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Introduction

The effects of the Pechenga-Nikel industrial complex and Severonikel Plant of the Kola GMC in the Kola Peninsula (Nikel/Zapoljarny and Monchegorsk) on freshwaters are studied using water quality data in lakes in the Finnish Lapland. The study is part of the larger project "The effects of the Kola air pollution sources in the areas of the Kola Peninsula and Finnish Lapland", financed by the Finnish Academy of Sciences for the years 2004–2007.

The main pollution agents from the Kola Peninsula are acidifying pollutants, mainly sulphate, and heavy metals. From 1990 to 2003, sulphur emissions decreased 68% and 82% at Nikel and Monchegorsk, respectively (Hole *et al*. 2006). Despite reductions in the emissions during the 1990s, non-ferrous metal production remains the dominant source of acidifying gases, mainly sulphate, to the atmosphere within the arctic. Main sources of acidifying nitrogen compounds in the arctic are transportation, and oil and gas activities (Hole *et al*. 2006). However, despite the local emissions most of the acidifying compounds in the arctic air come from sources at lower latitudes, mostly in Europe, North America and Asia (Hole *et al.* 2006).

High-latitude ecosystems are particularly sensitive to pollution. Highest sulphur deposition in Finnish Lapland was measured in Vätsäri area, north from the Lake Inarijärvi, at distance 40–50 km from the metal smelters in Nikel (Tuovinen *et al*., 1993). The Vätsäri area is also the area with the lowest buffering capacity in the waters (<50 µeq/l in many lakes).

The first signs of the effects of acidic deposition in Finnish waters were noticed in the early 1970s (Kenttämies 1973). Concentrations of all measured anions and cations, except bicarbonate, increased from the late 1960s to the early 1980s (Forsius *et al*. 1990). In the 1980s, there were two main characteristic in the deposition of acidifying compounds in Finland: decreasing gradient from south to north, and elevated deposition in northeastern Lapland originating from Kola Peninsula (Tuovinen *et al*. 1990).

This study concentrates on lakes in the southeastern parts of the Finnish Lapland, because the effects of the metallurgical industry, most closely smelters in Nikel and Zapolyarny, in the northernmost Lapland has been studied by the Interreg IIIA Kolarctic project " Development and implementation of an environmental monitoring and assessment system in the joint Finnish, Norwegian and Russian border area during the period 2003–2006 (Stebel *et al*. 2007). In the vicinity of the southeastern Finnish Lapland is situated the Severonikel plant of the Kola GMC JSC in Monchegorsk.

The Severonikel plant is the largest smelter in Murmansk Oblast, processing rich copper-and-nickel ore and nickel matte from Norilsky Combinat and the Pechenganikel Plant. The plant announces to use also scrap metal, waste and raw materials from domestic and international suppliers. Wastewater and atmospheric emissions from the plant are formed in hydro- and pyrometallurgical processing of the raw materials and in the production of sulphuric acid from the production waste. In addition, heavy oil (230 000 tons in 2002) is burnt in a heat power plant, to provide heat supply and partial electric power supply to the plant.

The sulphate and metal emissions announced by the Severonikel plant are presented in Fig. 1 and Fig. 2. During the period 1990–2002, sulphate emissions were at their maximum of 287 kt in 1990, and declined during the 1990's to below 50 kt/yr. Copper and nickel emissions peaked to over 6 kt/yr in the late 1980's , but declined during the first half of the 1990's to below 1 kt/yr. According to Hole *et al*. (2006), the development of the emissions from the more northern Nikel smelters has followed the same development as the Monchegorsk smelters.

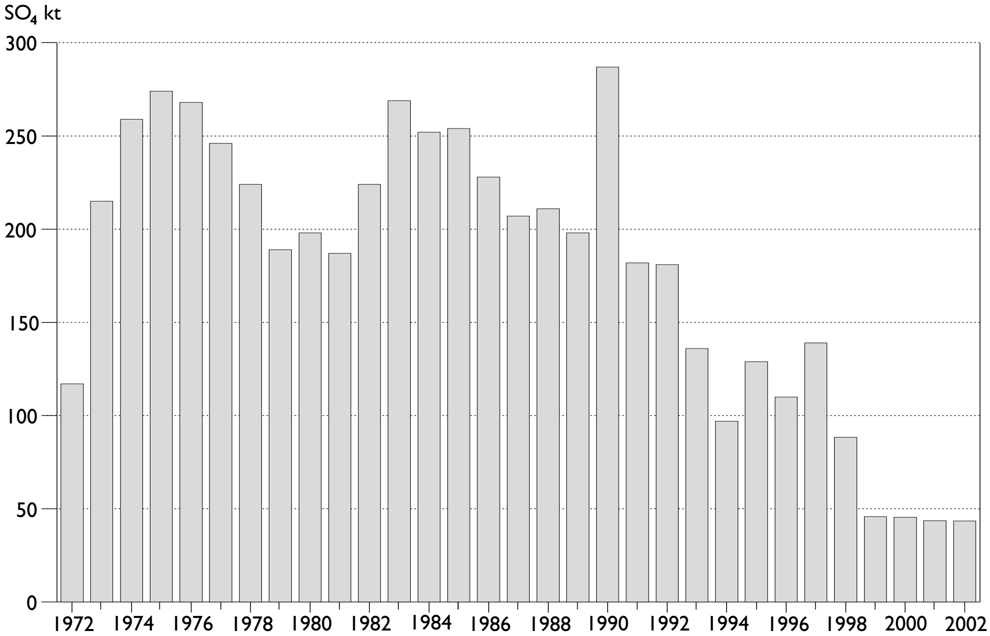

Fig. 1. Sulphate emissions from Monchegorsk combinate during 1972–2002. Source: Ministry of Natural resources official statistics; coal-fired power plant emissions: VTI/IVL, 2004.

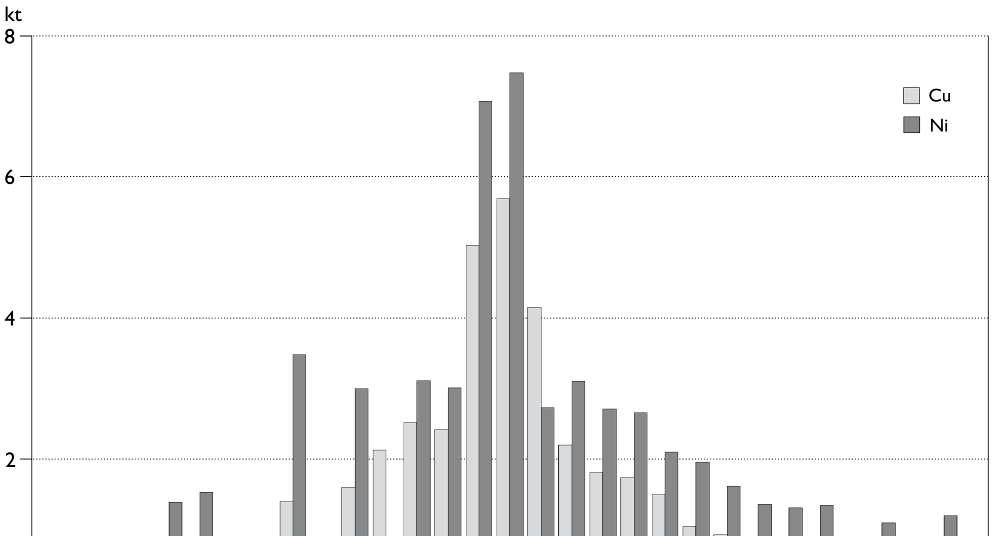

Fig. 2. Copper and nickel emissions from Monchegorsk combinate during 1972–2002. Ministry of Natural resources official statistics; coal-fired power plant emissions: VTI/IVL, 2004.

The most dominating direction of winds is from west in the area of Kuusamo, southwest from Monchegorsk. Secondly the winds prevail from the east (Fig. 3).

In 1988, the total sulphur deposition in Svanvik (northeastern Norway) and in the eastern border of Finland was measured to be around 60 meq/m^2/yr (Forsius *et al.* 1990). According to Tuovinen & Laurila (1992), the deposition was above 1,0 g/m^2/yr (20,8 meq/m^2/yr) in the eastern parts of Inari, but below the level of 1,0 g/m^2/yr in the municipalities south and west from Inari.

The alkalinity values consistently increased and sulphur concentrations decreased in Finnish Lapland in the 1990s, indicating recovery from the acidification (Tammi *et al.* 2003). Sulphate deposition decreased at Nellimö (in southeastern part of Inari) from 0,33 g /m^2 during 1981–1985 to 0,16 g /m^2 during 1996–2000, according to Finnish Environment Institute data (Tammi *et al.* 2003).Minnow populations also showed recovery in the Vätsäri area in the late 1990s, compared to 1993 (Tammi et al. 2003).

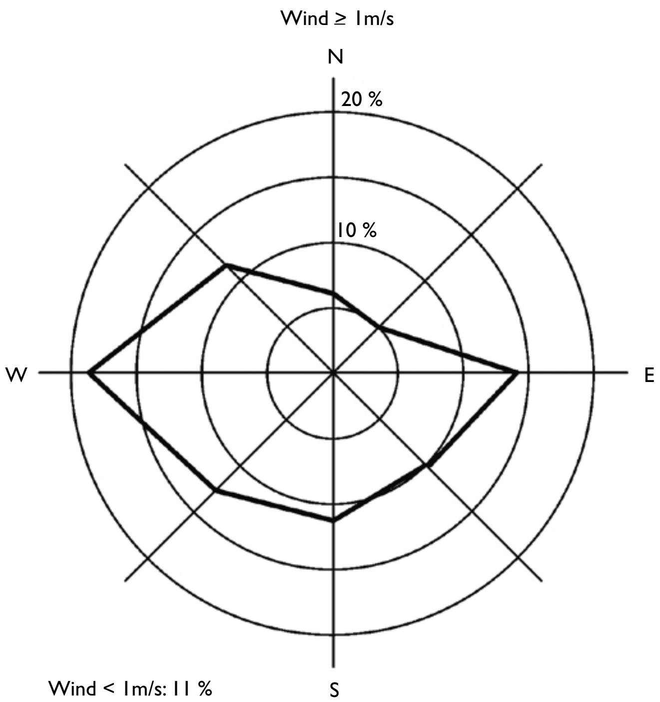

Fig. 3. Percentage of time for each wind direction during 1961–1990 in Kolvanki, Kuusamo. Figure from the Finnish Meteorological Institute (1991).

The acidity of Finnish lakes is dependent upon the atmospheric loading of sulphate, the catchment sensitivity, and the amount of organic anions present (Forsius *et al.* 1990). Of these, sensitivity is dependent on soil geochemistry, catchment size and runoff rentention time (Kähkölä 1996).Of lakes with pH less than 5,3, 56–81 % was estimated to be naturally acidic (pH <5,3) (Forsius *et al.* 1990).

Critical load is defined as the highest load that will not cause chemical changes leading to long-term harmful effects on the most sensitive ecological systems. For sensitive areas, with quartz, granite, or gneiss bedrock, the critical load is estimated to be in the range 20–50 meq/m^2/yr, e.g. in Ähtäri, southern Finland, 20 meq/m^2/yr (Kauppila *et al.* 1990).

Arctic Monitoring and Assessment Programme (AMAP) has indicated that the impact of the oil and gas industry, and natural sources including forest fires, may increase in the future (Hole *et al.* 2006). Also the importance of nitroxen oxide emissions is increasing in the arctic. These reasons, with the fact that most pollutants in arctic air originate from sources outside the arctic, have resulted in AMAP recommending monitoring and research be carried out to provide more data on effects and trends in the most impacted areas of the arctic (AMAP 2006).

Material and methods

Altogether 30 lakes were studied for their water quality (Table 1). Five of the lakes, situated in western Finnish Lapland (municipalities of Enontekiö, Kittilä and Muonio), are used as reference sites.

Table 1. Location, surface area, and water quality of the studied lakes. Reference lakes are marked with asterisk.

Lake	Municipality	Coord.	Coord.	Area	total P	total N	TOC	Colour
		YK-North	YK-East	[ha]	[µg/l]	[µg/l]	[mg/l]	[mgPt/l]
Kenttälammit Kotala	Salla	7436528	3584872	2,1	9	480	6,1	15
Nuottalampi	Salla	7409770	3560070	3,3	6	283	5,4	19
Pikku Haltiajärvi	Salla	7466871	3603832	1,3	7	159	1,8	4
Ruuhijärvi	Salla	7418379	3574123	66,4	13	548	4,1	11
Lastenlampi	Posio	7328970	3536700	4,1	6	330	4,1	12
Miilulampi	Posio	7338100	3554750	2,0	6	298	2,2	6
Näskäjärvi	Ranua	7345500	3489000	547,9	7	248	5,3	37
Siurulampi	Savukoski	7520802	3577241	4,5	16	557	8,7	54
Arvolampi	Sodankylä	7508180	3522550	14,9	8	493	5,1	19
Auveelampi	Sodankylä	7509480	3523900	9,2	10	228	6,7	58
Hankarimpilampi	Sodankylä	7532270	3490420		9	518	7,9	48
Joutolampi 2	Sodankylä	7445590	3461860	13,1	17	754	10,7	81
Makiankalanlampi	Sodankylä	7437340	3467550	9,5	17	472	13,6	132
Suopalampi	Sodankylä	7442068	3460789	38,9	13	305	5,6	40
Joulujärvet VI	Inari	7706458	3584704	36,6	4	149	2,3	5
Kalaton Kampajärvi	Inari	7627540	3560772	11,9	5	223	4,3	10
Keittämättömätjärvet	Inari	7609250	3550160	17,8	6	306	5,0	24
Lampi 219	Inari	7708923	3584543	5,6	4	133	2,4	7
Lampi 222	Inari	7708833	3582618	23,6	5	123	2,1	7
Lampi 3/88	Inari	7709055	3583966	4,7	4	111	1,7	5
Lampi 432	Inari	7596380	3531710	5,9	8	426	6,5	28
Lampi D49	Inari	7619820	3552320	1,9	11	551	8,0	61
Peuranampumajärvi	Inari	7627178	3564424	7,4	6	242	4,8	15
Sierramjärvi	Inari	7678153	3496122	107,9	4	110	2,3	9
Äälisjärvi	Inari	7707210	3580852	396,5	3	120	1,6	4
Hietajärvi*	Enontekiö	7598784	3404554		5		2,3	5
Käyräjärvi*	Enontekiö	7576341	3387159		7	400	7,2	31
Mustajärvi*	Kittilä	7501251	3414022	3,6	9	352	5,5	33
Rautujärvi*	Enontekiö	7588286	3360453		5	210	3,4	11
Sarvijärvi*	Muonio	7559331	3379272		9	145	1,8	8

Small remote lakes with no significant anthropogenic impacts and oligotrophic character were selected for the study, because the effects of the airborne deposition is most easily seen in these lakes. The study lakes are included in the monitoring network "Acidification monitoring of surface waters" in Finnish Lapland.

The study lakes in the eastern Lapland are situated in the area of six municipalities (Fig. 4). Salla is the closest municipality to Monchegorsk, forming with Posio and Ranua southern part of the study area. North from Salla are situated Savukoski and Sodankylä, situated north from Monchegorsk and south from Pechenganikel. Inari in the north is more impacted by the Pechenganikel smelters, and is studied only for comparance with the other municipalities. The reference lakes are situated in Kittilä, Enontekiö and Muonio in the western Finnish Lapland.

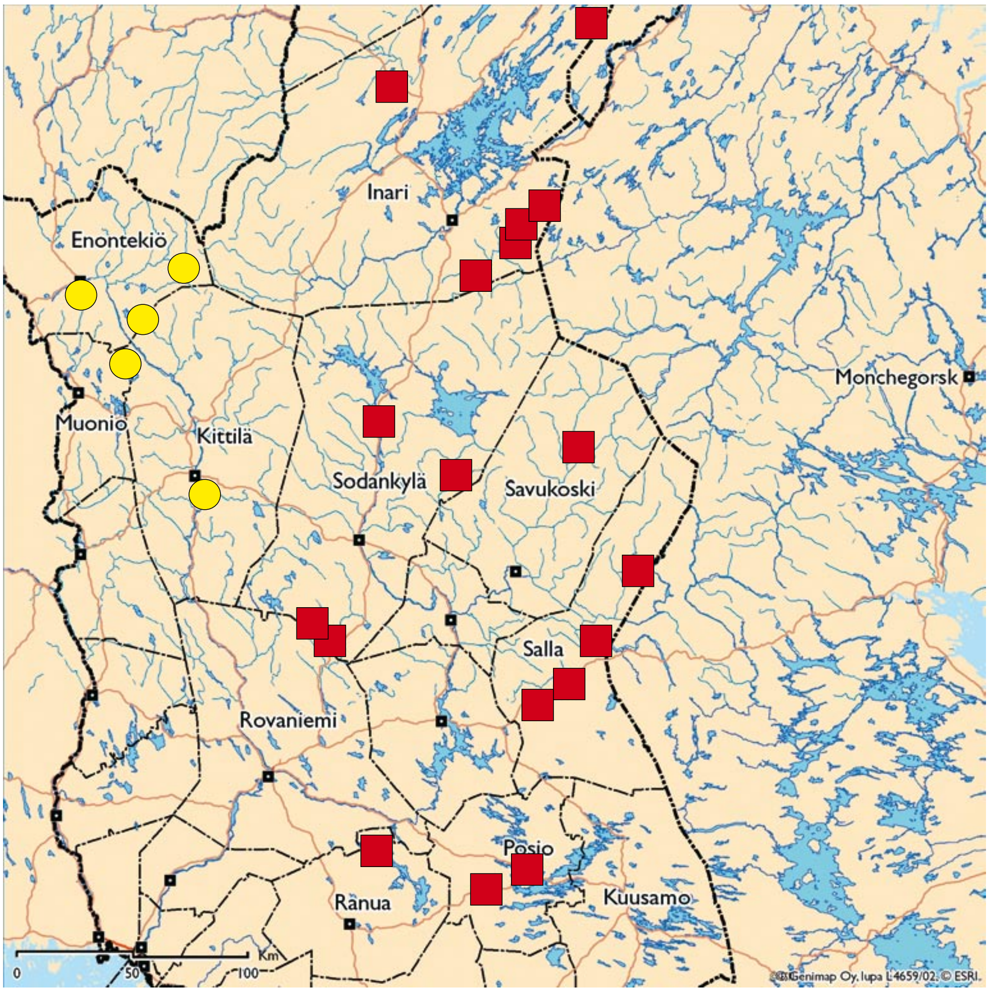

Fig. 4. Location of the studied lakes and areas of municipalities in northern Finland. Study lakes are marked by red colour, reference lakes by yellow.

Only late summer or autumnal data (mostly September–November) is used. One surface sample (0–1 m) from each lake is used for each year in the analyses. The water quality samples were analyzed in the laboratory of the Lapland Regional Environment Centre, using standardised methods.

Data on wet deposition of sulphate and heavy metals was collected at the meteorological station of Oulanka, situated in Kuusamo, south from Salla and east from Posio. The deposition was measured once every month, and the monthly values are summed into annual deposition values. Measurements on metals are available only for the period 2000–2005.

The SO_4 concentrations were not corrected for non-marine values, because chloride was not measured for many of the sampling occasions. This has no large effect on the results, since the marine influence (Cl concentrations) is low in the studied area.

The development of the water quality (sulphate, pH, alkalinity, Al, Cu, Ni) is first studied commonly for the area of Salla, Posio, Ranua, Savukoski and Sodankylä, excluding the reference area and Inari municipality, mostly for the period 1990 to 2006. Developments in the water quality variables are presented as box-plots of the autumnal values of each year.

Mean values of sulphate, alkalinity and pH during 1991–1995 and 1996–2000 are compared to the period 2001–2005 by paired T-tests. After that, the water quality in different municipality areas is compared, including Inari municipality and the reference area.

Results

Meteorological data

The annual rainfall for the period 1990–2005 in Oulanka, Kuusamo, is presented in Fig. 5. During the study period, the amount of rainfall was higher than average (508 mm/yr) during years 1991, 1992, 1995, 1998, 2000 and 2005. No significant difference was found in the rainfall between the five-year periods 1991–1995, 1996–2000, 2001–2005.

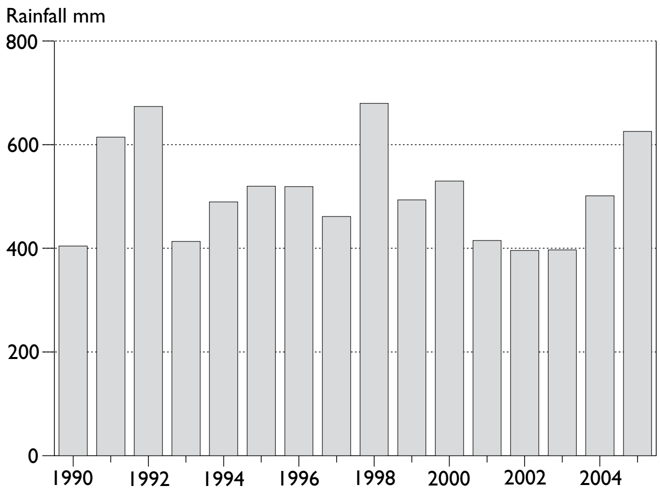

Fig. 5. Mean annual rainfall (mm), measured in the sulphate collector at the Oulanka research station.

The acidity of the rain was highest in the beginning of the observation period. pH below 4.5 was measured for several months during the year 1990 (Fig. 6).

Sulphate deposition in Oulanka was at its highest level in 1991–1992, and has decreased to about one third of the maximum value after that (Fig. 7). The critical load is estimated to be mostly 20–50 meq/m^2/yr in the area, and only for the most sensitive areas below 20 meq/m^2/yr (Henriksen *et al*. 1994). These deposition values observed, about 2–6 meq/m^2/yr are very unlikely to exceed critical loads for area.

Deposition of metals (Cr, Cu, Ni) appear to have increased during 2000–2005, although trends are not clear for this short period (Fig. 8).

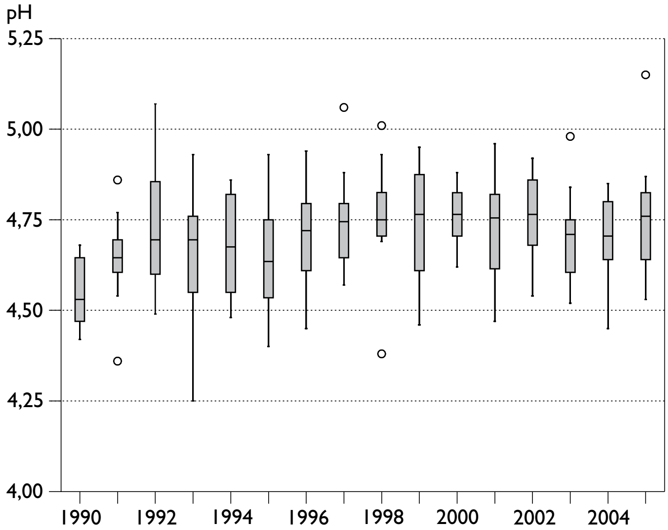

Fig. 6. Annual mean value of monthly measurements of rain water pH at the Oulanka research station.

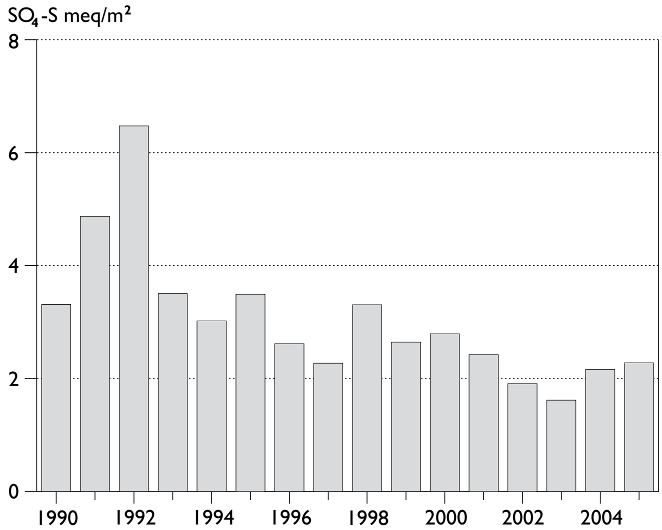

Fig. 7. Annual wet sulphate deposition [meq/m²] at the Oulanka station.

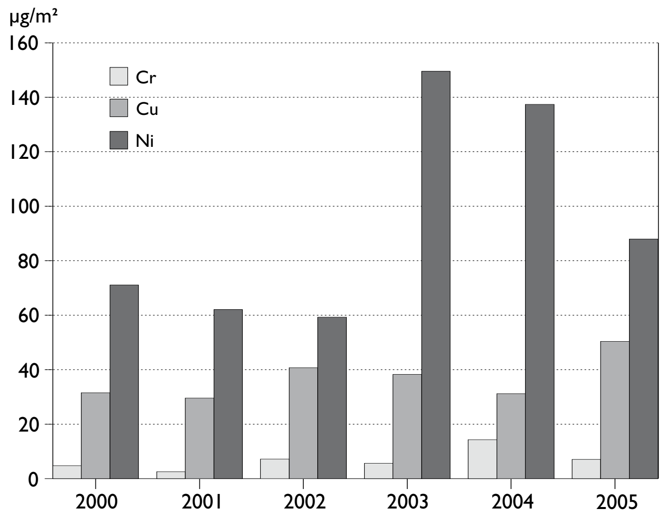

Fig. 8. Annual deposition of chrome, copper and nickel (µg/m²) in rain water at the Oulanka station.

Lake water data

The amount of samples for each year is reasonably stable for the period 1990–2006, except lower for the years 1990, 2002 and 2006. For the area of Inari municipality in the north, more affected by the Nikel smelters, the number of samples used is also reasonably stable, except for the year 1990 (Fig. 9).

Low base cation (Ca+Mg+Na+K) concentrations indicate sensitivity to acid ification. Concentrations below 200 µeq/l are considered low, which is the case for most of the study area. Highest concentrations are found in Inari, and lowest in the Posio municipality (Fig. 10). Note that the number of lakes studied is low for some municipalities (two lakes in Posio and one lake in Ranua and Savukoski).

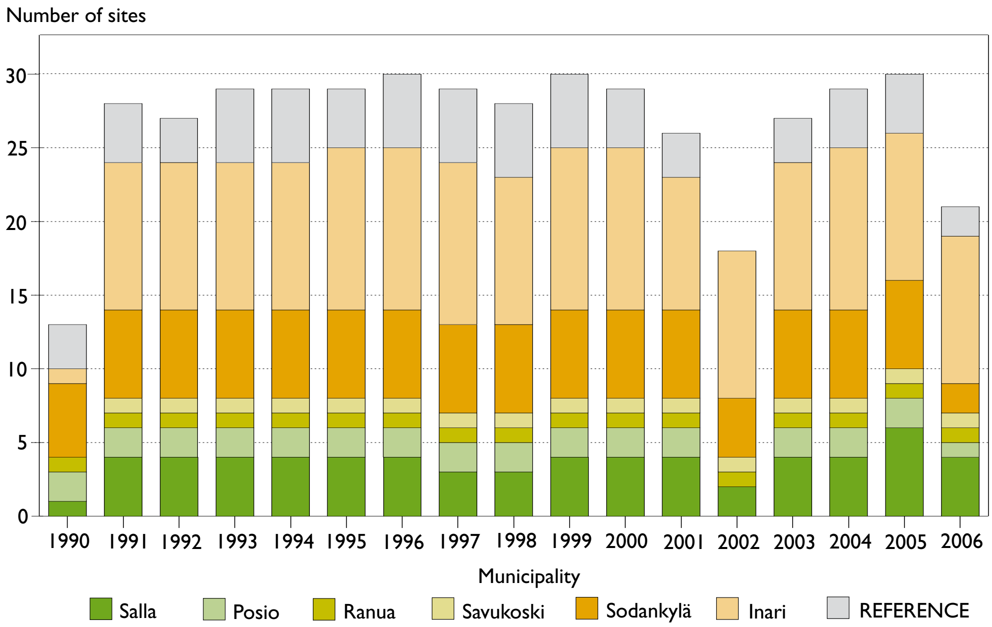

Fig. 9. Number of studied lakes for each year, in the municipalities of Salla, Posio, Ranua, Sodankylä, Savukoski, Inari, and reference sites.

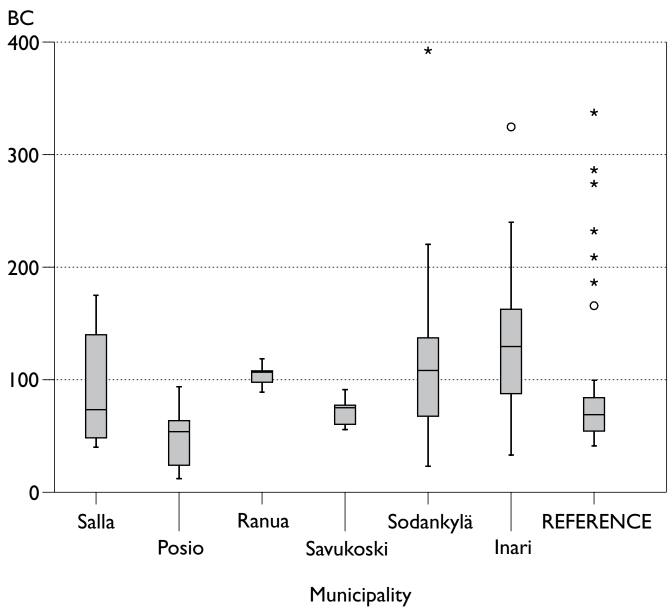

Fig. 10. Base cations [µeq/l] in lake waters in the municipalities of eastern Finnish Lapland, and in the reference area, based on the data from the years 1990–2006.

Sulphate

The development of autumnal sulphate concentrations in the lake waters in the study area is presented in Fig. 11. Sulphate concentrations declined from around 30 µeq/l to around 20 µeq/l during the 1990s. No more decline is seen after the 1990s.

The studied period is divided into 5-year periods, and the statistical significance of the decline in the mean sulphate concentrations is tested by paired T-tests. The decline in the sulphate concentrations is statistically significant from 1991–1995 to the 1996–2000, but no significant change from 1996–2000 to 2001–2005 is found (Table 2).

The trends in the municipalities are compared in the Fig. 12. Declining trend is seen for all the sub-areas, including reference area. SO_4 concentrations are higher in the area of Inari, reflecting the influence of Nikel/Zapoljarny smelters.

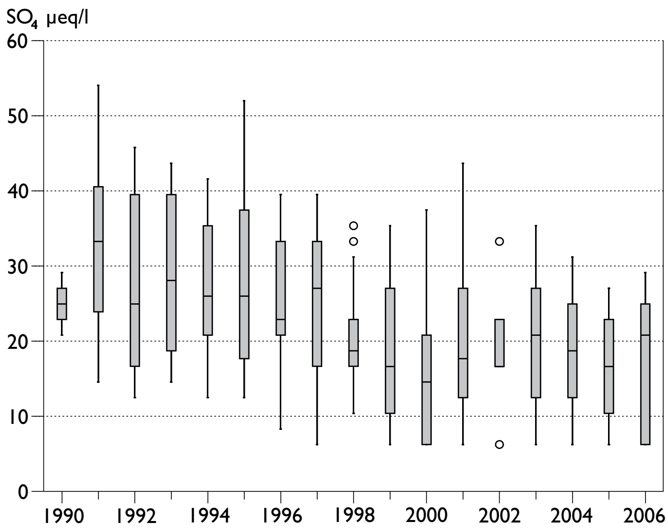

Fig. 11. Autumnal sulphate concentrations [µeq/l] in lake waters: mean values in the combined area of of Salla, Posio, Ranua, Savukoski and Sodankylä.

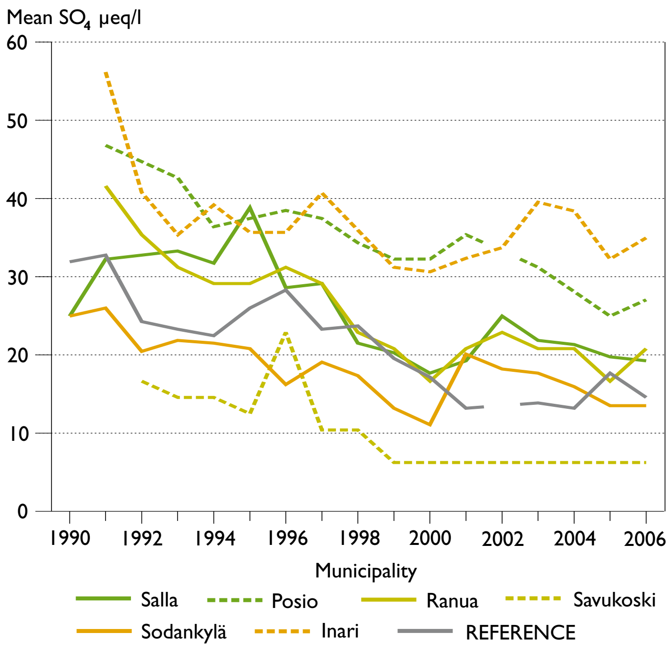

Fig. 12. Mean autumnal lake water sulphate concentrations [µeq/l] in the areas of the municipalities, and in the reference area.

Table 2. Independent samples T-tests for the mean SO_4 concentrations, for periods 1991–1995 and 1996–2000 against the period 2001–2005.

Period	Mean SO_4 values [µeq/l]	Sig. difference to next period
1991–1995	28,7	<0,001
1996–2000	20,7	0,355
2001–2005	19,2	

pH

Development of the pH values is presented in the Fig. 13. pH values have remained quite stable during the study period. Generally the values are between 5,5 and 6,5. A slight increase in the mean pH value is seen from the period 1991–1995 (5.95) to 2001–2005 (6,06), but the increase is not statistically significant (Table 3).

The lowest pH values (<5,0) are found in three lakes: one in Posio, one in Inari and one in Sodankylä. The lowest measured value, 4,58, was measured in Joutolampi, Sodankylä, in 1992. The mean values are low for the municipality of Posio, because only two lakes were included (Fig. 14).

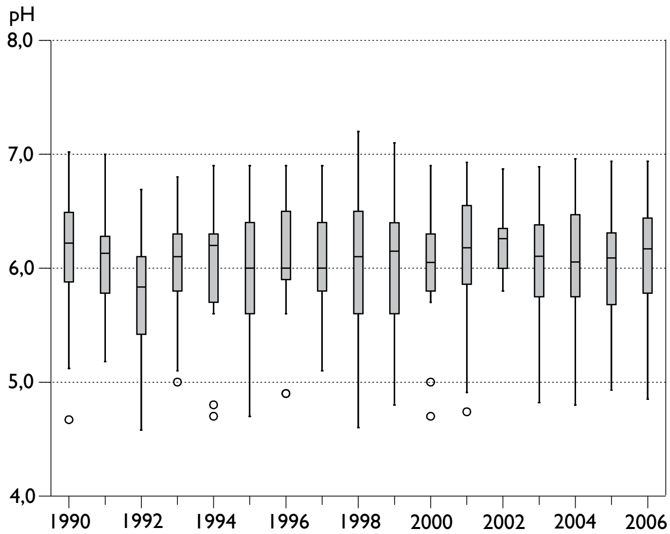

Fig. 13. Autumnal pH of the lake waters: mean values in the area of Salla, Posio, Ranua, Savukoski and Sodankylä.

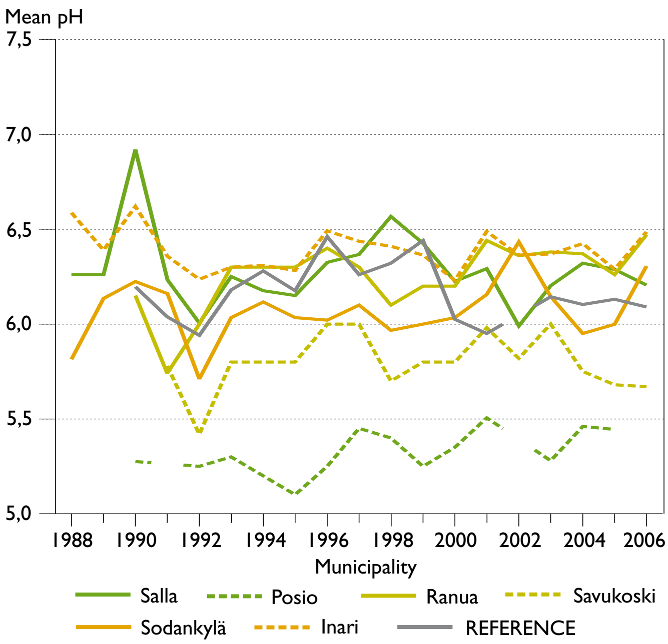

Fig. 14. Autumnal pH values in different areas: mean values in the lakes of Salla, Posio, Ranua, Savukoski, Sodankylä, Inari and reference area. Note that the first values are from the year 1988.

Table 3. Independent samples T-tests for the mean pH values, for periods 1991–1995 and 1996–2000 against the period 2001–2005.

Period	Mean pH value	Sig. difference to next period
1991–1995	5,95	0,492
1996–2000	6,02	0,676
2001–2005	6,06	

Alkalinity

Alkalinity value, or acid neutralizing capacity (ANC), of 20 µeq/l has been found to be the critical value for fish in freshwaters (Henriksen *et al*. 1990, 1994). Of the studied lakes, 10 out of 30 have mean alkalinity value <20 µeq/l. These lakes are scattered around the study area, including reference area.

The autumnal alkalinity values have increased from year 1990 (mean 24 µeq/l) to the year 2006 (mean 44 µeq/l). Lowest mean value 22 µeq/l is recorded for the year 1994, and the highest mean value 46 µeq/l for the year 2002 (Fig. 15). The alkalinity values have increased more in Inari, than in the other municipalities (Fig. 16).

The number of lakes with alkalinity below 20 µeq/l has decreased during the study period. In 2006, all lakes in the municipalities of Ranua, Savukoski and Sodankylä reached alkalinity value above 20 µeq/l (Fig. 17). This more likely reflects the decreased acidifying load from western Europe than from the Kola Peninsula, because in three of the four reference lakes alkalinity also increased from below to above 20 µeq/l.

In table 4, the test results for the differences in mean alkalinity values between the five-year periods is presented. Mean alkalinity value has increased, but the increase is not statistically significant.

Table 4. Independent samples T-tests for the mean alkalinity values, for periods 1991–1995 and 1996–2000 against the period 2001–2005.

Period	Mean alkalinity value [µeq/l]	Sig. difference to next period
1991–1995	23,7	0,146
1996–2000	32,7	0,585
2001–2005	36,3	

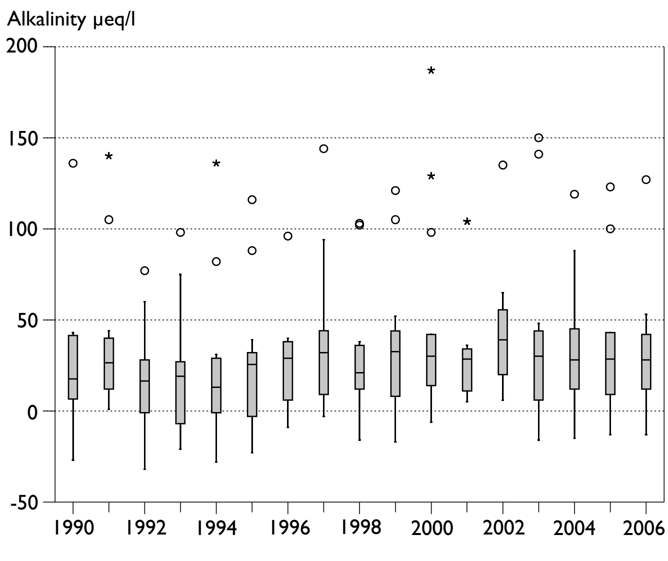

Fig. 15. Autumnal alkalinity [µeq/l] of the lake waters: mean values in the area of Salla, Posio, Ranua, Savukoski and Sodankylä.

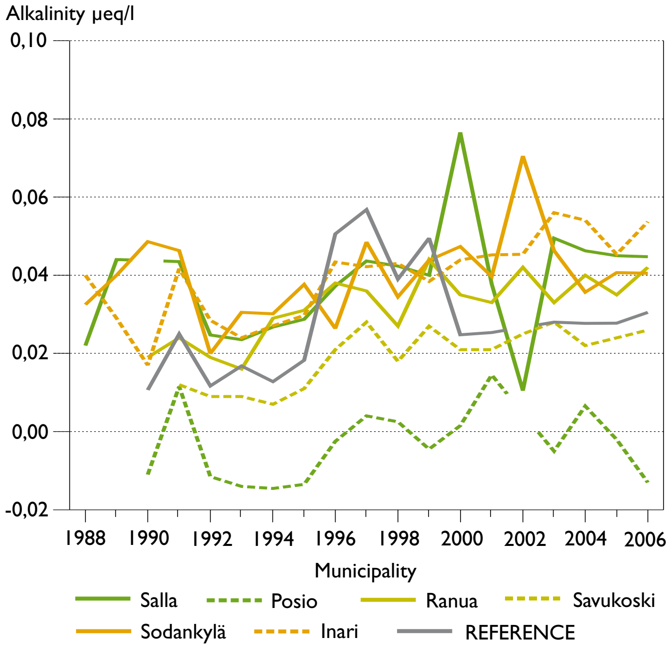

Fig. 16. Mean autumnal lake water alkalinity values [µeq/l] in the municipalities, and in the reference area. Note that the observation period starts from the year 1988.

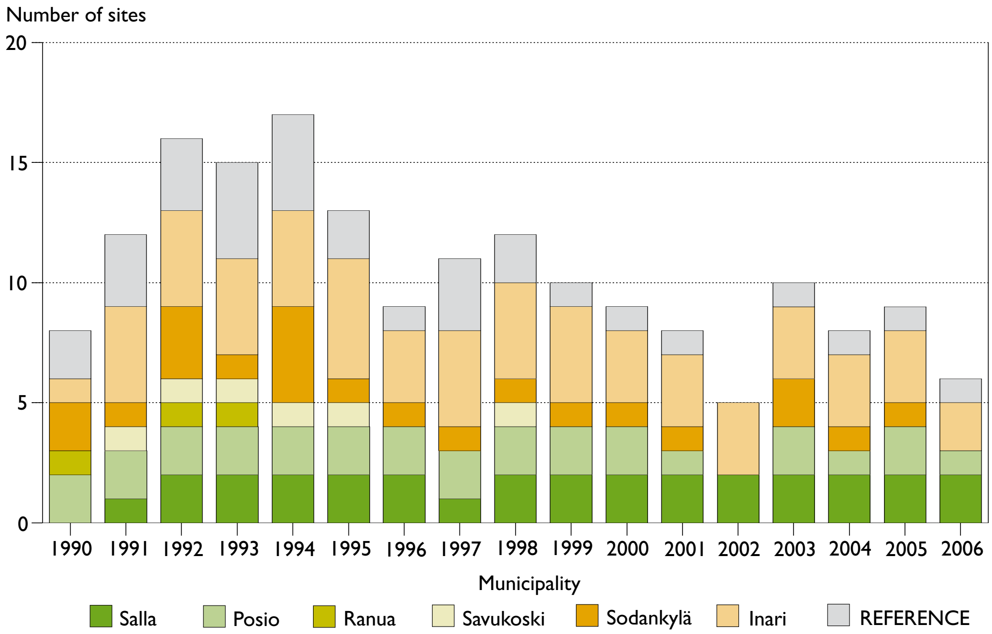

Fig. 17. Annual number of lakes with autumnal alkalinity value below 20 µeq/l, presented separately for the different municipalities and reference area.

Aluminium

The development of aluminium concentrations annually is presented using reactive Al concentrations, because more valid measurements are available for reactive than labile Al. Reactive aluminium concentrations in the area of Salla, Posio, Ranua, Savukoski and Sodankylä is presented in Fig. 18. The median concentrations were elevated in many lakes in 1998–1999 and in 2006. When comparing the 5-year periods for labile Al, the mean concentration is highest for the period 1996–2000, but the differences are not statistically significant (Table 5).

Mean labile aluminium concentration in the lakes was 9 µg/l (range 0–50 µg/l). According to Puro-Tahvanainen & Luokkanen (2007), in the Finnish northern Lapland lakes the mean labile Al concentration was 8 µg/l, and maximum 20 µg/l, for the period 2000–2005.

According to Wilander (1999), concentrations of labile aluminium over 25–75 µg/l are considered toxic for the biota. According to Verta *et al.* (1990), when labile Al concentration is >50 µg/l and pH is less than 5,3, the conditions are considered toxic for e.g. perch and brown trout. This was estimated to the case for 7 % of lakes in Finland (Verta *et al*. 1990). In this study the maximum concentration of labile Al found was 50 µg/l, and so toxic effects of aluminium are unlikely in the study lakes at the present concentration levels.

The aluminium concentrations are dependent on the amount of humic compounds (total organic carbon). According to these results, reactive aluminium concentrations appear to have increased in the reference area, but not in the other areas (Fig. 19).

Labile Al mean concentration was significantly higher during 1996–2000, than in 1991–1995 (Table 5). This is probably due to rainy years 1998 and 1999, which increased the amount of Al binding organic matter in the waters.

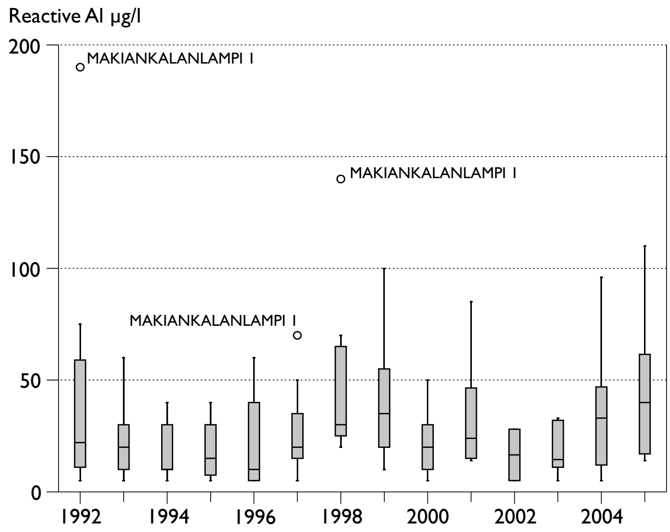

Fig. 18. Autumnal reactive aluminium concentrations (µg l^{-1}) in lake water: mean values in the area of Salla, Posio, Ranua, Sakoski and Sodankylä.

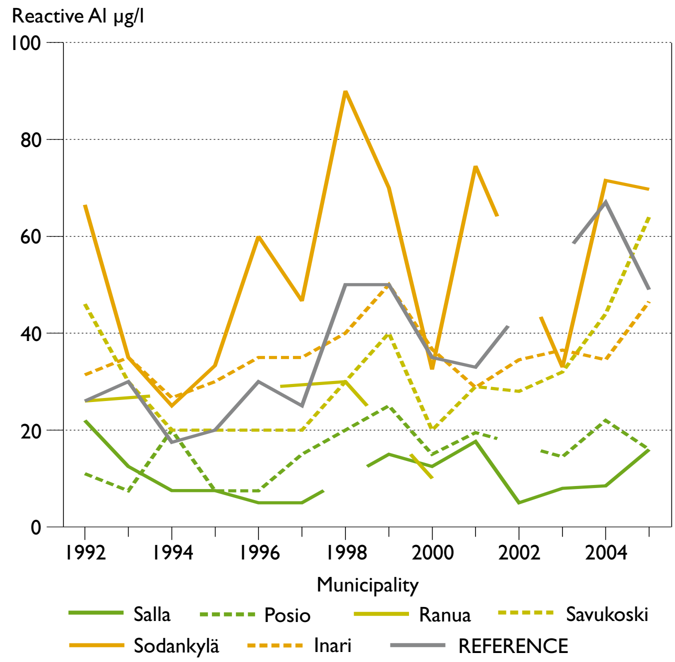

Fig. 19. Mean autumnal reactive aluminum concentrations (µg l^{-1}) in the municipalities of Salla, Posio, Ranua, Sodankylä, Savukoski, and in the reference area.

Table 5. Independent samples T-tests for the mean labile aluminium values, for periods 1991–1995 and 1996–2000 against the period 2001–2005.

Period	Mean labile Al [µg/l]	Sig. difference to next period
1991–1995	6,25	0,005
1996–2000	11,80	0,080
2001–2005	8,10	

Copper

Copper concentrations have been below 1 µg/l, with the exception of one measurement in Nuottalampi in 1996 (Fig. 20). According to Alm *et al*. (1999), concentrations below 3 µg/l cause little risk for toxic effects. Limit for acceptable concentration in EU is 5 µg/l (Alm *et al*. 1999).

The copper concentrations appear to have increased during the study period in Inari (Fig. 21). In other municipalities no trends are found (Table 6). Median concentration in the reference lakes is 0,15 µg/l. No significant changes in the copper concentration are found between the 5-year periods (Table 6).

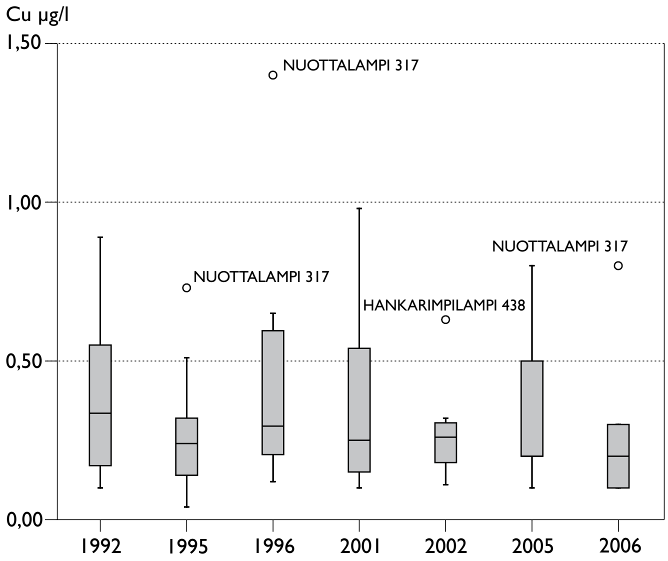

Fig. 20. Development of copper concentrations (µg l^{-1}) in the lake waters: autumnal mean values in the area of Salla, Posio, Ranua, Savukoski and Sodankylä.

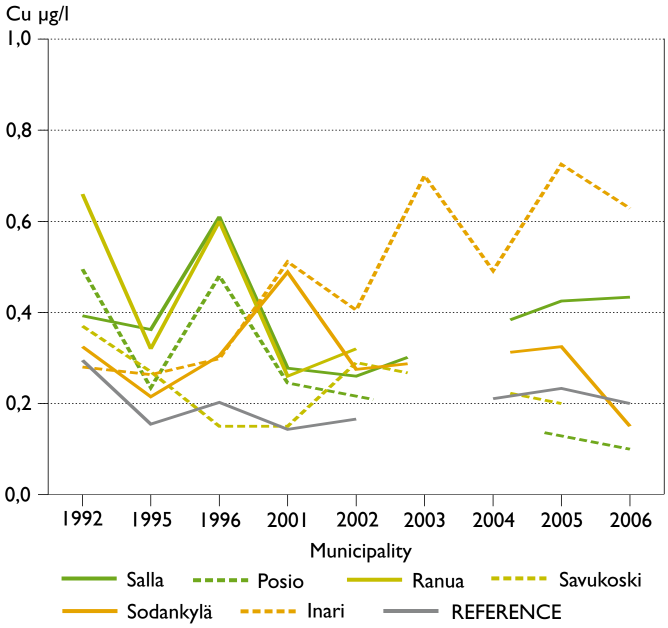

Fig. 21. Mean autumnal copper concentrations (µg l^{-1}) in the lakes of the municipalities of Salla, Posio, Ranua, Sodankylä, Savukoski, Inari, and in the reference area.

Table 6. Independent samples T-tests for the mean copper concentrations, for periods 1991–1995 and 1996–2000 against the period 2001–2005.

Period	Mean Cu [µg/l]	Sig. difference to next period
1991–1995	0,33	0,235
1996–2000	0,45	0,324
2001–2005	0,34	

Nickel

Nickel concentrations have been below 1 µg/l, except in 2001 in some of the lakes (Fig. 22). These lakes are mostly in the area of Inari, where the nickel concentrations, as well as copper concentrations, have increased after 1996 (Fig. 23). The concentrations are still fairly low: concentrations more than 15 µg/l are measured closer to the Nikel smelters (Puro-Tahvanainen & Luokkanen 2007), and concentrations below 15 µg/l are considered to indicate low risk for biological effects (Alm *et al*. 1999).

The mean nickel concentration have not changed considerable during the study period. Lowest mean concentrations are recorded for the late 1990's (Table 7).

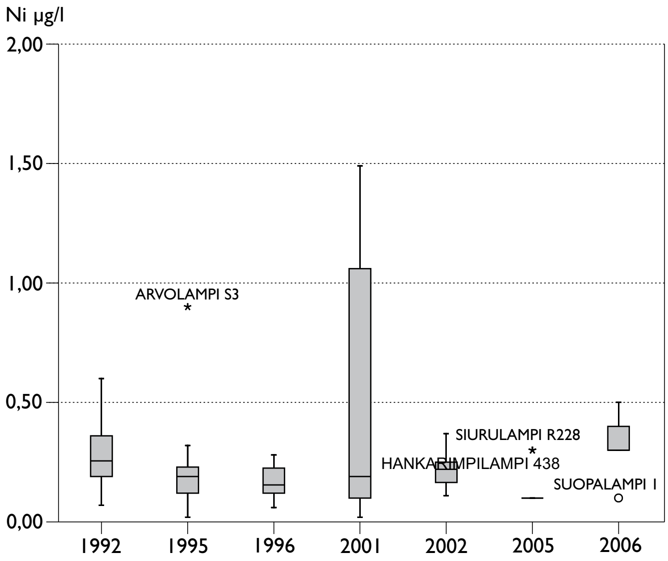

Fig. 22. Development of nickel concentrations (µg l^{-1}) in the lake waters: autumnal mean values in the area of Salla, Posio, Ranua, Savukoski and Sodankylä.

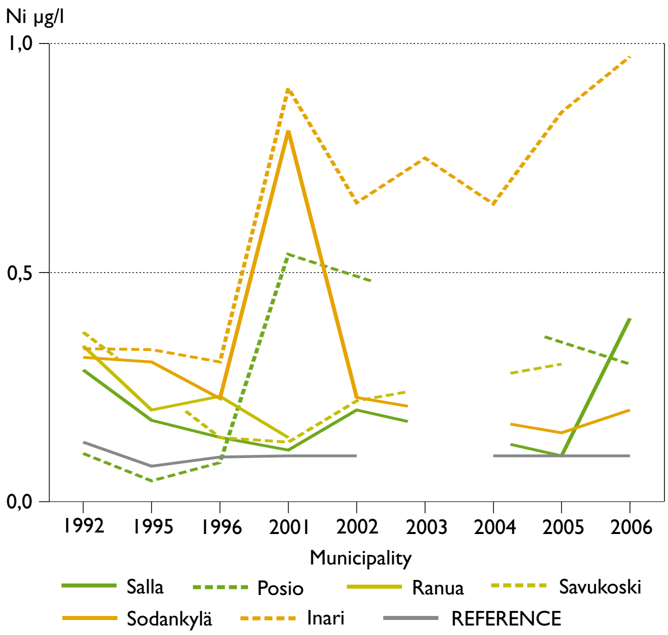

Fig. 23. Development of nickel concentrations (µg l^{-1}) in the lakes: autumnal mean values in the municipalities of Salla, Posio, Ranua, Sodankylä, Savukoski, Inari, and in the reference area.

Table 7. Independent samples T-tests for the mean nickel concentrations, for periods 1991–1995 and 1996–2000 against the period 2001–2005.

Period	Mean Ni [µg/l]	Sig. difference to next period
1991–1995	0,25	0,125
1996–2000	0,17	0,109
2001–2005	0,28	

Other metals

Table 8 lists mean and maximum concentrations of arsenic, cadmium, chrome, lead and zink in the study area, together with the median values in the reference area and in northern Finland according to Mannio (2001).

Alm *et al.* (1999) created a classification system for biological effects associated with the metal concentrations: class 1 = no or very small risk; class 2 = small risk; 3 = some biological effects are possible; class 4–5 = elevated risk. The median arsenic, zink, copper and nickel concentrations for all the 5-year periods indicate class 1 conditions. Median chrome concentration indicate class 1 conditions for the period 1991–2000, and class 2 conditions for the period 2001–2005. Lead concentrations indicate class 2 conditions for 1991–2000 , and class 1 conditions for 2001–2005. Cadmium is the only one of the metals, for which the concentrations indicate class 2 conditions for the whole study period.

Table 8. Median concentrations of some metals (µg/l) in the studied lakes in Salla, Posio, Ranua, Savukoski and Sodankylä, median values in the reference lakes, and in northern Finland according to Mannio (2001).

Metal	1991–1995	1996–2000	2001–2005	Reference	Mannio (2001)
As	0,18	0,16	0,14	0,09	0,17
Cd	0,01	0,06	0,02	0,02	0,02
Cr	0,29	0,24	0,31	0,11	0,24
Pb	0,26	0,23	0,15	0,08	0,25
Zn	1,90	1,35	1,30	1,00	1,84

Discussion

The concentrations and trends of sulphate and metals in the lakes in eastern Lapland (south of Inari) are close to the concentrations and trends seen in the reference lakes, with the exception of elevated nickel concentrations in the lakes of Salla in 2006. Acidification is not detected in the area, after the acidification trend to the early 1990's, and recovery during the late 1990's.

Background non-marine sulphate concentration for dilute lakes is estimated to be 15 µeq/l (Brakke *et al*. 1989). At the time of higher sulphate emissions in the 1980's, median sulphate concentration in northern Finland was estimated to be 35 µeq/l (Forsius *et al.* 1990). Mean sulphate concentration in the lakes studied here, excluding the area of Inari, decreased from 29 µeq/l during 1991–1995 to 19 µeq/l in the period 2001–2005, which is near the estimated background level. In Inari, area of Raja-Jooseppi closer to the Pechenganickel smelters, the sulphate concentrations are higher, around 30–40 µg/l.

According to the announced emissions from the Monchegorsk during 1990–2002, the sulphate emissions were at their highest in the year 1990, after which they decreased to their present level by the year 1999. The wet deposition in Oulanka, Kuusamo, peaked in 1991–1992. The emissions and deposition levels do not correspond at the annual level, but the trends are similar: decline during the 1990's, and steady levels after that. Annual rainfall measurement partly explains the deposition data: SO_4 levels are elevated for the years with rainfall higher than usual.

The mean concentration of SO_4 in the lake waters reached it maximum in 1991, and has decreased since. The concentrations follow the decline in the emissions from Monchegorsk.

The rain was most acidic in the year 1990 in Oulanka, but the acidification is seen only after some delay in 1992 in the lake waters in Salla. The delay can be explained, at least partly, by the higher level of leaching of base cations from the catchments to the lakes during 1989–1991 (Fig. 24).

The lakes recovered from the acidification during the mid- or late 1990's, as could be expected from the decreased levels of acid deposition. The amount of lakes with alkalinity below 20 µeq/l has been at the pre-acidification level after the year 1996. Almost all sulphate concentrations measured are far below values that would cause acidification in the lakes.

Also the AMAP report (AMAP 2006) indicates decreasing or flat trends for sulphate concentrations in air for all monitoring sites after the 1980s. In Jäniskoski, however, total sulphate concentration in air was elevated from long-term values below 0,5 $\mu g/m^3$ to about 0,8 $\mu g/m^3$ during summer 2003, which is the last value presented in the AMAP report.

Sulphate concentrations decreased in the 1990s not only in the study area but allover northern arctic (Canada, Svalbard, Fennoscandia and NW Russia; AMAP, 2006). This decreasing trend is seen also in the reference sites. This leads to conclusion,

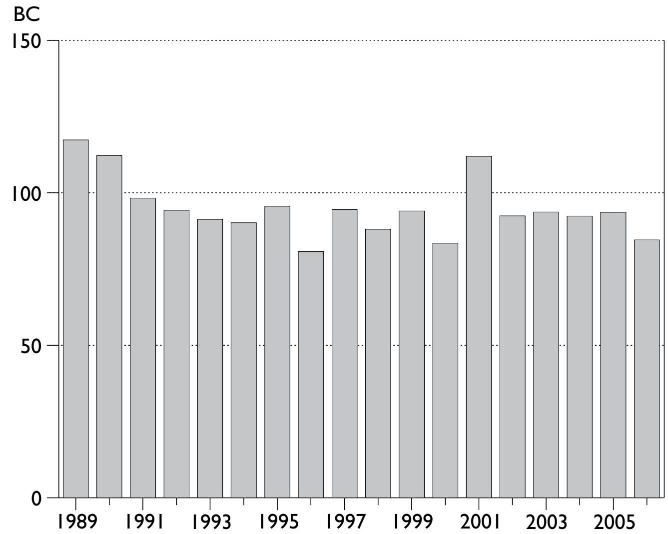

Fig. 24. Concentration of base cations (μeq/l) in the lakes of Salla, Posio, Ranua, Savukoski and Sodankylä during the period 1989–2006.

that the increased alkalinity in the studied lakes is at least partly due to the decreased deposition from the western Europe.

One should notice that, according to Kämäri (1998) around 75 % of the deposition of acidifying compounds could occur in the form of dry deposition, which should also be monitored. Model predictions, based on full implementation of the agreements made so far, indicate that the decreasing trend in sulphate deposition is like to level off after 2010 (AMAP, 2006).

Data on the deposition of metals and their concentrations in lakes is much more sparse than the data on sulphate and acidification. Generally, no clear trends are seen in the concentrations of metals in the lake waters. The copper and nickel values are far below safe limits (3 and 15 μg l^{-1}, respectively).

Weak increasing trend in the copper and nickel is seen in Inari, where also Puro-Tahvanainen & Luokkanen (2007) observed the same increasing trend (area of Raja-Jooseppi, south of Lake Inari). This trend is probably due to the smelters in Nikel, but increased concentration of nickel is seen also in the lakes of Salla in 2006, and there is some increases in the deposition of metals in Kuusamo (Oulanka station) during the period 2000–2005.

North Atlantic Oscillation (NAO) affects the long-range transport of pollutants from Europe, North America and Asia to the arctic. The NAO index was strongly positive during 1990–1995, which increased the deposition of pollutants in the arctic. During 1996–1999 the NAO index was negative, not favouring the long-term transport of pollutants to the arctic. Climate models predict that the frequency of positive phases is likely to increase in the near future (AMAP, 2006).

The influence of the NAO must be considered in any studies on trends in arctic pollution (AMAP, 2006). This climate phenomenon probably explains part of the decreasing trend seen in the sulphate deposition in the Finnish Lapland during the 1990s.

Recommendations for future monitoring

Monitoring should be carried out southwest from the Montshegorsk industrial complex (ie. in the municipalities of Salla and Kuusamo, because they are still at the risk for high fall-out events from Montshegorsk. Also other areas sensitive to acidification should be monitored. These are areas with low buffering capacity, caused by the hard bedrocks.

Small headwater lakes and rivers are considered the most sensitive freshwater systems, that should be monitored for acidification. A spatially covering net of sites, and in addition a small number of frequently monitored sites is recommended for effective monitoring of the acidification trends.

Biological methods (periphyton and fauna) are recommended for running waters. Water quality in running waters is very variable, which makes the chemical monitoring of the water quality problematic. Biological methods overcome this problem, collecting information from the whole growing season.

Sampling during autumnal overturn in the lakes best reflects the general water quality in the lakes (Mannio, 2001). Episodic acidifying events (high sulphate deposition, spring snow melt) need to be studied by frequent sampling (days-weeks) and/or biological methods in selected sites with low buffering capacity. Sampling of biota suits well the needs of detecting the effects of the episodic events, and so the amount of biological sampling (benthic fauna, fish) should be increased also for lakes.

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Abstract

This study presents water quality data for 30 small lakes in Finnish Lapland during 1990–2006. The presentation is concentrated on the southeastern Finnish Lapland (municipalities of Salla, Posio, Ranua, Savukoski, Sodankylä), and the results are compared to the results in the most northern Lapland (Inari municipality).

Sulphate emissions from the Kola Peninsula, as well as deposition of sulphate in Lapland declined in the 1990's. In consequence, the number of lakes with measured alkalinity below critical level (20 µeq/l) declined in Finnish Lapland to near pre-acidification level.

Sulphate concentrations in lake waters declined along with the deposition in the 1990's. No further decline in the concentrations are detected after the year 2000.

Metal concentrations in the lakes do not follow any clear trends in the study area, except for the slightly elevated nickel concentrations in Inari and Salla municipalities. However, mean copper and nickel concentrations are far to near pre-acidification level.

Based on the results, monitoring of sulphate and metal concentrations is recommended to be continued for the easternmost areas in Salla and Inari. Biological methods (diatoms, zoobenthos) would enhance the early detection of possible acidification in surface waters in the future.

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Julkaisun osat/ muut saman projektin tuottamat julkaisut	www.ymparisto.fi/lap/julkaisut	
Tiivistelmä	Tutkimus selvitti vedenlaadun muutoksia Lapin pienissä järvissä. Tulosten esittely keskittyy Kaakkois-Lappiin (Sallan, Posion, Ranuan, Sodankylän ja Savukosken kunnat), ja tuloksia verrataan pohjoisempaan Inarin itäosien alueeseen. Sulfaattipäästöt Kuolan metallisulattamoista, ja myös sulfaatin laskeuma Itä-Lappiin, pienenivät 1990-luvun aikana. Laskeuman vähenemistä on seurannut myönteinen kehitys järvien happamoitumistilanteessa: järvien, joiden alkaliniteetti on ollut alle kriittisen rajan (20 µeq/l), määrä on vähentynyt lähelle happamoitumista edeltänyttä tasoa Sulfaattipitoisuudet pienissä järvissä vähenivät laskeuman pienenemisen myötä 1990-luvulla. 2000-luvulla sulfaattipitoisuudet eivät ole enää pienentyneet. Järvien metallipitoisuuksissa ei ole nähtävissä selkeitä trendejä, paitsi hieman kohonneet nikkelipitoisuudet Inarin ja Sallan alueilla. Keskimääräiset kupari- ja nikkelipitoisuudet ovat kuitenkin lähelle happamoitumista edellyttänyttä tasoa. Tulosten perusteella sulfaatti- ja metallipitoisuuksien seurantaa tulisi jatkaa erityisesti itäisimmillä Sallan ja Inarin alueilla. Biologisten menetelmien (piilevät, pohjaeläimet) käyttö seurannoissa parantaisi mahdollisten pintavesien happamoitumisongelmien nopeaa havaitsemista tulevaisuudessa.	
Asiasanat	happamoituminen, järvet, Kuolan niemimaa, Lappi, metallit, Montshegorsk, pintavedet, sulfaatti	
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As part of the larger project "The effects of the Kola air pollution sources in the areas of the Kola Peninsula and Finnish Lapland", this study presents water quality data for 30 small lakes in Finnish Lapland during 1990–2006.

From 1990 to 2003, sulphur emissions decreased 68 % and 82 % at Nikel and Monchegorsk, respectively. During the same period, the number of lakes with measured alkalinity below critical level (20 µeq/l) have declined in Finnish Lapland close to pre-acidification level.

EFFECT OF THE KOLA AIR POLLUTION SOURCES IN FINNISH LAPLAND SURFACE WATERS DURING 1990—2006

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