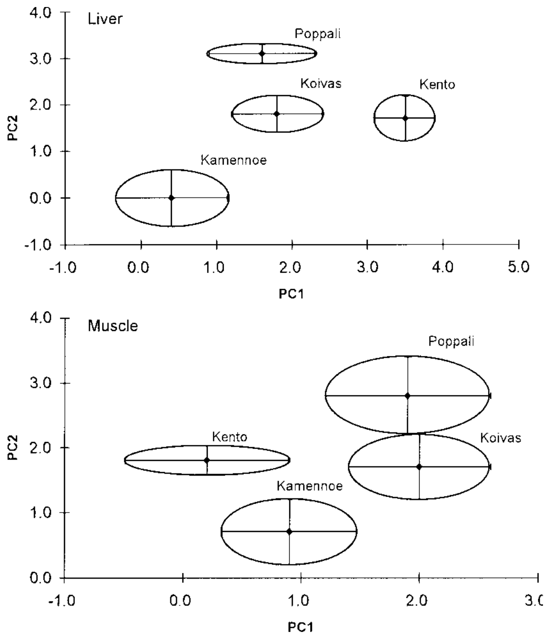

Fig. 2. Graphical presentation of the PCA results on liver and muscle in four lakes: Poppalijärvi, Koivas, Kento and Kamennoe. The first principal component (PC1) indicates the total concentrations of all heavy metals; the second component (PC2) indicates contrast between two groups of metals so that the smaller numbers represent higher concentrations of Cu + Zn + Cd, while the larger numbers indicate higher concentrations of Hg + Ni + Cr. Mean point values for the four lakes and 95% confidence limits (ellipses) are presented (PCA, log-transformed data).

Table 4. Some histological characteristics of perch liver cells in the lakes of Kostomuksha area. Three individuals from each lake were used. The number of measured cells is 30 for each individual. Averages and standard errors are shown. Values with no common letter (superscript) differ at least at $P < 0.05$ level.

	Kenti-Kento system			Control	
Index	Poppalijärvi	Koivas	Kento	Kamennoe	*P*
Size of hepatocyte, µm^2	396.0 ± 45.0	380.0 ± 36.0	497.0 ± 45.0	417.0 ± 38.0	ns
Size of nucleus, µm^2	76.0 ± 7.0^a	90.0 ± 7.0^{ab}	126.0 ± 10.0^b	72.0 ± 7.0^a	***
Hepatocyte·nucleus^{-1}	5.4 ± 1.0	4.3 ± 0.5	4.0 ± 0.3	5.9 ± 0.5	ns
Number of nuclear pores	10.0 ± 1.0^a	10.0 ± 1.0^a	15.0 ± 2.0^{ab}	16.0 ± 1.0^b	***
Distance betw. membranes of adj. cells, nm	19.0 ± 2.0^a	13.0 ± 2.0^a	12.0 ± 2.0^{ab}	8.0 ± 1.0^b	***
Size of mitochondria, µm^2	2.0 ± 0.3^a	3.4 ± 0.5^{ab}	4.7 ± 0.7^b	4.6 ± 0.8^b	***
Size of peroxisomes, µm^2	0.4 ± 0.0	0.4 ± 0.0	0.5 ± 0.1	0.6 ± 0.1	ns
Size of lysosomes, µm^2	1.5 ± 0.4	1.5 ± 0.3	1.1 ± 0.4	0.7 ± 0.2	ns

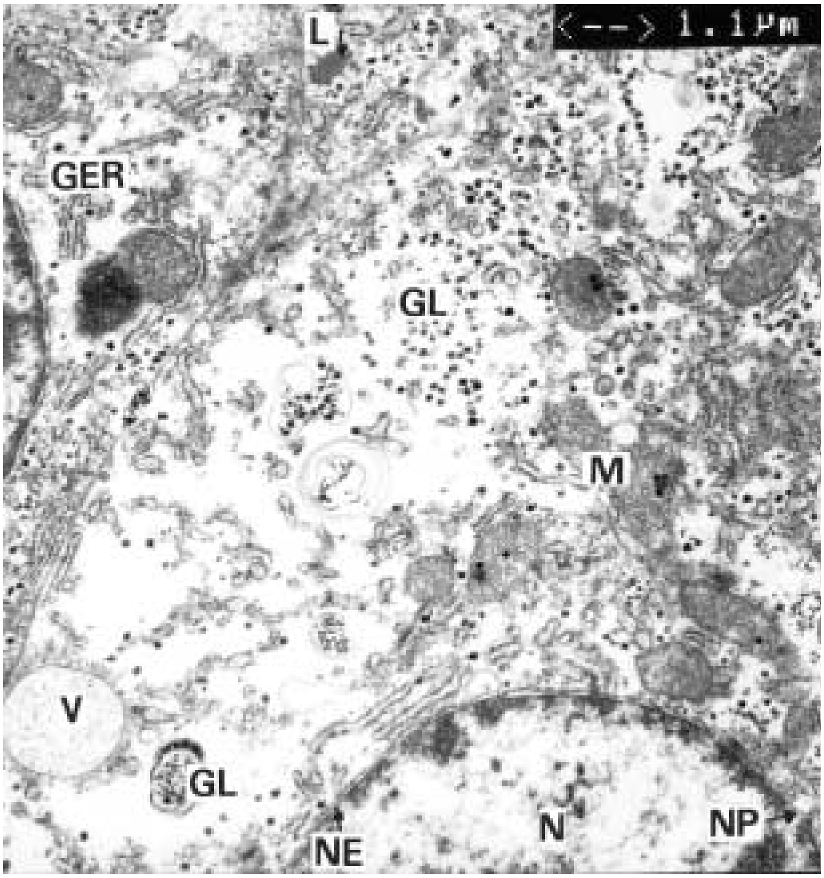

Fig. 3. Electronmicroscopical structure of the hepatocytes of perch in Poppalijärvi. The following symbols are used in this and in the next photos; D = desmosomes; GER = granular endoplasmic reticulum; GL = glycogen rosettes and glycogen filled vesicles; L = lysosomes; M = mitochondrion with black granules of a certain type inside; N = nucleus; NE = nuclear envelope; NP = nuclear pore; V = vesicle with non-electronic dense material inside.

concentration in perch muscles (Table 3) was 1.45 μg g^{-1} dry weight (> 0.3 μg g^{-1} wet weight). The estimated level of natural Hg in the control lake, Kamennoe, was 57% of that in Poppalijärvi, > 0.17 μg g^{-1} wet weight. In a recent review by AMAP (1998), the highest values for Hg in fish muscle in Arctic fresh waters were 0.32 μg g^{-1} wet weight for Finnish Lapland, 0.25 μg g^{-1} for Norway and 0.28 μg g^{-1} for Sweden.

The most remarkable features of the Kenti–Kento lake system are the high pH and the high mineral content. In comparison with the control lake, Poppalijärvi is characterised by a shift in the potassium–sodium ion ratio towards potassium. The K ion level in Poppalijärvi exceeds the natural level in the control lakes. The alkaline pH may lead to a reduction in levels of free metal ions in the water. This probably affects all metals in fish from all lakes in the Kenti–Kento system.

High pH and high mineral content make the process of Hg methylation slower (Linnik and Nabivanets 1986). In our lakes, the pH showed a clear gradient from high values in the more polluted Poppalijärvi (pH 7.6–8.2) to normal slightly acidic (pH 6.6) water in lakes Kento and Kamennoe.

The high concentration of mercury recorded in all the lakes investigated may also be partly caused by atmospheric pollution. Rühling and Steinnes (1998) reported relatively high concentrations of Hg in moss samples (> 0.4 μg g^{-1} dry weight, while the median value of the 60 samples in Karelia was 0.070 μg g^{-1}) near the Kuito lakes some 40 km north of Kostomuksha.

In piscivorous fish like perch and pike the level of Hg has been reported to be lower in neutral than in acidic waters (Verta 1990, Haines *et al.* 1995), and the raised mineral concentration can reduce Hg uptake by fish (Watras *et al.* 1995).

In general, fish accumulate Hg in the form of methylmercury (MeHg). The percentage of methylated mercury of the total amount of mercury appears to vary between studies but is usually

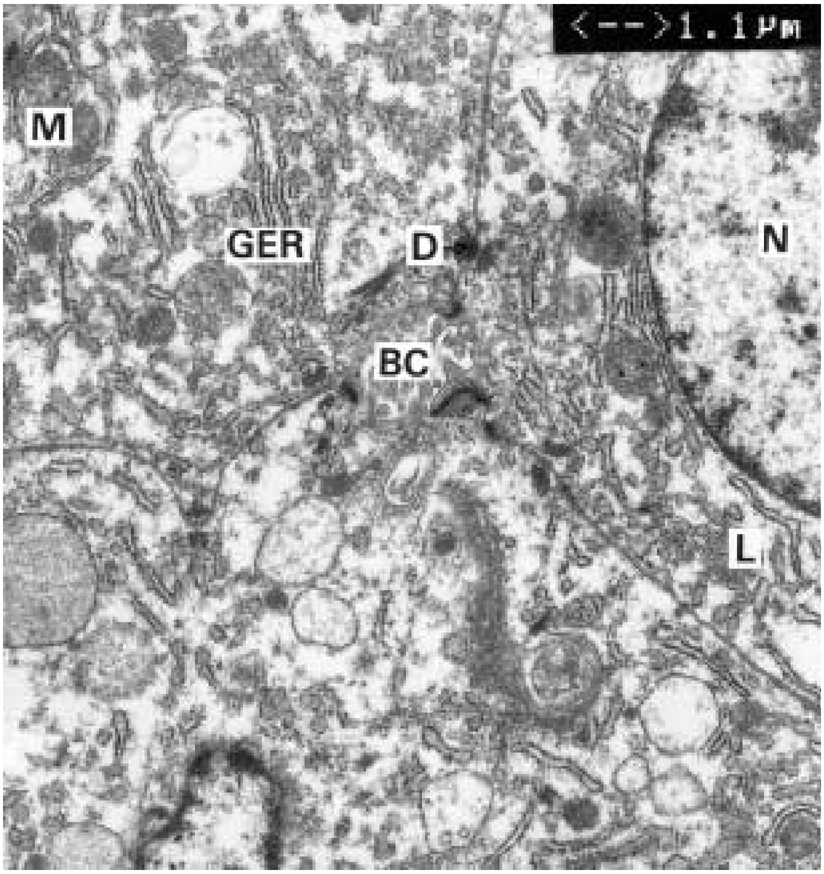

Fig. 4. Electronmicroscopical structure of the hepatocytes of perch in Lake Koivas. BC = bile canaliculus. For other symbols *see* Fig. 3.

within the range of 80%–99% for muscle tissue (Grieb *et al*. 1990). An increased proportion of inorganic Hg is often found in liver tissue, which results in a much lower percentage. The ratio of methylated to total mercury in liver reported in published data is between 0.4 and 0.8. These observations can be explained by the synthesis of metallothioneins (MT) in the liver, which effectively bind inorganic Hg in preference to MeHg (Downs *et al.* 1998).

Nickel concentrations as high as 1.5 μg g^{-1} dry weight have been reported in fish organs (Schmitt and Brumbaugh 1990, Kelley 1995, Allen-Gill 1997). Here, the maximum values for Ni were at about the same but the median values were clearly lower (Table 3). Nevertheless, in Poppalijärvi we observed Ni accumulation in the liver cells of perch. This metal, due to its transition to soluble and labile forms, is most toxic in an alkaline environment with a pH of 7.5–9.5. We also recorded smaller mitochondria sizes in liver cells of perch from Poppalijärvi, and larger lysosome size in Poppalijärvi and Koivas as compared with other lakes.

Chromium concentration in the tissues is also high in Poppalijärvi. The light increase of Cr in tissues (Table 3) may indicate the total influence of chromium. The chromium concentration in water was higher in Ahvenjärvi, a lake upstream from Poppalijärvi; *see* Table 1.

The highest concentrations of copper in water and in fish, as opposed to those of nickel, were recorded in the control lake, Kamennoe. The reason for this is unclear, but local geological features could be involved since unusually high concentrations of copper have been reported for till in the Kamennoe area (Koljonen 1992). Other factors behind this unexpected result could be the higher pH and a possible higher level of ligands in the Kenti–Kento system.

In the Kenti–Kento system, copper and zinc concentrations do not exceed natural levels; i.e.

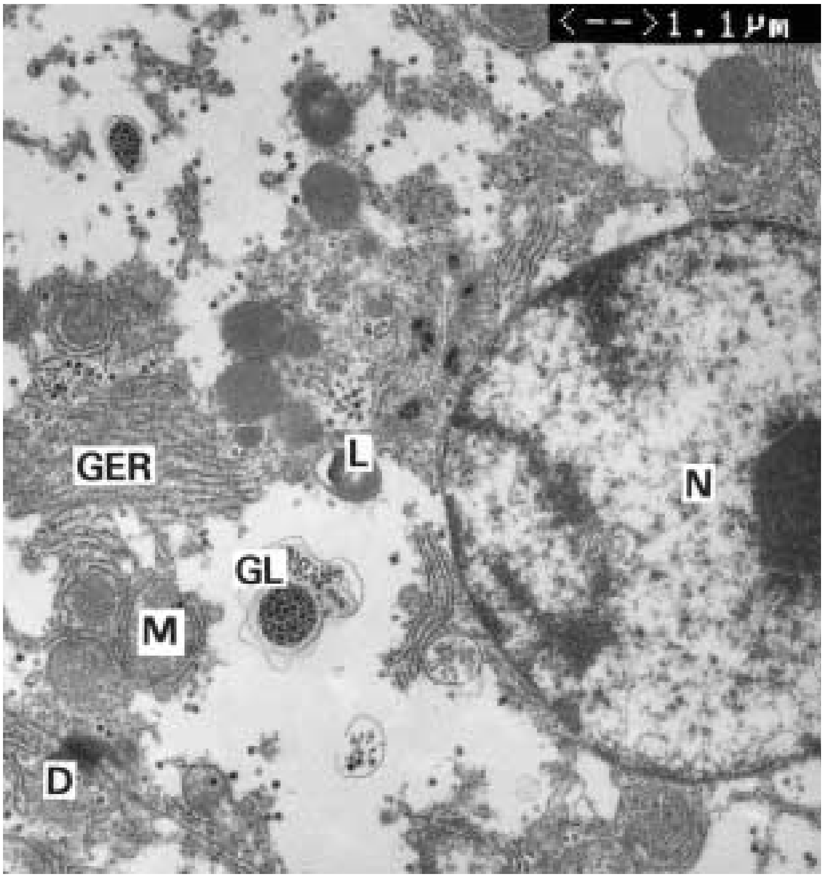

Fig. 5. Electronmicroscopical structure of the hepatocytes of perch in Lake Kamennoe. For other symbols *see* Fig. 3.

the KMP causes no increase in the concentrations of these metals.

The cadmium concentrations measured here in fish (highest in the control lake: 2.34 μg g^{-1} dry weight, > 0.36 μg g^{-1} wet weight) were higher than those reported in most other investigations (e.g. Allen-Gill *et al*. 1997, for review of Arctic areas, *see* AMAP 1998). The cadmium concentrations in the liver of northern pike from Lake Manitoba in Canada was 0.13 μg g^{-1} wet weight but was as high as 0.55 μg g^{-1} wet weight in lakes Flin Flon, which were contaminated by smelting operations (Harrison and Klaverkamp 1990). In addition to waste waters, atmospheric fallout may contribute to these high concentrations in the Kenti system.

The combined effects of all environmental factors lead to changes in the structure of liver cells. These changes are shown in the increasing distance between hepatocytes, increasing lysosome size, decreases in the number of pores in nuclei and decreases in mitochondria size. All these changes are directed towards protecting cell viability and indicate the presence of a toxic influence in the upper part of the Kenti–Kento lake-river system.

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