The effects of airborne emissions from the Pechenganickel smelters on water quality and littoral fish communities of small watercourses in the joint Finnish, Norwegian and Russian border area

Electrofishing in the vicinityof the Pechenganickel industrial complex. Photograph: Antti Lappalainen

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Abstract

The Pechenganickel smelters in Nikel and Zapoljarnyi, north-western Kola Peninsula, have been among the world's largest point sources of sulphur dioxide (SO_2), nickel (Ni) and copper (Cu) emissions. In order to study the effects of airborne emissions on aquatic ecosystems in the area, the water quality of 35 extremely small lakes and brooks at distances of 1 - 50 km from the smelters were surveyed, and the fish of stony shores of these lakes and brooks were sampled by electro-fishing. The results clearly demonstrated that airborne emissions from the smelters have not caused any widespread damage to the fish populations, not even in the most sensitive small waters, in the joint Russian, Norwegian and Finnish border area. The small waters close to the smelters (within an ca. 10 km radius) are well buffered against the effects of high sulphate deposition. The extremely high concentrations of heavy metals (Ni and Cu), however, are a local threat to biota in small waters in the area, and there are a few lakes that have apparently completely lost all their fish populations. In the area, acidification is currently a problem only in a set of extremely small waters in areas at higher altitudes, located 15 - 50 km from the smelters. In these water the buffering capacity is low (< 0.05 mmol/l) and some fish populations, mainly minnow, have most probably disappeared. During the past decades the SO_2 emissions have decreased to approximately one third of the maximum level in the late 1970s, and this is reflected as an overall recovery of the buffering capacity of small lakes e.g. in the Finnish border region, 40 - 50 km west of the smelters.

1. Introduction

The major metallurgical industries in the north-western part of the Kola Peninsula are located close to the joint Russian, Norwegian and Finnish border area. The smelters were originally constructed to process locally mined ore, and have been in operation since 1932 and 1955, respectively. Annual SO_2 emissions from the Pechenganikel smelters reached a peak of around 400 million kg in the late 1970s. The emissions have subsequently been considerably reduced and, in the beginning of the 2000s they were around 100 - 150 million kg annually. In addition to sulphur deposition, high heavy metal deposition (primarily Ni and Cu) is a serious threat to the environment. The highest annual Ni and Cu emissions, 555 and 335 tonnes, respectively, occurred in 1978. There has also been a decrease in heavy metal emissions since the 1970s. In the beginning of the 2000s, annual Ni and Cu emissions from the Pechenganikel smelters were around 350 and 180 tonnes, respectively.

Sulphur emissions from the Pechenganikel smelters are known to have caused surface water acidification in the Norwegian-Russian border area (Nost et al. 1991, Traaen et al. 1992, Moiseenko 1995), but the extent of the acidification problem in the Kola region is still unclear (Kashulina et al. 2003). Reinmann et al. (2000) argued that the emissions ‘do not seem to present a major threat on a regional scale’. Acidinduced damage to fish populations has been mainly studied in the Norwegian Jarfjord area, 30 km north-east from the Nikel and Zapoljarny smelters, using gill net series. The extent of damage has been relatively small, as only 14 arctic char (*Salvelinus alpinus*) or brown trout (*Salmo trutta*) populations in small (3 - 15 ha) lakes were identified as either extinct or at various stages of extinction (Hesthagen et al. 1998). Surveys conducted in the Finnish border region, 40 - 50 km west from the smelters, found that buffering capacities of a set of small (3 - 6 ha) lakes was below 0.05 mmol l^{-1}, and the results of an electrofishing survey revealed signs of acidinduced damage in local minnow (*Phoxinus phoxinus*) populations (Lappalainen et al. 1995, Tammi et al 2003). The state of fish populations in the smallest waters along the increasing sulphate and heavy metal deposition gradient between the Finnish border region and the smelters is still mostly unknown. In the industrial areas close to the smelters, however, the buffering capacity of the lakes is generally high (> 0.2 mmol l^{-1}) due to natural factors (e.g. bedrock geology) and local dust emissions containing alkaline particles (Moiseenko 1995, Reimann et al. 1999).

According to Moiseenko et al. (1995), the area of high Ni and Cu concentrations in water and lake sediments is limited to a 30 km zone around the Pechenganikel smelters. The range of metal concentrations in lake water in this area were 10 - 145 µg/l for Ni and 1 - 117 µg/l for Cu. Moiseenko et al. (1995), Amundsen et al. (1997), Moiseenko and Kudryatseva (2001) and Lukin et al. (2003) studied the contamination and effects of heavy metals, especially Ni and Cu, on local fish populations, mainly whitefish (*Coregonus lavaretus*), brown trout and arctic char, collected by gill nets from the large basins of the Paz River system or from other lakes on the Kola Peninsula. The general conclusion has been that the prevalence of fish diseases and pathological abnormalities, especially in the kidneys and liver, has been very high (around 90 %) in waters with high Ni and Cu concentrations.

The main objective of this study was to obtain an overview of the current effects of airborne pollution on water quality and littoral fish populations in small headwater lakes and brooks, which are considered to be the most sensitive waters to the effects of anthropogenic activities. The study area covers the industrial area around the Nikel and Zapolarny smelters and extends for 40 - 50 km to the west into the Norwegian and Finnish border areas. Standard gill net series were used in earlier fish surveys carried out in the Norwegian and Russian areas (Hesthagen et al. 1998). In this study, however, we used electrofishing sampling, enabling us to effectively sample fish even in very small waters where it is normally extremely difficult to sample the fish usually present in such waters, e.g. minnows, dwarf burbot populations and juvenile brown trout, using standard gill net series. Another objective was to follow up trends in water quality and fish populations at the sites on the Finnish side which were surveyed earlier in 1993 and 2000, where some signs of recovery were already reported (Tammi et al. 2003). The third objective of this study was to briefly evaluate the usefulness of these survey methods in the longterm monitoring of the effects of airborne pollution on small waters in the region.

2. Materials and methods

The study area was located in the joint Russian, Norwegian and Finnish border area, and it was further divided into three sub-areas (Fig. 1). Sub-area A was located in the industrial area, close to the Nikel and Zapolarnyi smelters. This sub-area receives the highest sulphur and heavy metal deposition in the Kola region, the annual sulphate, Ni and Cu deposition being 350 mg/m^2, 1 mg/m^2 and 1.8 mg/m^2 respectively (Paatero et al. 2006). Sub-area B consisted of two higher elevation areas, Sametfjället and Brannfjället in Norway, 20 - 30 km west of the industrial complex, which annually receive 400 mg/m^2 SO$_4$, 3 mg/m^2 Ni and 4 mg/m^2 Cu. Sub-area C was located in Vätsäri, an uninhabited area in Finland, 40 - 50 km west of the smelters. The SO$_4$, Ni and Cu depositions in this area were 2000 - 3000 mg/m^2, 40 - 300 mg/m^2 and 40 - 200 mg/m^2 respectively. The climate in the area is very severe with long winters and 6 - 8 months with a continuous snow cover. Atmospheric deposition accumulates in the snowpack during the winter, and the pollutants are released into lakes and brooks during the spring flood period. This is most probably a critical period for the local fish populations.

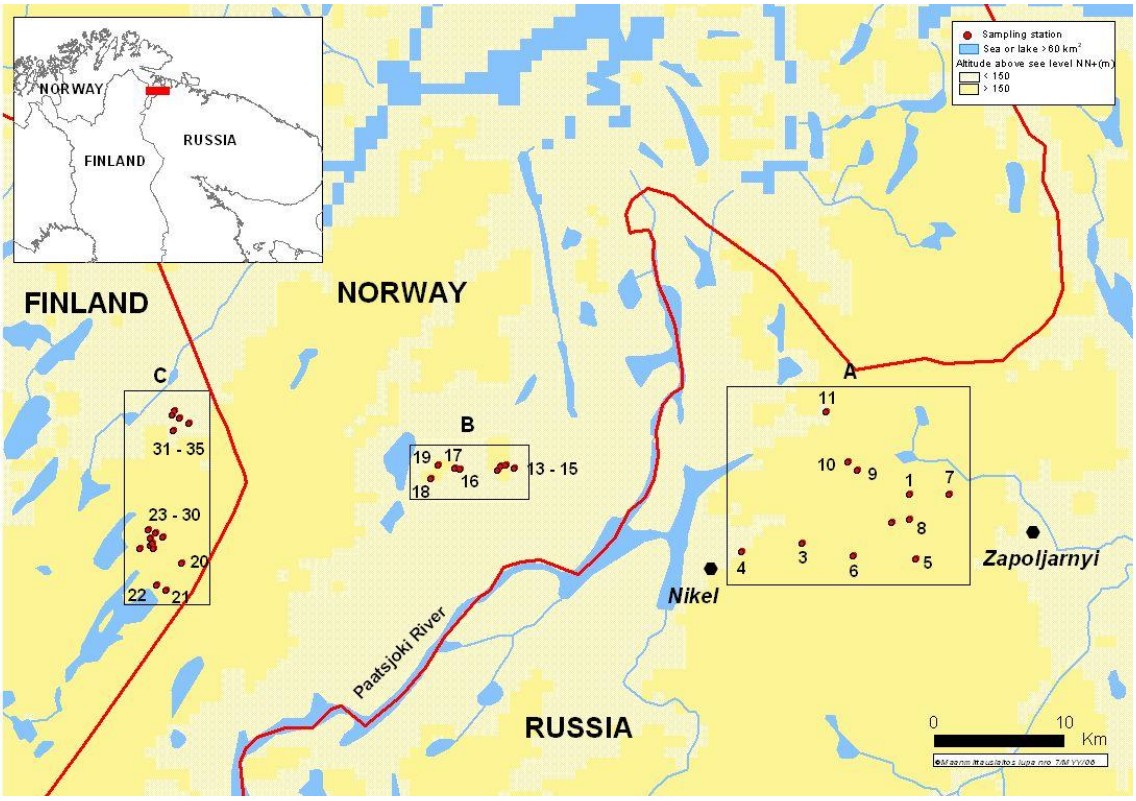

Figure 1. Map showing the 35 lakes and brooks investigated in the joint Finnish, Norwegian and Russian border area.

The goal in the final selection of lakes and brooks inside the sub-areas was to find waters which were the most sensitive to airborne pollution. Thus, all of the lakes were small (2 - 14 ha) headwater lakes, and the brooks were small (width 1 - 5 m) ones running out of small headwater lakes. A common criterion for the selected lakes was that they should be deep enough (depth > 2 - 3 m) for fish to survive during the winter. Another common criterion for both lakes and brooks was that there should have suitable stony habitats for effective electrofishing. Due to the relatively large differences in altitude over a short distance, natural obstacles to migration are common and the fish populations in most of the lakes sampled were isolated from each other.

In sub-area A, nine small (2 - 5 ha) lakes and two small brooks were sampled in 2005. The distance from the smelters varied from 1 to 16 km, and the sites were located at an altitude of 120 - 320 m above sea level (asl). In sub-area B, eight small (2 - 14 ha) isolated lakes at 120 - 173 m asl were sampled in 2004. In sub-area C, eight small (2 - 6 ha) lakes, three brooks connecting 21 - 34 ha lakes and five brooks or outlets of small (4 - 13) lakes were sampled in 2005. All the sites in sub-area C were located 93 - 240 m asl, and they had been sampled earlier in 1993 and 2000 (see Tammi et al. 2003).

Electrofishing was carried out in mid-September, using Hans Grassl IG200 - 2 portable equipment. The brooks or stony shorelines of the lakes were fished only once and without any closing nets. The actual fishing sites were selected from among the most potentiallooking shores. At each site, the surface area fished (8 - 300 m^2) was measured in order to obtain semi-quantitative estimates of littoral fish densities. The length of each fish was measured individually. Water samples were taken at the same time as the electrofishing, the only exception being the sulphate samples in sub-area B, which were taken in April 2005. The samples from sub-areas B and C were analysed in the laboratory of the Lapland Regional Environment Centre according to SFS standards. Water samples from sub-area A were analysed at the laboratory of the Institute of Northern Ecology Problems (INEP), following the same standards. Differences in the means of water quality parameters between sampling years in sub-area C were tested by the paired t-test. Differences in the means of water quality parameters between the three sub-areas were tested by ANOVA and Tukey’s tests. Heavy metal concentrations were not analysed in the samples taken in 1993 and 2000 in sub-area C.

3. Results

Water quality

The mean alkalinity values, as well as the mean sulphate concentrations, were significantly higher ($p < 0.005$) in sub-area A, close to the smelters, than in sub-areas B and C (Tables 1 and 2). The pattern was similar for the Ca concentrations, although the differences in the means were significant ($p < 0.005$) only between sub-area A and C. The mean concentrations of Ni and Cu were also the highest in sub-area A and lowest in sub-area C, the differences being significant ($p < 0.05$) between sub-area A and the other two, but not between sub-areas B and C. The situation as regards the total aluminium concentrations was the reverse, because the mean concentrations were significantly lower on sub-area A, close to the smelters, than in sub-areas B and C. In sub-area A, low alkalinity values (close or below 0.05 mmol/l) were found only at sites 9 and 10, which were located more than 14 km from the smelters.

Littoral fish communities/species composition

The electrofishing surveys in 2004 and 2005 yielded a total of seven fish species. In sub area A (in Russia), burbot was the most frequently caught species, and was found in two lakes out of eleven (Table 1). Brown trout was found in both brook surveys (sites 6 and 11), and according to the length distributions of 5.7, 9.8, 9.0 and 8.8 cm and (5.3, 5.9, 5.9, 5.1, 5.0, 9.5, 9.9, and 9.4 cm, the year classes 0+ (5 - 6 cm-long) and 1+ (8 - 10 cm-long) were caught. A single pike was caught in one lake. In sub-area B (in Norway), burbot was found in three lakes out of eight, minnow and perch (*Perca fluviatilis*) in two lakes, and brown trout and three-spined-stickleback (*Gasterosteus aculeatus*) in one and the same lake. In sub-area C (in Finland), minnows were found in eight sites out of sixteen. Both burbot and brown trout were found in two sites. Ten-spined stickleback (*Pungitius pungitius*), perch and pike were each found at one site.

Table 1. Altitude, surface area (for lakes only), chemical parameters and fish species caught at the study sites in September 2004 or 2005. M = minnow, T = brown trout, B = burbot, Pi = pike, Pe = perch, Te = 10 - spined stickleback, Th = 3 - spined stickleback. A double symbol indicates a density of more than 10 fish/ha.

Site N:o	Altitude (m)	Area (ha)	Alkalinity (mmol^{-1})	Sulphate (mgl^{-1})	Ni (µgl^{-1})	Cu (µgl^{-1})	Zn (µgl^{-1})	Ca (mgl^{-1})	Mg (mgl^{-1})	Al (µgl^{-1})	Fish
Russia											
	210	4	0.337	14.2	31.6	6.6	2.3	9.3	1.4	7	B,B
2	187	2	0.104	10.9	89.0	10.8	3.6	5.0	0.8	5	-
3	280	3	0.267	115.5	260.0	21.4	16.0	32.1	9.5	81	-
4	120	4	0.331	39.6	360.0	43.8	5.6	16.1	2.7	33	-
5	318	5	0.142	11.7	28.6	4.4	2.8	4.6	1.2	25	B
6	255	-	0.136	9.3	23.7	4.5	3.0	4.2	0.8	11	T
7	215	4	0.197	9.6	64.0	13.1	1.7	4.6	1.4	12	Pi
8	287	3	0.316	18.6	-	-	0.8	11.5	1.7	-	-
9	230	2	0.057	7.7	74.0	18.6	2.7	3.2	0.6	11	-
10	290	2	0.021	8.7	154.0	20.1	4.6	2.5	0.7	32	-
11	210	-	0.159	7.2	20.5	7.4	3.4	3.6	1.0	21	T,T
Norway											
12	145	9	0.072	2.9	4.8	2.5	<1.0	1.8	0.6	38	T
13	166	3	0.024	2.4	8.3	2.7	1.3	1.1	0.4	39	-
14	170	2	0.013	3.3	7.3	2.4	1.6	1.0	0.5	69	-
15	173	2	0.006	3.4	10.6	3.6	1.9	0.7	0.5	57	-
16	114	3	0.071	2.9	2.9	1.7	<1.0	1.6	0.7	21	B,Pe,Pe
17	120	4	0.085	3.8	3.6	2.4	<1.0	1.8	0.8	40	M,M,B,Pe,Pe
18	152	14	0.083	2.8	2.0	1.7	<1.0	1.9	0.6	51	M,M,B,Th,Th
19	159	2	0.057	2.4	4.9	2.4	<1.0	1.6	0.6	110	
Finland											
20	160	-	0.063	1.6	1.2	1.1	<1.0	1.2	0.4	32	-
21	161	-	0.069	1.6	1.4	1.3	1.0	1.3	0.5	40	Te
22	161	-	0.058	1.5	1.3	1.1	<1.0	1.3	0.4	35	M
23	220	2	0.088	1.6	1.1	1.1	<1.0	1.5	0.6	58	T
24	240	2	0.048	2.0	2.1	1.9	<1.0	0.8	0.3	71	-
25	235	5	0.018	1.7	1.9	1.0	1.8	0.5	0.2	24	-
26	235	2	0.021	2.2	2.0	1.2	1.6	0.7	0.3	75	-
27	220	2	0.013	2.0	2.2	1.7	1.0	0.6	0.3	110	M,M
28	219	6	0.044	2.2	-	-	-	1.1	0.4	37	M
29	210	3	0.038	1.8	1.2	1.2	<1.0	1.0	0.4	36	M,M
30	235	5	0.026	1.8	1.3	1.3	1.5	0.7	0.3	42	M,M
31	129	-	0.094	1.3	1.6	1.1	<1.0	1.8	0.6	47	Pe
32	93	-	0.077	1.7	1.1	1.0	1.2	1.7	0.5	44	M,M
33	136	-	0.063	1.5	1.2	1.0	1.1	1.5	0.4	49	M,M
34	110	-	0.089	1.5	1.3	1.5	1.5	1.8	0.5	47	B
35	95	-	0.077	1.7	1.0	1.1	1.3	1.5	0.4	42	M,Pi

The proportion of sites where no fish were caught was the highest (55%) in sub-area A, close to the smelters. In five of the six sites without any fish, the Ni and Cu concentrations were exceptionally high (Ni > 70 µg/l, Cu > 18 µg/l). Unfortunately, heavy metal analysis on the samples from site 8 failed in the laboratory but, based on the location of the lake, it can be assumed that heavy metal concentrations were also high in this lake because no fish were caught. In sub-area B, no fish were caught in 50 % the sites, i.e. four out of eight. In this sub-area, the lakes without any fish were typically the smallest lakes located at a relatively high elevation and which had the lowest alkalinity values (in most cases < 0.05 mmol/l) (Table 3). In sub-area C, no fish were found in four out of 16 sites, i.e. in 25 % of sites surveyed. Three of these sites were small lakes where the alkalinity was low, below 0.05 mmol/l. In addition to these sites, no fish were caught in one brook (site 20) in which several species and individuals has been found there during the surveys conducted in 1993 and 2000. In 2005, sites 20 - 24 were visited on a day when the weather was severe and there was some wet snow, which may have affected the results for these brooks. In general, no fish were caught when the Ni concentration exceeded 64 µg/l, and the catch of one fish at a Ni concentration 64 of µg/l is based on one pike caught at site 7. Fish were rarely observed at sites where the alkalinity was lower than 0.05 mmol/l.

Table 2. Average water quality parameters in sub-areas A - C (This will later be substituted by a figure, number of samples and standard errors will be added).

	Sub-area A / RU	Sub-area B /NO	Sub-area C / FI
Alkalinity (mmol/l)	0.188	0.051	0.055
Sulphate (mg/l)	23.0	3.0	1.7
Kalsium (mg/l)	8.8	1.4	1.2
Nickel (µg/l)	110.5	5.5	1.5
Copper (µg/l)	15.1	2.4	1.2
Aluminium (µg/l)	23.8	53.1	49.3

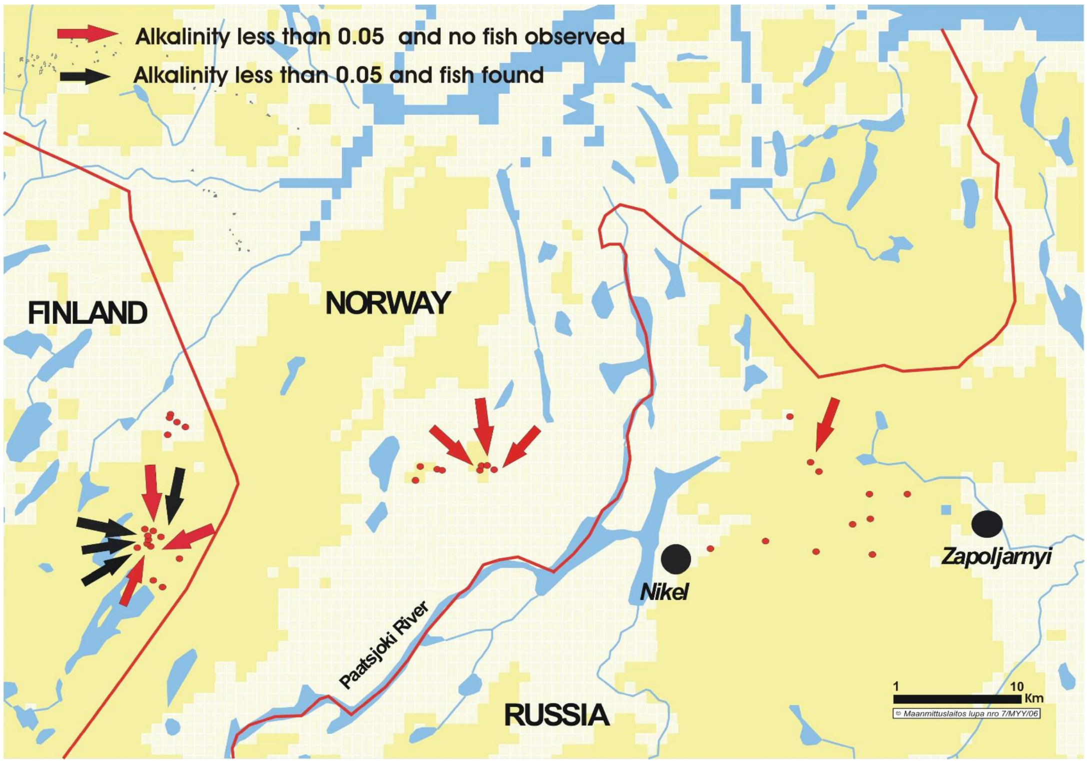

Figure 2. Location of study sites with alkalinity less than 0.05 mmol/l.

Table 3. Chemical properties of water samples (0 m) taken in mid-September 1993, 2000 and 2005 at the Finnish study sites.

Location	Alkalinity (mmol l^{-1})			Sulphate (mg l^{-1})			Aluminium (µg l^{-1})		
	1993	2000	2005	1993	2000	2005	1993	2000	2005
Joulujärvi area (brooks)									
Site 20	0.031	0.066	0.063	2.7	2.1	1.6	24	31	32
Site 21	0.040	0.051	0.069	2.7	2.0	1.6	32	29	40
Site 22	0.024	0.041	0.058	2.7	1.9	1.5	33	26	35
Äälisjärvi area (lakes)									
Site 23	0.047	0.076	0.088	2.3	1.8	1.6	49	46	58
Site 24	-0.004	0.015	0.048	2.7	2.0	2.0	20	29	71
Site 25	-0.004	0.013	0.018	2.7	1.9	1.7	15	15	24
Site 26	0.002	0.020	0.021	3.0	2.4	2.2	31	33	75
Site 27	-0.002	0.016	0.013	2.7	2.2	2.0	39	28	110
Site 28	0.020	0.029	0.044	2.7	2.3	2.2	26	26	
Site 29	0.019	0.026	0.038	2.8	2.2	1.8	22	24	36
Site 30	0.012	0.022	0.026	2.6	2.0	1.8	13	19	42
Vuontisjärvi area (brooks)									
Site 31	0.058	0.075	0.094	2.2	1.7	1.3	35	62	47
Site 32	0.061	0.067	0.077	2.5	1.9	1.7	24	36	44
Site 33	0.047	0.051	0.063	2.6	1.9	1.5	26	51	49
Site 34	0.073	0.083	0.089	2.4	1.8	1.5	33	72	47
Site 35	-	0.074	0.077	-	2.2	1.7	-	30	42

Water quality and fish catches in sub-area C during 1993, 2000 and 2005

The alkalinity values at all the sampling sites in sub area C were significantly higher and the sulphate concentrations lower in 2000 than in 1993 (Table 3), and the differences were statistically significant (paired t-test, $p < 0.001$). In 2005, the alkalinity values were still higher and the sulphate concentrations lower than in 2000 ($p < 0.001$). The total aluminium concentrations showed no significant differences between 1993 and 2000, but the total aluminium concentrations were significantly higher in 2005 than in 2000 ($p < 0.05$). In 2005, the alkalinity was still low ($<$ 0.05 mmol/l) in the small upland lakes (sites 24 - 30), the only exception being site 23, which is connected to an adjacent larger lake.

Minnow has generally been the most abundant species caught in sub-area C during all three surveys (Table 4), the highest densities in suitable habitats being ca. 50 - 100 individuals/10 m^2. In most of the small upland lakes (sites 23 - 30) and in the outlets and brooks between small lakes (sites 31 - 35), minnows occurred consistently at almost same the sites during the three surveys (Table 4). However, in the brooks connected to larger lakes (sites 20 - 22) the minnow observations were less consistent. Juvenile brown trout and burbot were the next most abundant species in sub-area C. These species, brown trout particularly, were occurred consistently at the same sites in 1993 and 2000, but in 2005 juvenile brown trout and burbot were missing from most of the sites.

4. Discussion

Surface water acidification

The effects of high sulphur emissions from the Pechengasnikel smelters are clearly evident in our study area as high sulphate concentrations, particularly in sub-area A, and as lower sulphate

Table 4. Densities (ind./100 m^2) of minnow, brown trout and burbot at the Finnish study sites in 1993, 2000 and 2005.

	Minnow			Brown trout			Burbot		
	1993	2000	2005	1993	2000	2005	1993	2000	2005
Joulujärvi area (brooks)									
Site 20	1	-	-	19	7	-	1	7	-
Site 21	5	4	-	3	1	-	1	Location	-
Site 22	-	13	2	-	-	-	2	2	-
Äälisjärvi area (lakes)									
Site 23	1	-	-	-	-	-	1	1	-
Site 24	-	-	-	-	-	-	2	2	-
Site 25	-	1	-	-	-	-	-	-	-
Site 26	-	-	-	-	-	-	16	-	-
Site 27	12	28	131	-	-	-	-	-	-
Site 28	17	-	8	-	-	-	-	10	-
Site 29	30	73	17	-	-	-	-	-	-
Site 30	6	5	13	-	-	-	-	-	-
Vuontisjärviarea (brooks)									
Site 31	20	-	-	-	-	-	4	-	-
Site 32	16	13	10	9	2	-	-	-	-
Site 33	46	79	101	-	-	-	13	4	-
Site 34	422	755	900	-	-	-	-	-	3
Site 35	87	73	2	-	-	-	13	-	-

concentrations on moving west into Norway and Finland. The highest concentrations in the industrial area (up to 115 mg/l) were at the same level as the highest values (116 and 123 mg/l) measured there earlier in stream waters (Väisänen et al. 1998). In the Finnish border area, located 40 - 50 km west from the smelters and almost diametrically opposite the prevailing south-westerly winds, the mean sulphate concentrations in 2005 were close to the median value (1.7 mg/l) of 190 randomly sampled lakes in northern Finland (Forsius 1992). However, the sulphate concentrations have decreased from the earlier levels (2.2 - 3.0 mg/l) measured in 1993.

The currently high sulphur concentrations have not, however, led to low buffering capacities (< 0.05 mmol/l) in the vicinity of the smelters, even though the waters are small and among the most sensitive ones to acidification. The Kola smelters emit considerable amounts of alkaline particulate and the deposition of this material may account for the rise in pH and buffering capacity in the immediate vicinity of the smelters (Moiseenko 1995, Reinmann et al. 1999). Dust from local strip mining activities may also be a source of base cations (Kashulina et al. 2003). In our study area, the few poorly buffered lakes (alkalinity < 0.05 mmol/l) were located at a distance of at least 10 km from the smelters, and they were all extremely small lakes located at altitudes above the coniferous tree line.

Hesthagen et al. (1998) reported acid-induced damage to fish populations in the Norwegian Jarfjord area, 30 km north-east from the Nikel and Zapoljarnyi smelters. In this area, 14 arctic char or brown trout populations of small (3 - 15 ha) lakes were identified as either extinct or in various stages of extinction (Hesthagen et al. 1998). Minnow is one of the most sensitive species to acidification (Muniz 1984, Berqvist 1991). Lappalainen et al. (1995) and Tammi et al. (2003) suggested that the presence of only a few large, old minnows or the total absence of minnows in the most poorly buffered lakes in sub-area C are signs of acid-induced damage. Similar potential signs of acid induced damages were also found in the Norwegian border area, where no fish were found in the most poorly buffered small lakes. Due to their invasion history, minnow, burbot and pike are not distributed in the northernmost parts of the Norwegian border region and Jarfjord area (Hesthagen et al. 1998), although minnows have been found e.g. in a large (1 700 ha) lake 2 km from the Nikel smelter (Lukin et al. 2003). Thus, the original distribution area of minnows should also cover the small lakes in the industrial area, especially as there were abundant habitats suitable for this species. It is likely that the minnow populations have disappeared from the small waters in the industrial area. Minnow may be more sensitive to high heavy metal concentrations than e.g. burbot and pike, which were found in the area, or the buffering capacity and consequently the pH may have been temporarily too low for this acid-sensitive species at the time when the smelter industry was established in the area a number of decades ago.

Heavy metal pollution

In our study areas, the effects of Ni and Cu emissions from the Pechenganikel smelters were still clearly evident in the small waters in the Norwegian, as well as in the Finnish border region: the average values measured in the latter region (Ni 1.5 µg/l and Cu 1.2 µg/l) are still higher than the medium values for small lakes in Finland (Ni and Cu 0.4 µg/l) (Skjelkvåle et al. 2001). Heavy metal emissions from the Pechenganikel smelters have decreased and, at the beginning of the 2000s, they were approximately half the level they were in the late 1970s. Thus, heavy metal concentrations in lake water have most probably been even higher during previous decades.

High heavy metal concentrations are the most likely reason for the lack of fish in the immediate vicinity of the Pechenganikel smelters. Fish reproduction and early life stages are generally considered to be the most sensitive to surface water acidification, but reports of the effects of Ni and Cu pollution on fish have focused on the accumulation of metals in fish tissues and the prevalence of fish diseases and abnormalities in adult individuals (Moiseenko et al. 1995, Amundsen et al. 1997, Moiseenko and Kudryatseva 2001 and Lukin et al. 2003). Moiseenko et al. (1995) presented critical levels for Ni and Cu concentrations in lake water based on the occurrence of fish diseases. The critical levels in well-buffered waters, such as our lakes in sub-area A, were 20 µg/l for Ni and 8 µg/l for Cu. These figures seems to fit our data fairly well because only a few burbot and pike were found in lakes with slightly higher concentrations, the highest concentrations with fish catches being Ni 64 µg/l and Cu 13 µg/l. In the Russian area, brown trout were found in brooks where the Ni and Cu concentrations were very close to the critical values. It is evident that the lakes with Ni and Cu concentrations above the critical levels are located within a 10 km radius of the smelters, where the highest Ni concentration in rainwater have also been observed (Karaban and Gytarsky 1995). The total number of such lakes is most likely a few dozen.

Evaluation of the survey methods

This study focused on extremely small waters, which are usually the most sensitive to the effects of airborne emissions, especially to acidification. These waters and fish populations were used as ‘first sign’ indicators of the impact of pollution. Electro-fishing is a suitable survey method in these small waters because the fish typically present in these waters, e.g. minnow, dwarf burbot or juvenile brown trout, are difficult or impossible to catch by the standard gill nets usually used in surveys (e.g. Hesthagen et al. 1998) due to their small size and preference for shallow stony habitats. Our results from the fish surveys in the Finnish border region during mid-September in three separate years showed that especially minnow, within its distribution area, is an excellent indicator species in small lakes and brooks running between small lakes because it is regularly and numerously found at the same sites and it is known to be sensitive at least to acidification (Muniz 1984, Bergquist 1991).

There has been a decreasing trend in the sulphur and heavy metal deposition from the Pechenganikel smeltes, and a recovery of surface waters is expected and is already underway in this arctic region. Basic information about the recovery of the small waters can be obtained by monitoring the water quality alone. One disadvantage of using fish populations as indicators of the recovery of very small, isolated waters is that, once the fish population has been lost completely, it cannot recolonize the waters without human assistance. Colonization is, however, possible in small river systems where e.g. brown trout can return to their ancient spawning and nursery areas from lower parts of a river if there are no barriers to migration. Recovery from less severe damage to fish populations, caused e.g. by partial or occasional reproduction failures, can also be monitored in small waters by electro-fishing (Tammi et al. 2003).

The recommendations for long-term monitoring include two scenarios. In the first scenario, the decreasing trend in the airborne emissions in the region will continue or emissions will stabilize at close to the level in the early 2000s. The state and recovery of small lakes and brooks in the region could be monitored cost effectively by surveying the water quality at 5 to 10-year interval. The 8 sites in Norway and 11 in Russia, used in this study, are appropriate sites for a long-term monitoring programme. On the Finnish side, the number of monitoring sites could also be close to 10, and the most sensitive sites in this study (e.g. sites 23 - 30) would be a suitable choice. In the second scenario, the emissions undergo a marked increase in the near future. In this case the littoral fish populations (together with water analysis) in the most sensitive small lakes are suitable indicators of the effects of emissions on fish populations. The fish populations investigated in this study could form the basis for regular and more intensive (e.g. 5 to 6-year intervals) monitoring. It is recommended that the set of sites monitored should be supplemented in the Norwegian area, and especially in the Russian area, in order to find 10 - 15 sites that currently have a littoral fish population in both countries. In the Russian area, most of the new sites should be located more than 10 km from the smelters.

5. Conclusions

The two Pechenganickel smelters have been among the world's largest point sources of SO_2 emissions, and they have been in operation in this arctic region since 1932 and 1955. However, airborne emissions from the smelters have not caused any wide spread damage to the fish populations even in the most sensitive small waters in the joint Finnish, Norwegian and Russian border region. The small waters close to the smelters (within a ca. 10 km radius) are well buffered against the effects of high sulphate deposition. However, the extremely high concentrations of heavy metals (primarily Ni and Cu) represent a local threat to the biota in small waters close to the smelters, and there are a few lakes that have completely lost their fish populations. Acidification is currently a problem only in a set of extremely small waters located at higher altitudes 15 - 50 km from the smelters. In this area some fish populations, mainly minnow, are most probably extinct. The SO_2 emissions from the smelters have decreased to approximately one third of the maximum level in the late 1970s, and this is reflected in recovery of the buffering capacity of small lakes e.g. on the Finnish side of the border, 40 - 50 km west of the smelters.

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